



Faculty of Engineering

**Characterisation of Hybrid Durian/Luffa and Ground Coffee
Waste/Luffa Fibre Polyethylene Composite**

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Characterisation of Hybrid Durian/Luffa and Ground Coffee Waste/Luffa
Fibre Polyethylene Composite

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

This research explores the development of advanced materials known as natural fibre reinforced polymer (FRP) composites with the aim of enhancing overall quality of life. Hybrid fibres derived from durian/luffa and Ground Coffee Waste (GCW)/luffa were integrated into Polyethylene (PE) matrices to create hybrid natural fibre PE composites. The study involves a comprehensive examination of these composites through tensile testing, water absorption analysis, scanning electron microscopy (SEM), and Fourier-Transform Infrared (FTIR) analysis. Results indicate that the tensile strength of the durian/luffa PE (DLPE) composite surpasses that of GCW/luffa PE (CLPE) composites, highlighting its superior stress tolerance. Tensile modulus analysis reveals that CLPE exhibits greater elasticity than DLPE. Overall, the composites exhibit specific tensile strength and modulus, contributing to the creation of lightweight materials compared to neat PE. Water absorption testing reveals varied absorption rates, with DLPE samples absorbing more water than CLPE. SEM analysis indicates satisfactory fibre-to-matrix bonding with room for improvement, as observed gaps between fibres and matrix are present. FTIR analysis uncovers additional constituents in the chemical composition of GCW microfibrils compared to durian luffa fibres. The inclusion of natural fibres as an alternative to synthetic counterparts aligns with Sustainable Development Goals (SDG) standards. This research underscores the feasibility and benefits of fibre hybridization, emphasizing improved mechanical strength, environmental sustainability, and cost efficiency.

Keywords: Fibre reinforced polymer, hybrid fibre, tensile testing, mechanical, advanced materials

Pencirian Komposit Polimer Serat Hibrid Durian/Luffa dan GCW/Luffa

ABSTRAK

Penyelidikan ini meneroka pembangunan bahan terkini yang dikenali sebagai komposit polimer diperkuat serat semulajadi (FRP) dengan matlamat meningkatkan kualiti keseluruhan kehidupan. Serat hibrid yang diperolehi daripada durian/luffa dan Sisa Kopi Tanah (GCW)/luffa disatukan di dalam matriks Polietilena (PE) untuk membentuk komposit hibrid semulajadi PE. Kajian ini melibatkan pemeriksaan menyeluruh terhadap komposit ini melalui ujian tarik, analisis penyerapan air, mikroskopi elektron rentas (SEM), dan analisis Spektroskopi Infra Merah Fourier (FTIR). Keputusan menunjukkan bahawa kekuatan tarik komposit durian/luffa PE (DLPE) melampaui komposit GCW/luffa PE (CLPE), menunjukkan ketahanan terhadap tekanan yang lebih baik. Analisis modulus tarik mendedahkan bahawa CLPE menunjukkan keanjalan yang lebih tinggi berbanding DLPE. Secara keseluruhan, komposit menunjukkan kekuatan tarik dan modulus yang spesifik, menyumbang kepada pembentukan bahan ringan berbanding PE tulen. Ujian penyerapan air mendedahkan kadar penyerapan yang berbeza, dengan sampel DLPE menyerap lebih banyak air berbanding CLPE. Analisis SEM menunjukkan ikatan yang memuaskan antara serat dan matriks dengan ruang untuk peningkatan, kerana terdapat celah antara serat dan matriks. Analisis FTIR mendedahkan konstituen tambahan dalam komposisi kimia mikroserat GCW berbanding dengan serat durian luffa. Penggunaan serat semulajadi sebagai alternatif kepada serat sintetik sejajar dengan piawaian Matlamat Pembangunan Lestari (SDG). Penyelidikan ini menegaskan kebolehkeraan dan faedah hibridisasi serat, menekankan peningkatan kekuatan mekanikal, kelestarian alam sekitar, dan kecekapan kos.

Kata kunci: *Polimer diperkuat serat, serat hibrid, ujian tarik, mekanikal, bahan terkini*

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LIST OF ABBREVIATIONS

GCW	Ground Coffee Waste
FTIR	Fourier Transform Infrared
SEM	Scanning Electron Microscope
DLPE	Durian/Luffa Polyethylene
CLPE	GCW/Luffa Polyethylene
PE	Polyethylene
SDG	Sustainable Development Goals
FRP	Fibre Reinforced Polymers
PVC	Polyvinyl Chloride
PET	Polyethylene Terephthalate
PP	Polypropylene
PLA	Polylactic Acid
RIC	Resin Identification Code
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
AH	<i>Artocarpus heterophyllus</i>
MMC	Metal Matrix Composites
CMC	Ceramic Matrix Composites
PMC	Polymer Matrix Composites
CVI	Chemical Vapor Infiltration
PIP	Polymer Impregnation and Pyrolysis

CHAPTER 1

INTRODUCTION

1.1 Study Background

Polymers can generally be classified into two categories which are thermoplastics and thermosets. Thermoplastics are plastic materials that becomes soft or ductile at certain high temperatures and hardens upon cooling (Baeurle et al., 2006), hence it can be remoulded easily. Thermosets are soft or viscous state solids that change irreversibly into an insoluble polymer network by the action of heat or suitable radiation, or both (Horie et al., 2004).

By integrating reinforcing fillers, such as fibres, within a polymer matrix, synergistic mechanical properties that cannot be achieved by either component alone, results in a multi-phase material called a polymer composite (Wang et al., 2017) or also known as fibre-reinforced polymer (FRP) composite. Many applications in major fields such as construction, mechanical, automobile, aerospace, biomedical, and marine, utilises composite polymers with addition of natural or synthetic fibres in its fabrication, as the durability of FRPs are proven to be better than conventional materials alone (Rajak et al., 2019). Synthetic fibres common in FRPs are usually glass, carbon, or aramid (Alberto, 2013), which is not natural nor biodegradable, thus possessing a threat to the environment in relation to accumulation of plastic waste (Lebreton et al., 2017).

To combat this issue, research in alternatives for both matrix and filler, such as natural fibres, biopolymers, and chemical treatments, are constantly being engineered, as the worlds non-renewable resources are depleting by the second. Bongarde and Shinde (2014) stated that the utilisation of natural fibres such as coir, jute, bagasse, cotton, bamboo, and

hemp exist as lightweight, durable, renewable, cheap, and biodegradable substitutes for synthetic fibres in FRPs. Hybrid composites, composites comprising two or more fibres in a single matrix, have been gaining attraction amongst researchers, as it proves to exhibit enhanced characteristics when compared to homogenous FRPs (Noorunnisa Khanam et al., 2007; Jawaid & Abdul Khalil, 2011). The properties of the hybrid composite may reveal peculiar results in comparison with the individual components of the FRP composites (Jawaid et al., 2011).

Considering the unpredictable characteristics of hybrid FRPs that may manifest during experimental occasions, several researchers have utilised modern technology to predict the behaviour of FRP composites through finite-element analysis and simulation, hence reinforces the premise of the advantages brought by utilising fibres in composites (Kueh & Pellegrino, 2007; Naser et al., 2021).

1.2 Problem Statement

According to the Ministry of Energy, Science, Technology, Environment, and Climate Change (MESTECC) Malaysia ("Malaysia's Roadmap Towards Zero Single-Use Plastics 2018-2030", 2019), Malaysia's challenges include low recycling rates, uncertain biodegradability of plastics, and the high cost of current alternatives when compared to common plastics. Because of these factors, only waste materials such as clear polyethylene terephthalate (PET) bottles are recycled in large quantities, as Malaysia's recycling sector focuses exclusively on products that are easily collected and have a greater raw material value. Food packaging, plastic bags, and straws with little recycling value are nearly never recycled due to a lack of technology or commercial viability. Other than that, current biodegradable alternatives are higher in price than available plastics in Malaysia, which does

not encourage businesses to embrace alternative products. This is further augmented with arguments and challenges on the biodegradability of alternatives. On a wider scope, 55% - 60% of the 8 million tons of plastic waste that ends up in the oceans every year comes from several Asian countries (Gokkon, 2020).

Synthetic FRP composites serve as significant alternatives to the standalone polymers as they have more impressive properties such as impact strength and tensile strength. After these composites reach its end of the design life cycle and are required to be discarded, they pose a threat to the environment and industry if not disposed through correct means as they are usually costly and difficult to breakdown (Technotes, Boeing Environmental, 2003). Major drawbacks such as chemical pollution, use of hazardous chemicals, and requirement of large sums of financial, expert, and technical capabilities becomes liabilities towards the industry following recycling of synthetic FRP composites (Asmatulu et al., 2014). Moreover, it is reported that recycling and reclaiming synthetic FRP composites can lead to decrease in strength of materials (Henshaw, 2001) which is undesirable and inefficient. Thus, it is believed that the recycling of biowaste into composite materials will be greatly beneficial as it not only improves the environment, but it will also ensure conservation of non-renewable energy sources, impact the industry financially, and solve waste management problems of the society.

Thus, alternatives to synthetic FRPs are natural FRPs, which are more biodegradable and affordable. However current natural alternatives are no match in mechanical strength compared to synthetic FRPs (Begum & Islam, 2013), and the search for improvements in natural FRPs is still ongoing.

1.3 Objectives

- i. To conduct testing on the mechanical (tensile test) properties of the hybrid fibre composite fabricated.
- ii. To inspect the morphology (Scanning Electron Microscopy) of the hybrid fibre composite fabricated.
- iii. To compare water absorption properties of the Durian/Luffa/PE laminates with GCW/Luffa/PE laminates fabricated.

1.4 Hypothesis

It is believed that the produced hybrid natural fibre composites will have mechanical properties, such as tensile strength, tensile modulus, and water absorption on par with conventional PE polymers. Further, the SEM imaging will show that the natural fibres and PE polymer will have good adhesion between them.

1.5 Research Gap

The use of natural fibres in polymer composites is widespread, yet hybridisation using only natural fibres remains scarce. Most studies incorporate at least one synthetic fibre, compromising sustainability and recyclability due to pollution and limited renewability. This research addresses this gap by exploring fully natural hybrid fibre-reinforced polymer composites, enhancing mechanical properties while maintaining eco-friendliness.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

A respectable amount of research and studies have been done on FRP composites. Yet, investigations, improvements, and innovations on FRP composites is still ongoing and it continues to widen and contribute to engineering, daily life, and society. Hence, understanding and comprehension on aspects regarding FRP composites and its components, terms and structures must be known to further solidify the foundations of knowledge regarding this topic.

2.2 Polymers

The term polymer originates from the Greek word, *polumerēs*, where Poly means “many”, and the term *-mer* means “part” (polymer, 2011). The scientific definition of this term is, polymers are any class of natural or synthetic substances composed of large multiples of simple poly-functional molecules which are called monomers (Britannica, 2020.). Monomers are chained chemically together through a process called polymerization or curing to form polymers. Polymers are found almost everywhere and serve various purposes. They can be classified as either natural or synthetic. Natural polymers occur in plants, humans, animals, and minerals, while synthetic polymers include materials such as plastics and nylon. Although materials like concrete, glass, and paper are often associated with polymers, they are technically composites or amorphous solids rather than true polymers (Bradford, 2017; Perkins, 2020). The characteristics of polymers vary depending on the type of molecules they are composed of and how these molecules are linked together.

Over the centuries, the creation of synthetic polymers has brought great benefits and has proven to be impactful towards daily life. Synthetic polymers are derived from petroleum oil (Shrivastava, 2018), and several examples of these are, thermosets, which can be three-dimensional networks of polymers that do not easily melt once gone through its curing process, such as epoxy, Bakelite and silicone, while thermoplastics, can be one-dimensional linear chains that can be melted and reused (Perrin & Oueiny, 2017), such as polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC).

Thermosets have a common characteristic in where a distinct part of the molecules can undergo curing to form a specific type of link called crosslinks. According to Minnesota Rubber and Plastics (2019), polymerization process of thermoset polymers requires two-stages. The first is done to form a linear chain polymer with partially reacted portions. The second is to form final crosslinking. Thermosets are cured from its thermoset resin by either applied heat or suitable radiation, high pressure, or chemical reaction by curing agent (Minnesota Rubber and Plastics, 2019). Gotro (2014), states that the choice of hardener in curing of thermosets is important, as chosen hardeners must have functionality (f) equal to or greater than 3. In Figure 2.1, it can be observed that if the thermoset (A) has $f=2$ while the hardener (B) has $f=3$, it will lead to crosslinking and formation of the typical thermoset network. The use of a $f=2$ hardener leads to a linear polymer instead.

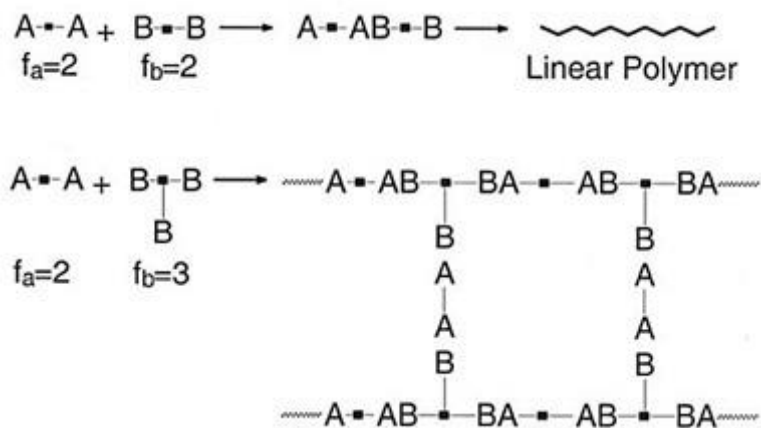


Figure 2.1: The use of hardener with different functionality in curing of thermoset resins.

Thermosets can be grouped by the basis of molecular weight of chain crosslinks. Short chains with many cross-links form thermoset resins (low molecular weight) and longer chains with fewer cross-links form elastomers (high molecular weight) (Gotro, 2014; Ratna, 2009). When excessive load is applied to hard thermosets, it may undergo permanent or plastic deformation. Elastomers can be deformed and reverted to their original shape on loading release because it is soft, springy, or rubbery in character.

Thermosets are also better suited to high temperature applications since they possess strong covalent bonds between polymer chains. The high resistance to heat and chemical degradation, and superior mechanical strength and hardness is due to the high crosslink density of a thermoset polymer. Although, this contributes to the high brittleness of the thermoset (Dodiuk & Goodman, 2013). It must be noted that curing of conventional thermosets in the industry is permanent and irreversible.

Thermoplastics soften when heated and eventually will liquefy under more heat and solidify if cooled and will exhibit glass-like brittleness under low temperatures without aid of any chemical addition. Thermoplastics can be reheated, reshaped, and solidified

repeatedly as this process is completely reversible (Monie et al., 2021). This characteristic of thermoplastics is what is sought after by manufacturers to be used in water bottles, plastic bags, and sports equipment. However, if it is subjected to very high or low temperatures, its physical properties can be lost (Strong, 2008). Thermoplastics possess greater molecular weight compared to uncured thermosets (Łątka et al., 2022).

Although if comparing thermoplastics to cured thermosets, the molecular weight of thermoplastics does not increase drastically such as cured thermosets because of the one-dimensional characteristic of its molecular chain, unlike in cured thermosets, the three-dimensional networks of 2 respective thermoset polymers crosslink to form a polymer network twice the weight when they were separate. A higher molecular weight means more links between molecules, thus more energy is required to break the links between molecules, which is the reason behind why cured thermosets have higher melting points compared to thermoplastics.

The lack of drastic increase in molecular weight in thermoplastics are what contributes to its reversibility and ease of moulding (Strong, 2008). Figure 2.2 shows how the molecular structure of thermoplastics is easily recycled due to the weak chains between thermoplastic linear chains.

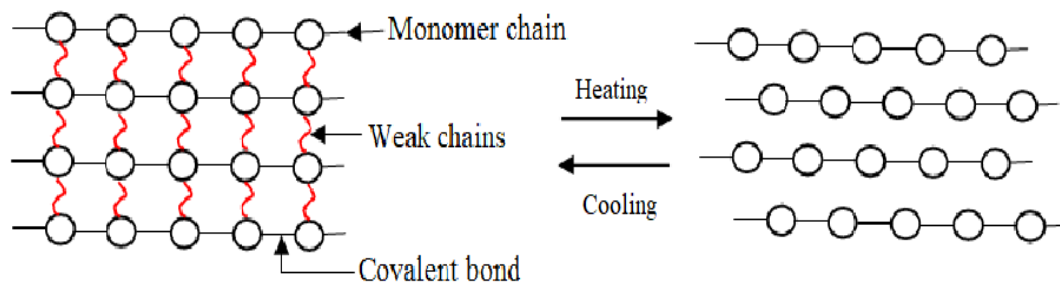


Figure 2.2: Thermoplastics and its recyclable molecular structure

Thermosets and thermoplastics are both types of polymers yet have distinct and different characteristics and properties. A short summary of comparison between thermosets and thermoplastics is simply stated as:

“Thermosets and thermoplastics come in a wide range of material options and can serve different applications if the limitations of the material are not likely to cause product failure under the intended operating conditions. The basic features of these materials remain the same: high versatility and recyclability. When it comes to useful applications in the real world, you would be hard-pressed to find a better example than the production of plastics through these two processes.” (Bîrcă et al., 2019).

Polymers can exist as hydrophilic or hydrophobic, depending on whether it is composed of natural or petrochemical origins (Finch, 1987). Hydrophobicity is the ability of a material to repel water while Hydrophilicity is vice versa (Law, 2014). In fact, more than two-thirds of hydrophilic or water-soluble polymers used in the industry are derived from polymers coming from renewable resources (Finch, 1987). A research paper worth reading further is on overcoming the incompatibility of hydrophobic and hydrophilic polymers such as the hydrophobic polymer, polytetrafluoroethylene (PTFE) and hydrophilic polymer

polyvinyl alcohol (PVA) where it is done simply by coating PTFE layers with PVA solution droplets (Meng et al., 2020). Despite that, most thermoplastics and thermosets have petrochemical origins, therefore it is safe to say that thermoplastics and thermosets majorly have hydrophobic attributes. The differences in certain characteristics between thermoplastics and thermosets can be seen in Table 2.1.

Table 2.1: Thermoplastics vs themosets.

Characteristics	Thermoplastics	Thermosets
Molecular structure	Linear weak molecular bonds.	Strong chemical crosslinking molecular bonds.
Mechanical	Flexible and elastic. Impact resistant. Crystallinity derives sturdiness.	Brittle and inelastic. Strong and rigid. Crosslinking derives sturdiness.
Melting point	Degradation points higher than melting temperature.	Degradation points lower than melting temperature.
Recyclability	Usage of heat or pressure to recycle and reuse.	Non-recyclable
Polymerisation	Addition polymerisation	Polycondensation polymerisation
Chemical resistance	Highly chemical resistant	Heat and chemical resistance.
Crack repair	Cracks can be repaired easily	Cracks are difficult to repair.
Process thermal aspect	Melting thermoplastics is endothermic	Crosslinking thermosets is exothermic
Solubility	Can dissolve in organic solvents	Do not dissolve in organic solvents

Few examples of thermoplastics and thermosets with their respective uses can be seen in Table 2.2 and Table 2.3.

Table 2.2: Thermoplastics, properties, and applications.

Thermoplastic	Properties and applications
Polyamide (nylon)	Tough and rigid material, used for power tool casings, bearings, and gears
Polymethyl Methacrylate (PMMA, acrylic)	Stiff, rigid plastic, used for signage, aircraft fuselage, bathtubs, and bathroom sinks.
Polyvinyl Chloride (PVC)	Tough, durable material, used for pipes, general household, and industrial fittings.
Polypropylene	Light, rigid material that scratches easily, chemical resistant, for lab equipment and kitchen utensils.
Polystyrene (PS)	Light, stiff, rigid, brittle, waterproof material used mainly for rigid packaging.
Polytetrafluoroethylene (PTFE)	Strong and flexible material used for non-stick cooking utensils or machine components
Low-density Polythene (LDPE)	Tough, relatively soft, chemical resistant material used for packaging, plastic bags, and toys.
High-density Polythene (HDPE)	Stiff, rigid, chemical resistant material, used for plastic bottles and casing for household goods.
Polyamide (nylon)	Tough and rigid material, used for power tool casings, bearings, and gears

Thermoplastics are a versatile class of polymers known for their unique properties, such as flexibility, recyclability, and ease of processing. These materials find extensive

applications across various industries, including automotive, packaging, and electronics, due to their ability to be moulded into a wide range of shapes and their durability.

Table 2.3: Thermosets, properties, and applications.

Thermoset	Properties and applications
Epoxy resin	Rigid material, brittle without reinforcement, used for adhesives.
Melamine formaldehyde	Rigid, stiff, and strong, chemical and water resistant, used for electrical insulation.
Polyester resin	Rigid, stiff, and brittle, used for bonding and casting.
Urea formaldehyde	Rigid, stiff, strong, and brittle used primarily in electrical devices due to its good electrical insulation properties.
Polyurethane	Rigid, strong, and durable material used in paint, insulating foam, shoes, car parts, adhesives, and sealants.
Phenol formaldehyde resin (PF)	Strong, heat and electrical-resistant material used in electrical items, sockets and plugs, car parts, cookware, and precision-made industrial parts.

In conclusion, thermosets are a class of polymers known for their exceptional heat resistance, durability, and excellent electrical insulation properties. These materials find widespread applications in industries such as aerospace and construction, where their ability to maintain structural integrity under extreme conditions is paramount. With their ability to maintain their shape and integrity under high temperatures, thermosets play a crucial role in various industries, contributing to the advancement of technology and innovation.

Table 2.4 states the Resin Identification Coding System, which is used internationally to identify the types of polymers used in different situations and conditions.

Table 2.4: Resin Identification Coding System and its uses.

Symbol and Abbreviation	Name	Uses
	Polyethylene terephthalate	Polyester fibres, thermoformed sheet, soft drink bottles, tote bags, furniture, carpet, panelling, and containers.
	High-density polyethylene	Bottles, shopping bags, milk jugs, recycling bins, agricultural tubing, base cups, automobile stops, playground equipment, and plastic lumber.
	Polyvinyl chloride	Pipe, window profiles, siding, fence, flooring, shower curtains, lawn chairs, non-food bottles, and children's toys.
	Low-density polyethylene	Plastic bags, different containers, dispensing bottles, wash bottles, tubing, and different moulded laboratory equipment.
	Polypropylene	Automobile components, industrial fibres, food containers, and dishware.
	Polystyrene	Toys, video cassettes and cases, clamshell containers, packing peanuts, and insulation board and other expanded polystyrene goods (e.g., Styrofoam)
	Others such as polycarbonate and polylactic acid (PLA)	Bottles, plastic lumber uses, headlamp lenses, and safety shields/glasses.

2.2.1 Polypropylene (PP)

PP is commonly utilized in both domestic and industrial applications, including kitchen utensils, food containers, and water bottles. Its unique qualities and flexibility to adapt to diverse production procedures distinguish it as a valuable material for a variety of applications. The current global need for the material generates an annual market of around 45000 million kilograms, and the demand is expected to expand to approximately 62000 million kilograms by 2020 (Creative Mechanisms Staff, 2016).

Propylene is a gaseous chemical formed from the thermal splitting of ethane, butane, propane, and the naphtha fraction of petroleum. Propylene is a hydrocarbon that consists of a single pair of carbon atoms connected by double bonds. Catalytic polymerization quickly breaks the double bonds, resulting in millions of propylene molecules linking together to form a huge, chainlike molecule. Propylene molecules have the chemical structure $\text{CH}_2=\text{CHCH}_3$ (Encyclopaedia Britannica, 2017).

Ziegler-Natta polymerization and Metallocene catalysis polymerization are the two main methods in producing PP. However, depending on the position of the methyl group (CH_3), PP can be further categorised into different groups (Baskaran & Sathiavelu, 2022). Seen in Figure 2.3 is the molecular structure of PP.

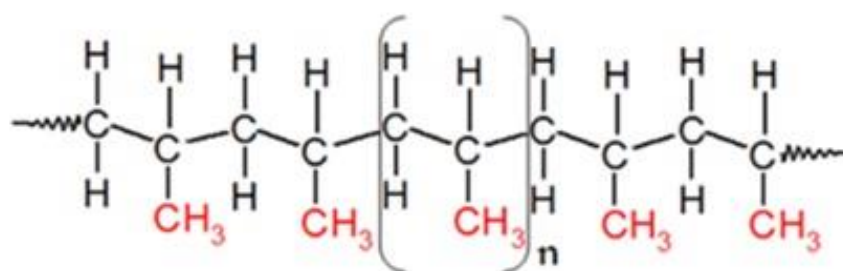


Figure 2.3: Molecular structure of PP plastic (C_3H_6)_n

Researchers have experimented and sought after many ways to make use of PP plastic and improve its usage and properties, especially in composite fabrication, seen in Table 2.5.

Table 2.5: Research in regards with PP.

Matrix	Properties and applications	Researchers
Cement-glass composite	Waste PP	Małek et al. (2021)
Alkali activated copper slag cement	PP fibre	Chakrawarthy et al. (2021)
Magnesium Phosphate cement Mortar	Micro-steel/ PP	Feng et al. (2022)
PP & recycled polyester & bicomponent fibre	Hemp	Stelea et al. (2022)
PP	Luffa/Coir	Sakthivel et al. (2014)

2.2.2 Polyethylene Terephthalate (PET)

PET plastic is a very popular thermoplastic in the industry and is constantly used to manufacture rigid and flexible packaging and containers, as it is light weight and has commendable mechanical properties. PET is manufactured by way of polymerization between ethylene glycol and terephthalic acid (Britannica, T. Editors of Encyclopaedia, 2020). Under the influence of chemical catalysts, ethylene glycol and terephthalic acid form of a molten, viscous mass that can be spun directly to PET fibres, which can be used as reinforcements in composites (Alani et al., 2020), or solidified for later processing as plastic plate samples.

Terephthalic acid is a dicarboxylic aromatic acid, which implies its molecular structure consists of six-sided carbon rings and two carboxyl (CO_2H) groups. Ethylene glycol is a diol, or alcohol with two hydroxyl (OH) groups. Ester (CO-O) groups are generated when the hydroxyl and carboxyl groups react in the presence of heat and catalysts. These ester groups serve as chemical bonds that join multiple PET units together to produce long chain polymers. Water is produced as a byproduct (Encyclopaedia Britannica, 2020). Figure 2.4 shows the molecular structure of PET.

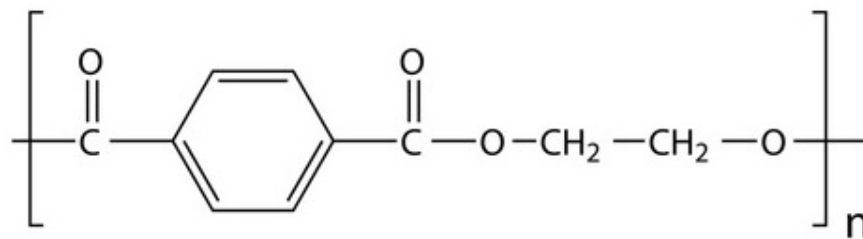


Figure 2.4: Molecular structure of PET plastic ($\text{C}_{10}\text{H}_8\text{O}_4$)_n

Researchers have experimented and sought after many ways to make use of PET plastic and improve its usage and properties, especially in composite fabrication, as seen in Table 2.6.

Table 2.6: Research in regards with PET.

Matrix	Properties and applications	Researchers
Green Ultra-High Performance Cementitious Composites (GUHPCCs)	Waste PET fibres	Alani et al. (2020)
PET	Sawdust	Rahman et al. (2013)
Epoxy	Kenaf / PET	Suriani et al. (2021)
Epoxy	Hemp / PET	Ahmad et al. (2018)
PET	Glass fibre	Yang et al. (2011)

2.2.3 Polyvinyl Chloride (PVC)

PVC is a thermoplastic widely used in building and construction applications, such as pipes, healthcare, electrical insulation, and automobile components. It is the third-most widely produced polymer, next to PP and PET (Bottausci et al., 2021). PVC is generally produced into two forms, respectively unplasticized (uPVC) and normal PVC. uPVC is rigid and brittle, hence it being less flexible in comparison to normal PVC. uPVC is usually utilised in plumbing, agriculture, and sewage purposes. Normal PVC, or PVC, is commonly used in construction such as electrical insulations, and can sometimes replace rubber as it is flexible (Creative Mechanism Staff, 2016).

When ethylene is reacted with oxygen and hydrogen chloride over a copper catalyst, the repeating monomer of PVC, which is vinyl chloride, can be obtained. However, it is noted that it is a carcinogenic gas that must be handled with caution (BrickAdmin, 2020). Through bulk, suspension, solution and emulsion polymerization of vinyl chloride, PVC can be manufactured (Saeki & Emura, 2002). Seen in Figure 2.5 is the molecular structure of PVC.

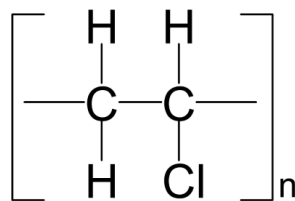


Figure 2.5: Molecular structure of PVC plastic (CH₂=CHCl)_n

Researchers have experimented and sought after many ways to make use of PVC plastic and improve its usage and properties, especially in composite fabrication, as seen in Table 2.7.

Table 2.7: Research in regards with PVC.

Matrix	Properties and applications	Researchers
PVC	BarChip 48 macro-synthetic fibre reinforced concrete	Far & Nejadi (2021)
PVC	Glass Fibre	Khan et al. (2021)
PVC/ENR	Oil Palm Empty Fruit Bunch	Ratnam et al. (2008)
PVC	Bamboo	Bahari & Krause (2016)
PVC	Rice Husk	Sudoł et al. (2022)
Review		Norfarhana et al. (2022)

2.2.4 Polylactic Acid (PLA)

Polylactic acid, also known as polylactide, is a polyester generated from renewable biomass, most fermented plant starch such as corn, cassava, maize, sugarcane, or sugar beet pulp (Rajeshkumar et al., 2021). The sugar in these renewable materials is fermented to produce lactic acid, which is subsequently processed into polylactic acid, or PLA. PLA is quite simple to work with, needing little effort to make quality parts. PLA plastic is most recognized for its application in the 3D printing business, where it is marketed in spools of filament, a stranded material, but it is also employed in other production contexts due to its unique qualities (Rogers, 2015). Some of the most popular applications are plastic films, bottles, and biodegradable medical equipment such as screws, pins, rods, and plates, which are expected to disintegrate within 6-12 months. PLA constricts when heated and is hence appropriate for use as a shrink wrap material. PLA is also valued for its eco-friendliness, biodegradability, and other properties because it is made from natural or recycled resources (Rogers, 2015). Figure 2.6 shows the chemical structure of PLA.

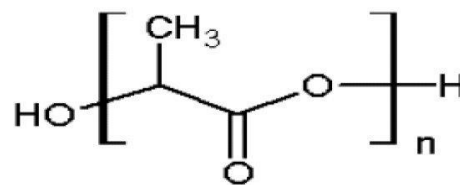


Figure 2.6: PLA chemical structure

PLA shares properties with polypropylene (PP), polyethylene (PE), and polystyrene (PS). It may be manufactured using existing production equipment (developed and originally used for petrochemical sector polymers). This makes it reasonably cost-effective to create. PLA is (C₃H₄O₂)_n. Table 2.8 presents recent research on PLA-based composites.

Table 2.8: Research in regards with PLA.

Matrix	Reinforcement	Author
PLA	Hemp Fibre	Islam et al. (2010)
Review		Valvez et al. (2020)
PLA	Banana/Sisal Fibre	Asaithambi et al. (2014)
PLA	Phosphate Glass Fibre	Hasan et al. (2013)
Review		Graupner et al. (2009)

2.2.5 Polyethylene (PE)

PE is widely used in the society as it is very easy to manufacture and has high mechanical properties which benefit many uses. It is a lightweight, durable plastic that is often used for frozen food bags, bottles, cereal liners, yogurt containers, etc. All plastics with Resin Identification Codes (RIC) 2 and 4 are made of polyethylene. PE can further be classified into several types, but here, we will focus on the 2 main types of PE which is high-density polyethylene (HDPE) and low-density polyethylene (LDPE), as it is the 2 most common types. They are distinct plastic grades, HDPE and LDPE, have differing structures and physical characteristics. Comparing HDPE with LDPE, the former has a greater density. However, when comparing the two, the density difference is just marginally different. The main difference between HDPE and LDPE is that HDPE has a higher strength to density ratio compared to LDPE. The weak intermolecular forces due to more side branches in the molecular structure of LDPE causes it to be weaker in terms of its tensile strength. However, LDPE is much more resilient in comparison to HDPE. This means the elasticity under deformation of LDPE is better than HDPE (Yashoda, 2016). Figure 2.7 is the molecular structure of PE. It is a fact that HDPE and LDPE both have the same molecular structure, however the differences are evident in Table 2.9.

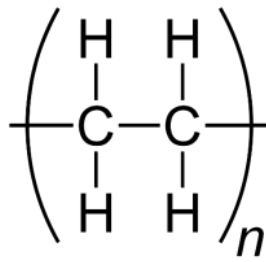
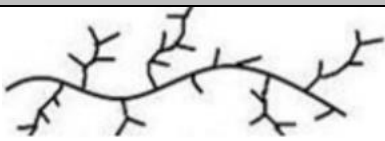


Figure 2.7: Molecular structure of PE plastic (C₂H₄)_n

Table 2.9: Differences between LDPE and HDPE (Sam et al., 2014).

Properties	LDPE	HDPE
Branch structure diagram	 LDPE	 HDPE
Density	0.91-0.94 g/cm ³	0.95-0.97 g/cm ³
Melting point	~115 °C	~135 °C
Crystallinity	Low (~55%)	High (>90%)
Transparency	Near Translucent	Milky White

Seen in Table 2.10, an abundance of research was also carried out in attempts to enhance the properties of PE.

Table 2.10: Research in regards with PE.

Matrix	Reinforcement	Author
Jute	LDPE	Ovalı & Sancak (2020)
Tampico and coir	Linear Low-Density PE (LLDPE)	Abhilash & Lenin Singaravelu (2020)
Zinc Oxide, Graphene Oxide, and Calcium Carbonate	HDPE	Rajan et al. (2022)
Coir	Recycled HDPE	Awodi et al. (2021)
Carbon Fibre	HDPE	Pearson et al. (2022)

2.3 Fibres as Polymer Composite Reinforcements

2.3.1 Synthetic Fibre

Most petrochemicals, the basic material used to make synthetic fibres, are derived from petroleum (Jenkins, 2018). Synthetic fibres are man-made fibres. About half of all fibres are synthetic, and they are used in every aspect of textile and fibre technology. The process of melt-spinning is the most popular way to make synthetic fibres, while there are other ways as well (Qin, 2016). It entails heating the fibre until it starts to melt, at which point the fibre must be immediately extracted with tweezers from the melt. The molecules would then be arranged in a parallel alignment as the next stage. This permits the fibres to solidify and orient while also bringing them closer together. In addition, many synthetic fibres offer consumer-friendly functions, such as stretching, waterproofing, and stain resistance (Jamir et al., 2018). In general, synthetic fibres are created by extruding fibre-forming materials through spinnerets into air and water, forming a thread.

Carbon Fibre

Carbon fibres are those that contain more than 90% carbon. Thermal conversion of organic fibres produces hundreds of filaments with diameters ranging from 5 to 10 μm . Carbon fibres, according to Pusch and Wohlmann (2018), have various advantages such as high stiffness, high tensile strength, high strength-to-weight ratio, good chemical resistance, high temperature tolerance, and minimal thermal expansion. Figure 2.8 depicts a sample of carbon fibre mat.

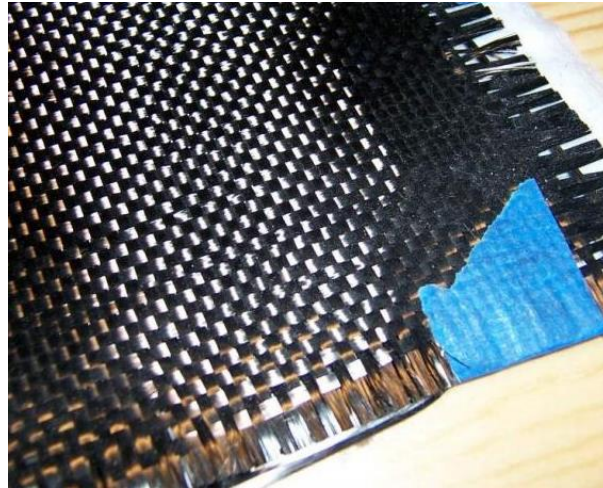


Figure 2.8: Carbon fibre mat

Carbon atoms are joined together in crystals that are generally parallel to the fibre's long axis to form carbon fibres, and this crystal alignment provides the fibre with a high strength-to-volume ratio. Several thousand carbon fibres are bundled together to create a tow, which can be utilized alone or woven into a fabric (Basu et al., 2023).

To create a composite, carbon fibres are typically mixed with other materials. For instance, carbon fibre reinforced polymer, which has a very high strength-to-weight ratio and is incredibly hard but slightly brittle, is created when it is baked after being infiltrated with a plastic resin. Compared to parts composed of metals like aluminium or other fibre reinforced composites, these composite components are lightweight and have extremely high mechanical characteristics. Aerospace and spacecraft parts, racing car bodies, golf club shafts, bicycle frames, fishing rods, car springs, sailboat masts, and many more parts requiring great strength and low weight are all made from carbon fibre reinforced composite materials. Particularly when it comes to lightweight constructions that lower energy use, the automotive industry is experiencing considerable growth. However, they are somewhat pricey when compared to fibres that are like them, including glass, basalt, or plastic (Pakdel et al., 2021). Various classes of carbon fibre can be seen in Table 2.11.

Table 2.11: The features of various carbon fibre classes (Mirdehghan, 2021).

Fibre Type	Acronym	Tensile Strength (GPa)	Young's Modulus (GPa)	Maximum Elongation (%)
High tension	HT	3 - 5	200 - 250	1 - 2
Intermediate modulus	IM	4 - 7	250 - 350	1 - 2
High modulus	HM	2 - 4.5	350 - 450	0.5 - 1
Ultra-high modulus	UHM	2.5 - 3	600 - 700	0.25 - 0.5

Glass Fibre

Glass fibres can be made in a range of compositions by adjusting the number of raw materials, such as sand for silica, clay for alumina, calcite for calcium oxide, and colemanite for boron oxide. Thus, different types of glass fibres with different ratios of silica or other materials demonstrate different qualities, including good mechanical qualities or resistance to alkali. The mechanical characteristics of glass fibre are like those of other fibres, such as carbon fibre and polymers. When utilized in composites, it is far less brittle and far less expensive than carbon fibre even though it is not as stiff. Because of its superior damage tolerance for impact loading, high specific strength, and stiffness, glass fibre reinforced composites are used in the marine and plumbing industries. Seen in Figure 2.9 is a sample of glass fibre.



Figure 2.9: Glass fibre (Jacoby, 2021)

Glass fibres are a highly diverse material class. In polymeric resins such as unsaturated polyester and epoxy, they are frequently used as reinforcing fibres. Compared to other reinforcing fibres, glass fibre is less stiff, but it has the unique advantage of combining a very high strength with a low density and a reasonably low cost. Preserving the glass fibre filaments from breaking or disintegrating is an important concern when producing glass fibre or composite materials. Reducing vehicle weight is the main approach to save energy in the transportation industry. The rise in the production of lightweight automobiles to around 50% illustrates the significance of glass fibre-reinforced composites in this regard. Table 2.12 is the features of glass fibre.

Table 2.12: The features of glass fibre (Hamad, 2017).

Fibre Properties	Quantities
Fibre length	12 mm
Specific gravity	2.68 g/cm ³
Modulus of elasticity	72 GPa
Tensile strength	1700 MPa

2.3.2 Natural Fibres

Fibres acquired naturally, not man-made, are considered natural fibres. They can be acquired from either plant, minerals, animals, or any other living organisms (Mohammed et al., 2015). Figure 2.10 further classifies natural fibres into classes of cellulose fibres, protein fibres and mineral fibres (Veerendra, 2023).

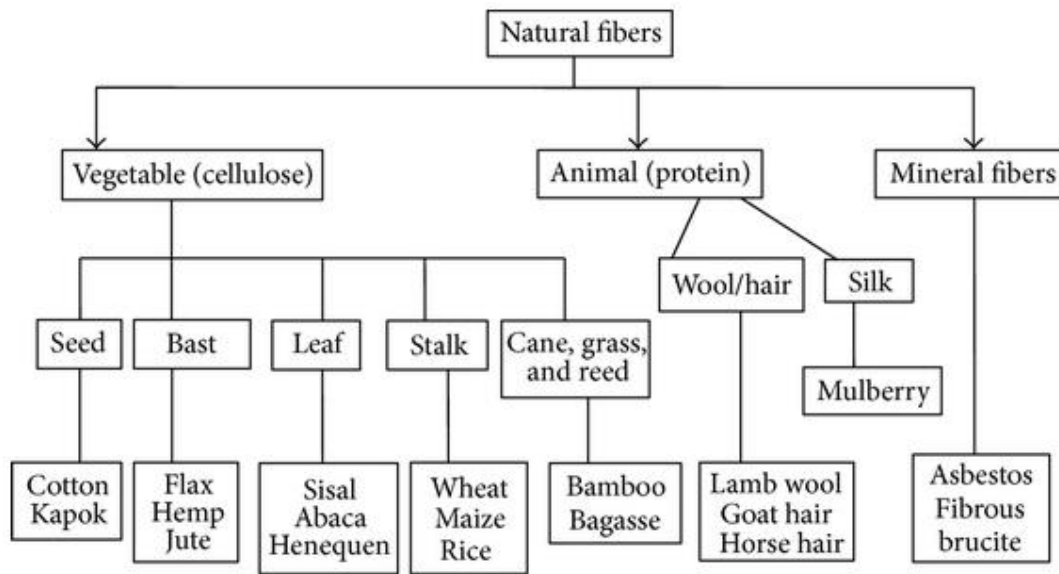


Figure 2.10: Classes and examples of natural fibres

The use of natural fibres dates to the 6th century BCE, where flax and wool fabrics were utilised by Swiss lake dwellers. During the 4500 BCE, hemp, which originated from Southeast Asia, was cultivated by China, while around the 3400 BCE, Egypt cultivated flax to produce linen. Other than that, in 2640 BCE, the first methods of spinning silk and cultivation of silkworms were traced back to China to create highly prized silk products (Encyclopaedia Britannica., 2020). The use of natural fibres varies, either in creation of clothes, bags, and traditional products, or in modern creations, such as fillers for composites. It must be noted that, extraction of natural cellulose fibres is required and usually involves

3 major processes, mechanical extraction such as hand scraping, chemical extraction such as use of alkali solutions, and through a process called retting (Hulle et al., 2015).

Retting is the process where diverse microbial populations and moisture in the environment are utilised to break down and dissolve pectin and other components that bind the fibres to the tissue or stem (Schlottenhofer & Yuan, 2017). The most common type of retting is natural water retting. Bundles of stalks are submerged in slow flowing water, such as slow streams or rivers, and is allowed to penetrate to the central stalk portion. The inner cells swell, and bursts the outermost layer, thus increasing absorption of both moisture and decay-producing bacteria. However, natural water retting requires about 2 weeks and precise timing to avoid under-retting or over-retting (Encyclopaedia Britannica., 2017). This process also is highly dependent on water temperature, seasons and water mineral content which determines the actual total time required for a complete retting.

Dew retting is a process in which the stems of plants are spread out in moist meadows, and the pectin decomposition is accomplished by moulds and aerobic bacteria. Dew retting is a common method in countries in Northern and Western Europe, and areas having limited water resources. Heavy dew falls overnight, and warm daytime temperatures are what spurred this method. This method is much more sustainable than using chemicals or water. Within 2-3 weeks, depending on the climatic changes, the fibre would be ready for extraction. Dew-retted fibre is generally darker in colour and of poorer quality than water-retted fibre (Encyclopaedia Britannica., 2017).

The modern way of retting is called tank water retting. Instead of being submerged in slow flows of water, several concrete vats of water are utilised to achieve this effect. Tank water retting allows enhanced control and outputs better uniform quality of fibres. The

process requires 4 to 6 days to complete and is effective in any season. In the first eight hours, the dirt and colouring matter is removed by the water, which is changed from time to time to assure clean fibre. The waste retting water, which requires chemical action to reduce harmful elements before it is released, is rich in nutrients and is usually used as liquid plant fertilizer (Encyclopaedia Britannica., 2017). After drying in open air or mechanical means, the final process of the retting process to obtain natural fibres is the removal of the brittle woody portion of the straw either by hand or by passing through machines such as rollers.

Mechanical extraction of natural fibres usually requires the use of force to do extract fibres from source either manually scratching or by machine. This method can yield high quantities of short fibres in shorter periods of time compared to retting but the chance of acquiring low quality fibre may ensue (Lee et al., 2020). Many different methods have been introduced by researchers worldwide. One of the many ways is by using machines such as decortication machines (Bacci et al., 2010). This method may be fast, and less tiring compared to manual extraction, however for different types of natural fibre sources, it may require different types of machines, which can incur large sums of financing. One other example is of manual mechanical extraction (Wolela, 2019). Here, hand scraping by using a knife, ceramic plate and so on, are scratched onto leaves or sources of fibres until the fibres are visible. This method is simple, cheap, and effective, however, hand scraping, or similar techniques, requires manual labour, and is much too tiring if required to be done at a large scale or the source is too dense to penetrate. Other than that, this method requires fibres to be extracted as soon as possible after harvest, to ensure the fibres are not too dry and become too difficult to extract.

Next, a method called Steam Explosion Method (Shinde et al., 2018) in mechanical extraction is used. This method requires low energy consumption by separating and fracturing the cell walls of a source and producing pulp. This can help in separating the lignin content from a plant surface. This method usually requires the plant to be heated and dried in ovens for a period. This can be seen in the steam explosion process for raw bamboo by slicing and heating it at 175 °C for 1 hour at 0.8 MPa. Then, steam is let out and this is repeated for nine extra times. Finally, it is dried in an oven at 105 °C for 24 hours. With this, the fibre cell walls are broken down and bamboo fibres becomes pulpy, thus eases extraction of long fibres (Shinde et al., 2018). However, the fibres yielded are usually dark in colour.

Then, in mechanical extraction, grinding and crushing can be used. This method usually requires the plant or organic source to be boiled or soaked in water, or dried before it is ground into pulp or powder and compiled to be into sheets of fibre or added to form composites directly. Researchers have extracted *Artocarpus heterophyllus* (AH) fibre by grinding in a blender, extracting the fibres, and thus drying to fabricate sheets to be used in composites (Nicholas Kuan, 2018). Another popular fruit used in research to be using grinding and crushing in extracting natural fibres to fabricate composites is orange peels fibre, where the peels after drying are ground to powder form and were sieved (Ojha et al., 2012). This method is simple and yields short fibre lengths, without incurring heavy finances. However, in mechanical extraction of fibres, researchers continue to find novel ways in extracting fibres. One research approach to extract fibre allowed researchers to extricate long and fine fibres. The mechanical properties of the untreated fibre by this novel method, such as the quality of longitudinal flex, was highly notable (Shinde et al., 2018).

Chemical extraction methods have been tested abundantly in research, and use of alkali solutions is recommended because the solution encourages the breaking down of composite fibre bundles to smaller fibres and reduces the fibre roughness and results in good quality fibre (Mumthas et al., 2019).

Table 2.13: Extraction methods of natural fibres.

Extraction Methods	Advantages	Disadvantages	Duration
Water Retting	Produces fibres with uniformity and of high quality	Pollution due to anaerobic bacteria, putrid odour, high cost to treat wastewater	7-14days, depending on environmental changes
Dew Retting	Easily remove Pectin materials	Contamination with soil, restricted to certain climates, differing quality, and reduced strength	2-3 weeks, depending on environmental changes
Chemical Retting	Obtain smooth and clean surface	Strength deterioration when concentration of NaOH more than 1% is used	60-75 minutes
Mechanical Retting	High quantities of short fibre can be obtained in a short period	Lower fibre quality	-

However, there is claim of deterioration in fibre strength when more than 1% concentration of NaOH is being used (Lee et al., 2020). The chemical extraction uses alkali solution to separate lignin content from the fibres. The chemical extraction of natural fibres is simple, effective, and usually only requires an average of 60 minutes (Wolela, 2019) at 5% concentration. The utilisation of alkali solutions of Sodium Hydroxide (NaOH) is usually used, however use of other alkali solutions such as Hydrogen Peroxide (H₂O₂) and Sodium

Benzoate ($\text{C}_6\text{H}_5\text{COONa}$) can be used (Lee et al., 2020). The most optimal extractions of natural fibres with this method used NaOH solution with optimum concentration (4-10 wt%) at 70°C for 60 minutes, then washed with distilled water right after (Wolela, 2019). One example is done by researchers where the use of grounded coffee wastes (GCW) is treated with NaOH solution of 1% concentration for as long as a day, then washed in distilled water till pH is equal to 7. The results presented by the researchers is that treated GCW exhibit better characteristics than untreated GCW (Tan et al., 2017). Table 2.13 shows the extraction methods mentioned above with its advantages and disadvantages. Most natural fibres, except for mineral fibres, in nature are hydrophilic, or have an affinity for water, as it is made up of constituents like cellulose, lignin, hemicellulose, pectin, waxes, and water-soluble substances (Girijappa et al., 2019). Unlike man-made fibres, fabricated from petrochemicals, they are total opposites of one another. Natural fibres will decompose at when kept at their respective decomposing temperature. There is no shrinkage, melting or high extensibility upon heating, nor do they become brittle if cooled to below freezing (Encyclopaedia Britannica., 2020). Figure 2.11 is the constituents of plant fibres.

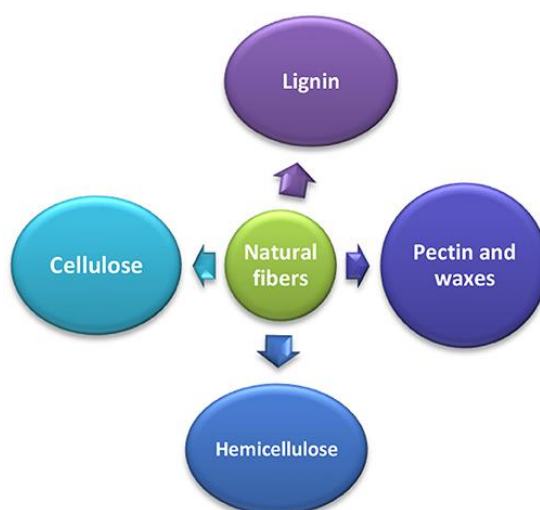


Figure 2.11: Constituents of plant fibres (Girijappa et al., 2019)

Luffa acutangula /Luffa cylindrica

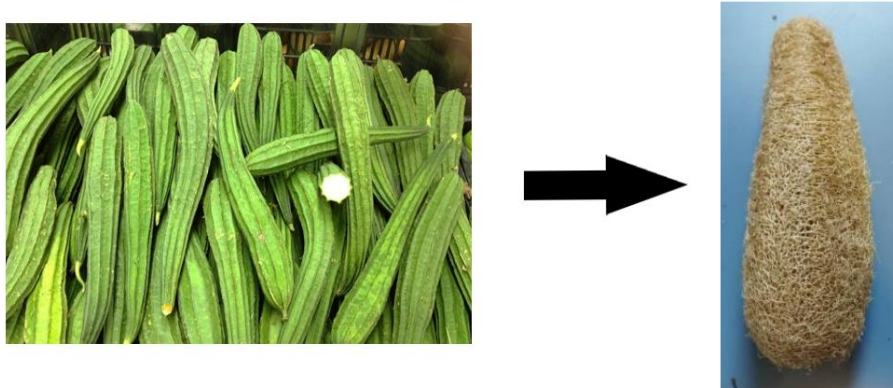


Figure 2.12: Fresh luffa ripens and dries into fibrous network

Figure 2.12 shows the luffa. Sponge gourd, or luffa, is a plant of to the Cucurbitaceae (or cucumber) family that grows in east and central Asia and south Asia. Its fruit, a gourd, is cylindrical and green in form, and it climbs on other physical surfaces that are solid. Its young fruits are utilized as natural cleaning sponges, while its mature fruit is eaten like vegetables. Like metals with a comparable density, luffa fibres exhibit significant strength, stiffness, and toughness (Jino et al., 2017). In addition to inorganic substances including glycosides, polypeptides, amino acids, proteins, and other molecules, lignin and hemicellulose/cellulose make up most of the chemical composition of luffa (Alhijazi et al., 2020). Table 2.14 lists luffa's characteristics. Luffa is a highly favoured material by researchers studying FRPs because its easily manufactured fibrous network of fibres makes it ideal for integration into the polymer matrix.

Table 2.14: Properties and chemical composition of luffa fibres (Alhijazi et al., 2020).

Density (gm/cm ³)	Diameter (μ m)	Aspect ratio	Microfibrillar angle (°)	Hemicellulose (%)	Cellulose (%)	Lignin (%)
0.56-0.92	270 $\pm$ 20	340 $\pm$ 5	12 $\pm$ 2	20.88 $\pm$ 1.4	63.0 $\pm$ 2.5	11.69 $\pm$ 1.2

Ground coffee waste (GCW)



Figure 2.13: Coffee beans ground into microfibre coffee wastes

CGW is shown in Figure 2.13. An estimated 6 million tonnes of residue from ground coffee are produced annually worldwide (Tokimoto et al., 2005). Numerous organic substances, including lignin, fatty acids, cellulose, hemicelluloses, and other polysaccharides, are present in GCW (Pujol et al., 2013). The environment is negatively impacted by the presence of chemicals and high concentrations of organic waste from the GCW. It is important to properly dispose of GCW to turn it into value-added products. GCW has been utilized as compost, a source of sugar, a metal ion absorbent, a precursor to activated carbon, and in the production of biofuels (Tan et al., 2017). The chemical composition of CGW is shown in Table 2.15.

Table 2.15: Chemical components of coffee ground (g/kg) (Baek et al., 2013).

Crude Fibre	Ether Extract	Ash	Nitrogen Free Extract	Etc
466-510	222-283	7-8	143-168	1.4-2.0

Current research suggests that GCW has tremendous promise in a wide range of composite engineering applications, including automotive, packaging, and lightweight furniture (Tan et al., 2017).

Durio zibenthinus



Figure 2.14: Durian peels processed into fibres (Lubis et al., 2018)

Peels from durian are seen in Figure 2.14. Known as the "King of Fruits," durian (*Durio zibenthinus*) is a prominent tropical fruit in southeast Asia. The surface of durian is covered in sharp thorns, according to its morphology (Aziz & Mhd Jalil, 2019). Depending on the species, the fruit has an oval, nearly spherical shape, and weighs, on average, between 2 and 4.5 kg. According to Ketsa et al. (2019), it has thick, semi-woody, green to yellowish-brown colour, and pyramidal thorns that are sharply pointed. Roughly 85% of the fruit is thrown away as waste, which could harm the environment if it is not disposed of properly (Torres-León et al., 2018). With an annual production of over 480000 metric tonnes of durian wastes, durian peel can be considered the main source of agricultural wastes that are growing in volume (Manshor et al., 2014). It will require more space for disposal, particularly in landfills. One method is to burn them, although this could cause environmental damage (Chua et al., 2023). The composition of durian peel fibres that improves the characteristics of composites while submerged in water is shown in Table 2.16 (Payus et al., 2021).

Table 2.16: Composition of durian peel fibres (Adunphatcharaphon et al., 2020).

Ash (%)	Hemicellulose (%)	Cellulose (%)	Lignin (%)
4.20	9.63	47.2	9.89

2.4 Composites

The composites' classification is shown in Figure 2.15. Composites are made up of two or more different materials together. Rather than occurring or forming organically, this multiphase material is purposefully manufactured (Callister & Rethwisch, 2018). Depending on the kind of materials being mixed, composite materials offer better qualities than those of the separate components when used alone (Ngo, 2020). Composite materials are typically made up of two parts: the matrix and the reinforcement. Metals, polymers, or ceramics are common examples of matrix materials. However, the reinforcements in composites might take the shape of particles, flakes, or fibres. Together, these different constituent components of the composite offer it special qualities like strength and light weight. Because many composites can be moulded into intricate patterns, they also offer design freedom (Amir et al., 2019). The fact that composite materials are so versatile and can be used in so many different industries is the main reason we need them.

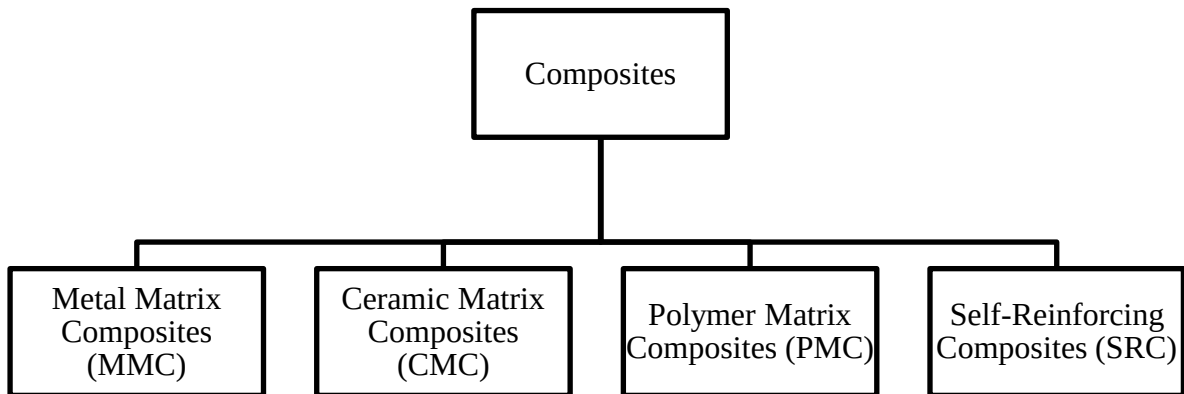


Figure 2.15: Classification of composites

Composites can be further classified into CMC, PMC, MMC, and SRC. These classifications have respective advantages and disadvantages among each other, such as cost, mechanical strength, chemical resistance, and ductility.

2.4.1 Metal Matrix Composites (MMC)

Seen in Figure 2.16 is the classification of MMC. MMCs are as its name, composites which are made up of monolithic metallic materials as the matrix (Li et al., 2021). Its reinforcement usually is comprised from ceramics, such as Al_2O_3 , SiC , B_4C , TiC , Si_3N_4 , AlN and ZrO_2 , and can be in the form of sheets, particles, or, continuous or discontinuous (short) fibres (Suresh et al., 2022).

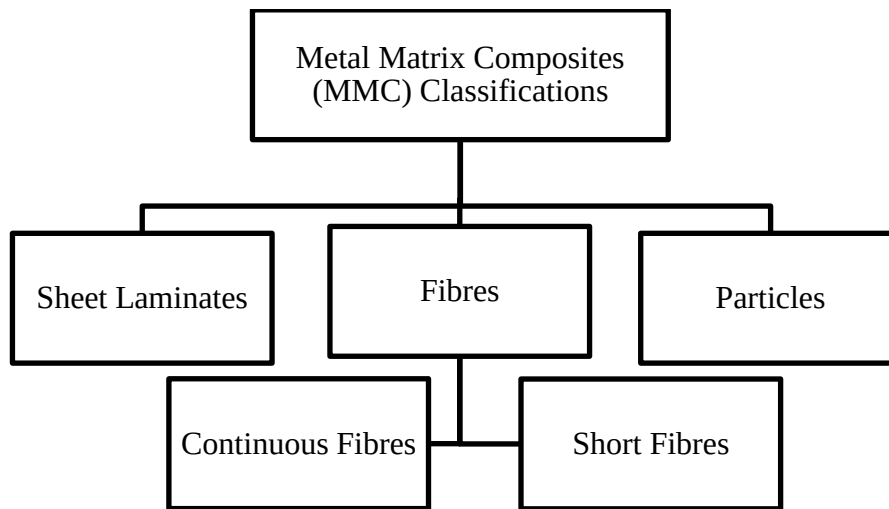


Figure 2.16: Classification of MMC

It must be noted that alloys and MMCs are different. The primary distinction is that when alloys are created, its component parts are often melted down and mixed to create an intermediate substance that is both chemically and structurally distinct from the original components. In MMCs, metallic and non-metallic materials may be mixed with a metallic matrix, but the various components do not undergo chemical alterations and stay unchanged from their initial states (BYJUS, 2021). Few examples of this composite can be seen in Table 2.17.

Table 2.17: Examples of MMCs previously fabricated.

Specimens (Type)	Fabrication	Impact Strength (J)	Tensile Strength (MPa)	Researchers, Year
0.2 vol% Graphene/Copper composites	Magnetron sputtering and graphene transfer	-	70	Lin et al. (2021)
Bio inspired carbon fibre/titanium/magnesium alloy AZ91 laminated composites	Squeeze casting	-	260	Hu et al. (2018)
Sisal reinforced aluminium laminates	Hand layup process and uniaxial cold compaction	34.05	-	Vieira et al. (2022)
Magnesium-intermetallic composites	Vacuum furnace diffusion bonding	14	-	Konieczny (2022)
4% Copper-Nickel coated carbon fibre aluminium alloy composites	Compo-casting	6.1	181.94	Gajalakshmi et al. (2020)

2.4.2 Ceramic Matrix Composites (CMC)

Figure 2.17 is the classification of CMC. CMCs were fabricated in hopes to overcome the problems derived from cracks by small defects or surface scratches on conventional ceramics like alumina, zirconia, silicon carbide, or carbon. Other than that, combining different ceramic matrix materials with special suitable fibres, new properties can be created and tailored for interesting technical fields, such as increased mechanical properties (Low, 2018).

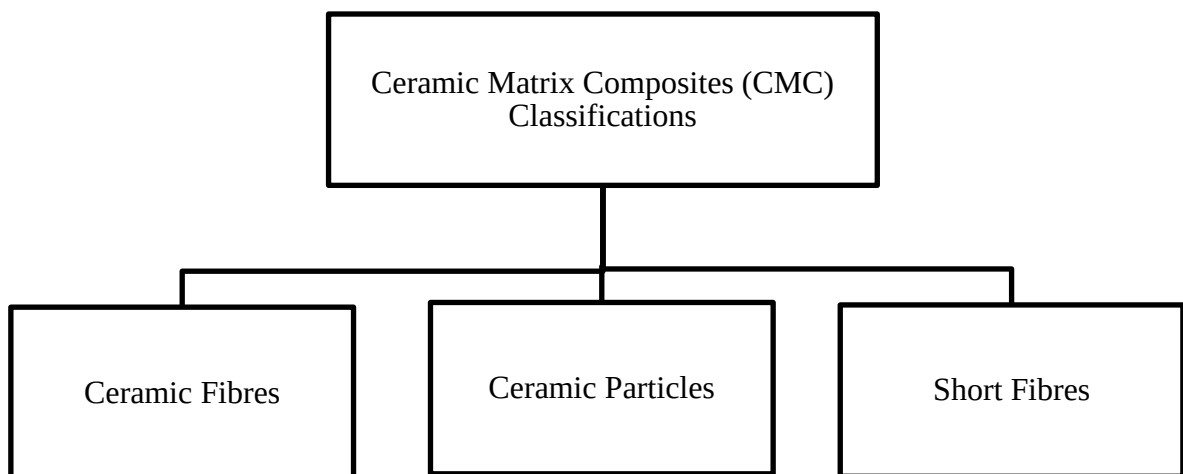


Figure 2.17: Classification of CMC

Ceramics generally have high melting temperatures, which means fabrications of CMCs are required to at least maintain this trait to be relevant in its field of use. Furthermore, forming techniques of these CMCs requires high temperatures, hence organic or polymeric fibre materials cannot be used in CMCs as reinforcements because of their degradation temperatures below 500 °C (L&L Special Furnace Co, Inc., 2022). Also, conventional glass

fibres, with melting or softening points below 700 °C, cannot be used for this purpose (Clau, 2008). Methods to form this composite can be seen in Table 2.18.

Table 2.18: Forming methods of CMCs (Dhanasekar et al., 2022).

Methods	Forming Temperature	Description
Sintering (Oxide and non-oxide)	Oxide: 1200 °C to 1800 °C Non-Oxide: 1600 °C to 2200 °C	This temperature is required to densify the ceramic matrix material and achieve the desired mechanical properties.
Chemical Vapor Infiltration (CVI)	800 °C to 1200 °C	CVI is a method that involves the deposition of ceramic material onto a preform using a gas-phase reaction.
Polymer Impregnation and Pyrolysis (PIP)	800 °C to 1600 °C	A polymer matrix precursor is impregnated into a fibre preform and subsequently pyrolyzed to form the ceramic matrix.
Liquid Silicon Infiltration	1400 °C to 1600 °C	Involves the infiltration of molten silicon into a fibre preform.

Fabrication methods for CMCs typically involve techniques such as chemical vapor infiltration (CVI) and polymer infiltration and pyrolysis (PIP). In CVI, a gaseous precursor infiltrates the ceramic matrix and forms a solid phase upon decomposition. PIP, on the other hand, relies on impregnating the ceramic preform with a polymer precursor, followed by pyrolysis to convert it into a ceramic phase. These methods enable precise control over material properties, making CMCs vital for aerospace and advanced engineering applications. Table 2.19 are few examples of CMC previously fabricated.

Table 2.19: Examples of CMCs previously fabricated.

Specimens (Type)	Thermal Characterisations	Fabrication	Researchers, Year
Carbon/Silicon Carbide composites	Ablation observed was due to a combination of oxidation, mechanical erosion, and recrystallization of the surface Silicon Carbide.	PIP	Yan et al. (2009)
Carbon/Silicon oxycarbide and Carbon/silicon boron oxycarbide composites	The C/SiBCO composites showed better thermal stability than the C/SiOC materials.	PIP	Siqueira et al. (2007)
Carbon/ZrB ₂ -SiC-ZrC	Carbon short fibre composite tested showed a high thermal conductivity compared to plain-woven.	Silicon melt-infiltration	Inoue et al. (2018)

CMCs represent a cutting-edge class of materials that offer a compelling solution to the challenges of high-temperature and high-stress environments. Their unique combination of ceramic matrices and reinforcing fibres provides exceptional thermal and mechanical properties, making them ideal for applications in aerospace, gas turbine engines, and other demanding industries. As technology continues to advance, CMCs hold the promise of revolutionizing various industries by enabling lighter, more efficient, and more durable components. With ongoing research and development efforts, CMCs are poised to play a pivotal role in shaping the future of engineering and manufacturing.

2.4.3 Polymer Matrix Composites (PMC)

Figure 2.18 is Polymer matrix composites (PMCs), which are well renowned in the field of materials engineering, as they have deliberately enhanced material strength, stiffness, density, and economical value of conventional polymers (Qiao et al., 2022). Their uses range from medical appliances (Tuloup et al., 2020) and automotives, to furniture and household appliances.

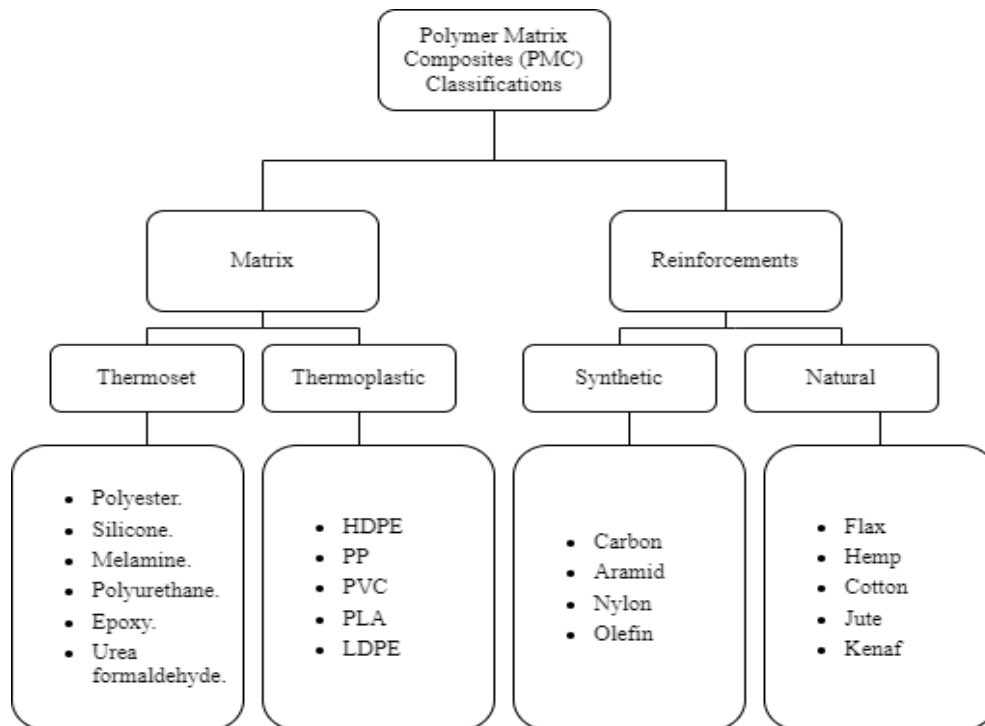


Figure 2.18: Classification of PMC

They are designed to transfer loads between fibres of a matrix and its matrices are typically either thermosets or thermoplastics, which are derived from petroleum oil. Reinforcements usually used in PMCs are also of synthetic origins, such as fibreglass, aramid, and carbon fibre, however use of natural fibres such as flax, cotton, kenaf, hemp, and bamboo does contribute to an increase in mechanical properties, however, it does still underperform in mechanical properties when compared to synthetic fibre reinforced PMCs,

as the natural fibre does not bond well with the polymer matrix interface, unless added with additives or hybridisation of the reinforcements (Ashothaman et al., 2023). Examples can be seen in Table 2.20.

Table 2.20: Examples of PMCs previously fabricated.

Specimens (Type)	Fabrication	Young's Modulus (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Researchers, Year
Epoxy/Kevlar	Chemical vapor deposition	16 - 22	300 - 375	160 - 250	Taraghi et al. (2014)
LDPE/Glass	Hot compression	1.5 - 2.5	45 - 90	15 -27	Jahan et al. (2012)
PLA/Nylon	Twin-screw extrusion	2 - 4	30 - 55	-	Thongpin et al. (2015)
Polyester/Banana	Hot compression	-	12 - 23	76 - 125	Dhakal & Keerthi Gowda (2017)

Polymer matrix composites are a versatile and widely used class of materials that offer a combination of strength, light weight, and corrosion resistance. They have found applications in various industries. By reinforcing polymers with materials like fibreglass, carbon fibres, or aramid fibres, engineers can tailor the properties of these composites to meet specific requirements, making them an essential part of modern material science and engineering. As technology advances, we can expect further innovations in the development and application of polymer matrix composites, paving the way for even more efficient and sustainable solutions in various fields.

2.4.4 Self-Reinforcing Composites (SRC)

Figure 2.19 is an example of SRC. Self-Reinforced Composites (SRC) are a category of composites which utilizes matrix with reinforcements of similar chemical composition. Unlike traditional fibre-reinforced composites (FRC), which are made up of different constituents, SRC materials consists of matrix phases and reinforcements of homogeneous material but shows different structures and performance (Zhang et al., 2021). The earliest instance of the SRC concept was by Capiati and Porter (1975), where gel-spun high-modulus polyethylene (PE) fibres were embedded in lower melting point PE resin. Advantages in comparison with traditional FRC is that SRC eliminates the problem of compatibility between the matrix and reinforcement, furthermore, supports the recycling of materials since they are of homogeneous materials (Zherebtsov et al., 2020). Several SRCs have proven to be advantageous in terms of its mechanical strength and has since been commercialized (Santos et al., 2021). Polymer SRCs, a class of SRCs, have various advantages, such as, high strength, and stiffness, excellent impact resistance at low density, and greater biodegradability (Babu et al., 2022). Table 2.21 is other examples of SRC.

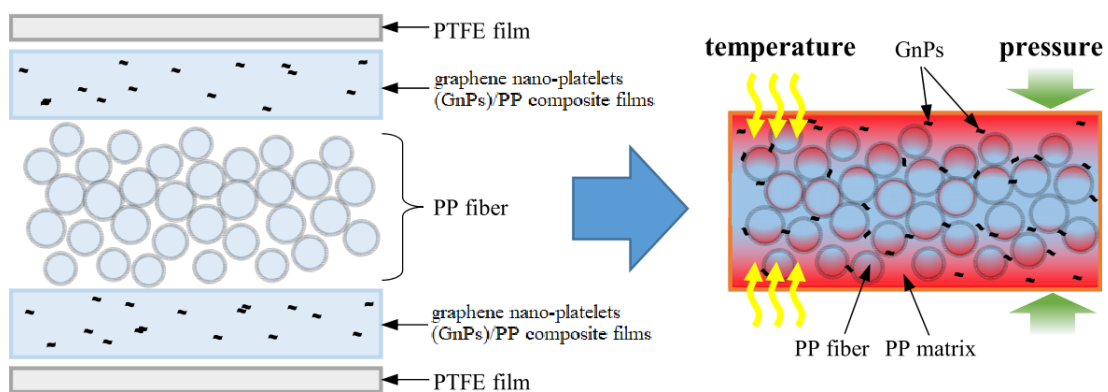


Figure 2.19: Example of SRC ; Self-reinforced composites based on polypropylene fibre and graphene nano-platelets/polypropylene film (Wang et al., 2022)

Table 2.21: Examples of SRCs previously fabricated.

Specimens (Type)	Type	Young's Modulus (MPa)	Tensile Strength (MPa)	Researchers, Year
Ultra-high-molecular-weight polyethylene (UHMWPE) fibres and HDPE filament	Continuous fibres SRC	8200	300.2	(Zherebtsov et al., 2020)
0.019 wt% GnPs/PP/SRC	SRC	3500	70	(Wang et al., 2022)
PURE (PP/co-PP)	Tapes	6300	200-210	(Vuba et al., 2023)
SRPET (PET/co-PET)	Fibres	4700	160-170	(Schneider et al., 2013)

The future of self-reinforced composites holds great potential for further advancements in material science and engineering. As researchers continue to explore novel combinations of matrix and reinforcement materials, as well as innovative manufacturing techniques, we can anticipate even more remarkable properties and applications for self-reinforced composites. These materials are likely to play a significant role in addressing the evolving demands for sustainable, high-performance materials in our rapidly changing world.

2.4.5 Synthetic Fibre Reinforced Polymer (SFRP), Natural Fibre Reinforced Polymer (NFRP), Hybrid Fibre Reinforced Polymer (HFRP) Composites

There has been a lot of research on fibre-reinforced polymer (FRP) composites over the last 20 years. This is not surprising, since some FRP composites are designed to intentionally improve material properties like stiffness, density, strength, and economy in the mechanical, aerospace, automotive, marine, and construction fields (Rajak et al., 2019), in ways that a traditional single pure polymer would not (Asmatulu et al., 2013). But to maintain the sustainability of the sources, the necessity for enhancing these attributes must be improved linearly (Rajak et al., 2019).

Combining two or more elements to create a new designed material is the idea underlying composite materials (Foo et al., 2011). Accordingly, natural, or synthetic fibres serving as load-bearing reinforcements, offering strength and stiffness, are embedded in polymer matrices that preserve the fibres' position and orientation while shielding them from potential harm in FRP composites (Asmatulu et al., 2013). The binder material, which holds or binds the filler material—typically a polymer matrix—and the filler material—typically fibres, sheets, pieces, particles, or whiskers of natural or synthetic material—are the basis for classifying composite materials (Rajak et al., 2019). This is further demonstrated in Figure 2.20.

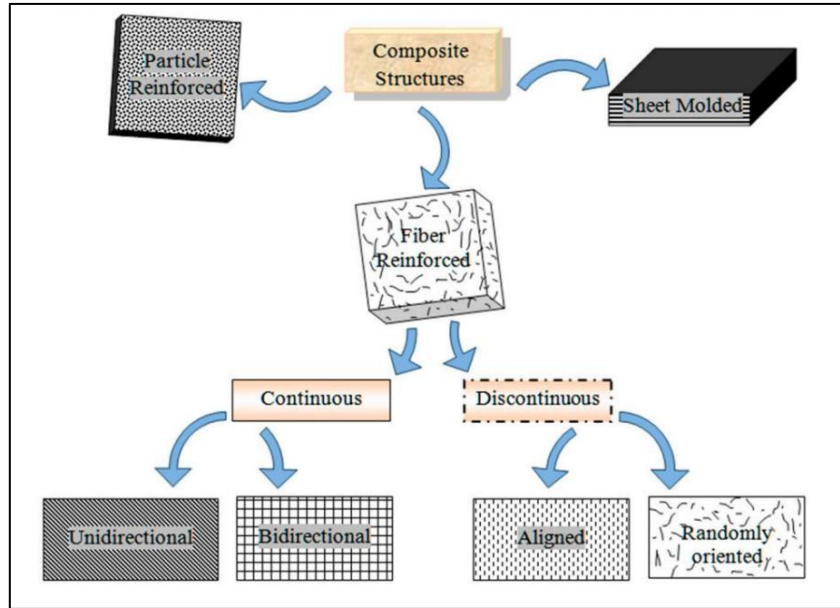


Figure 2.20: Classification of composites (Rajak et al., 2019)

Two main categories of FRP composites exist, which are the Synthetic FRP (SFRP) and Natural FRP (NFRP). Synthetic fibres materialised from glass, carbon, aramid, Kevlar, etc, are made from raw materials such as petroleum, based on chemicals, or petrochemicals (Jamir et al., 2018). The fabrication of synthetic FRPs is much easier than natural FRPs because their components, which is made up of synthetic fibres and synthetic polymers, are much more compatible in terms molecular characteristics; both synthetic fibres and synthetic polymers are made up of the same raw materials. SFRPs exhibit properties of high strength and high stiffness and have an exceptional fatigue life and adaptability against harsh environments, thus making it highly desirable in aircraft, military, and ship industries (Begum & Islam, 2013). However, due to this property of SFRPs, drawbacks such as high cost, difficult recycling and non-biodegradability are highlighted (Begum & Islam, 2013). Many different methods and solutions have been forwarded towards improving recyclability of SFRPs, but issues such as endangerment to the environment, use of highly harmful

chemicals and financial problems cannot be avoided (Asmatulu et al., 2013; Henshaw, 2001; Kubouchi et al., 1995).

Therefore, in efforts to overcome issues from SFRPs, the use of NFRPs is considered. Over the years, NFRPs have successfully proven their qualities in various fields of application (Begum & Islam, 2013). This is mainly due to it being renewable natural resources, easily available, good specific strength and stiffness, light weight, low cost, and biodegradable (Begum & Islam, 2013; Rajak et al., 2019). Compared to SFRPs, NFRPs can be much more environmentally friendly as it originates from organic sources, thus recyclability of NFRPs can help in decreasing environmental pollution. Due to these benefits, industries and manufacturers tend to seek for opportunities to use NFRPs over SFRPs (Rajak et al., 2019). Yet, it is regrettable to state that SFRPs mechanical strength is superior when compared to NFRPs and therefore NFRPs could not totally replace SFRPs in all applications (Begum & Islam, 2013). Much research into improving the flaws NFRPs possess and the look for more natural fibres to be used in polymeric matrices continues to be ongoing (Begum & Islam, 2013). Many review papers on NFRPs describing aspects of research done using natural fibres of different kinds. Rajak et al. (2019) reviews the manufacturing, properties, and applications of both NFRPs and SFRPs. Coir and jute NFRPs were reviewed intensively by Bongarde and Shinde (2014) in aspects of their manufacturing and characterisation. Saheb and Jog (1999) reviewed reported work on NFRP composites with reference to the type of fibres, matrix polymers, treatment of fibres and fibre-matrix interface.

HFRP composites are composites with mixtures of different fibres, either synthetic or naturally obtained, to make them more desirable for required situations. One research

conducted by Dan-mallam et al. (2012), where the prediction, using software (LAMINATOR), of the tensile properties of natural kenaf fibre and synthetic polyethylene terephthalate (PET) in reinforcing polyoxymethylene (POM) laminate composites. The researchers tested values of kenaf/POM, PET/POM, and a hybrid of kenaf/PET/POM composite, while neat POM laminate is used as control. This research only emphasizes on tensile properties at different fibre orientation using classical lamination theory in respect of its analytical design. The laminates were also orientated differently for comparison. The researchers also focus on objectives in regards of calculation of volume fraction of the fibre and matrix, critical volume fraction of the elongated fibre, ultimate strength of the fibre and matrix, orientation of fibres, and specific gravity of the fibre and matrix.

Hybrid fibre polymer composites can be classified into several categories, as the option of hybridisation varies, such as natural-natural fibre hybrid, natural-synthetic fibre hybrid, synthetic-synthetic fibre hybrid, or more than 2 fibre hybridisations. The goal to carry out these fabrications, is in hopes to cover up the flaws of the reinforcements in the composite. Furthermore, hybridisation of these fibres can be done in various methods of preparations especially in terms of fibre orientation or fibre type. Utilisation of synthetic hybrid fibres solves the problems of interlamination, and further enhances the mechanical properties of the material, as described in the research carried out by Priyanka et al. (2020). However, to keep up with the demands of recycling and sustainability, natural fibres with close mechanical values to synthetic fibres are used. This can be noted by the works of Dhinakaran et al. (2021), where palm fibres were used together with glass fibres in epoxy composites. Hence, a call to utilise hybrid natural fibres, as they are abundant, low cost, and eco-friendly is required. Thermoplastics in hybrid natural fibre composites are also regarded

to be exemplary composites as they can be recycled easily in comparison to thermosets (Gupta & Srivastava, 2015). Table 2.22 has some other examples of other hybrid composites.

Table 2.22: Examples of hybrid composites.

Composite	Matrix	Tensile strength (MPa)	Reference
Sisal/cotton	Isophthalic polyester	60	Sathishkumar et al. (2016)
Banana/jute	Unsaturated polyester	130	Alavudeen et al. (2015)
Sisal/bamboo	Polyester resin-methyl ethyl ketone	23.5	Mohan et al. (2021)

2.4.6 Coffee Waste Fibre Reinforced Polymer Composites

Coffee waste polymer composites are novel materials made by mixing polymers with coffee waste, including used coffee grounds. These composites provide a sustainable approach to material manufacturing and waste management. These composites lessen their impact on the environment and offer an alternative to traditional materials by making use of coffee grounds, which are plentiful and frequently thrown away. In addition to making the composites more environmentally friendly, the coffee waste may also give them special qualities like improved heat resistance or antibacterial activity. Polymer composites made from coffee waste offer a potential path toward sustainable material development that will improve technology while also preserving the environment.

Tapangnoi et al. (2022) used spent coffee grounds (SCG) that were refined by alkalization and bleaching to eliminate lignin and other non-polysaccharide components, yielding purified SCG (PSCG) with improved surface roughness and specific surface area.

PSCG was characterized with a variety of methods, including FTIR, XRD, BET, SEM, and TGA. Later, PSCG was treated with Bistriethoxysilylpropyl tetrasulfide (TESPT) and mixed with natural rubber (NR) to evaluate reinforcement in the biocomposite. The results showed that removing lignin and other components boosted cellulose content in PSCG. However, because to the predominance of polar hydroxyl groups, PSCG demonstrated poor compatibility with non-polar rubbers such as NR, resulting in minimal reinforcing. The addition of PSCG to NR enhanced hardness and modulus while decreased elongation at break. Tensile strength rose with PSCG loading before decreasing. The TESPT treatment improved reinforcement by boosting rubber-filler interaction and increasing crosslink density. Despite advances, PSCG remains an environmentally friendly but non-reinforcing filler due to its large particle size, making it suited for applications where significant mechanical strength is not required, such as floor mats and rubber level crossing panels.

Kueh (2021) covers the environmental harm posed by discarded coffee grounds (SCG) and the corrective measures adopted by researchers. The growing popularity of coffee use and processing generates enormous biowaste, needing adequate management for both human and environmental health. Several initiatives for repurposing SCGs are described, particularly in civil engineering applications. Silica fume is proposed as a possible additive to mix with SCG in future construction materials, solving both biowaste and industrial waste issues. As technology improvements drive manufacturing businesses, poor waste disposal causes long-term environmental problems. Globally, researchers are investigating novel techniques to repurposing biowaste and industrial waste for sustainability. SCGs, a prominent byproduct of coffee consumption, are examined in terms of value engineering prospects. It is determined that silica fume is a promising addition to mix with SCG. Waste-to-wealth programs are predicted to become more popular as knowledge of waste risks rises.

This will encourage a more environmentally friendly industrial revolution that is more efficient and has less of an impact on the environment.

To address environmental issues, Leow et al. (2021) seeks to convert spent coffee grounds (SCGs) into sustainable materials. Coffee oil with beneficial elements including fatty acids and caffeine with antioxidant qualities was obtained through oil extraction from SCGs. To create composites, extracted SCGs (ESCGs) were mixed with epoxy resin. Although the mechanical characteristics of ESCG composites were generally lower than those of pure epoxy, there were improvements when compared to SCG composites. Acetone-ESCGs showed the greatest improvement, raising the tensile strength, flexural strength, and flexural modulus to 23.4 MPa, 3.02 GPa, and 42.9 MPa, respectively. This study shows how coffee waste may be recycled by producing composites and extracting oil, with possible uses in furniture and decoration. It emphasizes how crucial it is to use SCGs to lessen waste in the environment and advance material sustainability.

Reusing spent coffee grounds (SCGs) as a sustainable filler for polyester poly(butylene succinate) (PBS) composites is covered by Gaidukova et al. (2021). When SCG loadings ranging from 20 to 60 weight percent were tested for composite performance, the results showed improved mechanical, chemical, and physical qualities in comparison to clean PBS. Composting conditions led to a faster decomposition, according to biodegradation research. For mechanical performance, 40 weight percent was found to be the ideal SCG loading. While SCG loading increased, thermal stability declined, and all samples showed strong crystallinity. Hemicellulose, cellulose, lignin, lipids, proteins, and minerals were discovered to be present in SCGs. The paper recommends more investigation into the SCG-based composites' environmental life cycle assessment.

The development of ecological composites is examined by Mendes et al. (2021) using high-density polyethylene (HDPE) at concentrations of 10–30% w/w and leftover coffee grounds (SCG). With SCG added, the mechanical properties considerably enhanced. The elasticity improved by roughly 13% at 10% w/w SCG, whereas the stiffness increased by 49% (modulus of elasticity) and 108% (modulus of flexion). The HDPE matrix showed homogeneous dispersion of SCG particles up to 20% w/w, maintaining the HDPE's thermal profile without the need for a compatibilizer. The process can produce environmentally friendly composites without sacrificing quality using leftover materials from the coffee industry. The incorporation of SCG particles increased extensibility and stiffness at the expense of a slight decrease in strength because to stress concentration processes.

Lee et al. (2023) discusses the possibilities of using sustainable technologies and long-term waste management techniques to turn coffee waste into useful items. Coffee trash contains a variety of substances that can be extracted or created, including as lipids, cellulose, lignin, antioxidants, caffeine, and biofuels. Spent coffee grounds (SCGs), leaves, blossoms, pulps, husks, and silverskin are examples of by-products from coffee farming, processing, and consumption that can be used to make profitable and health-promoting products. Particularly, SCGs can be used as a starting point to produce biopolymers such as polyhydroxyalkanoates, biodiesel, antioxidants, bio-oil, and bioethanol. However, because of the antimicrobial chemicals contained, pretreatment of SCGs is necessary for optimum enzymatic hydrolysis. The recovery of sugars and lipids from SCGs using acid hydrolysis appears feasible. Bomfim et al. (2022) discusses the potential of utilizing spent coffee grounds (SCG) as a valuable resource for various applications, including biofuel, biopolymer precursors, and composite production, due to coffee's status as the second most consumed beverage worldwide and its resultant high waste generation. SCG are rich in carbohydrates,

lipids, proteins, and minerals, making them suitable for extracting polysaccharides for fermentation into lactic acid, succinic acid, or polyhydroxyalkanoate (PHA), as well as extracting coffee oil for PHA synthesis. SCG can also serve as fillers for composite production with different polymer matrices, such as PP, PE, PU, PLA, epoxy, and rubbers, offering properties suitable for diverse applications like food packaging, automotive parts, and 3D printing. While there's significant research on combining SCG with various polymers, gaps in the literature remain, suggesting avenues for future research, such as direct synthesis of 2,3-BD from SCG, extraction of lactic acid and succinic acid for novel biopolymer applications, and further exploration of coffee oil in plastics for biopolymer synthesis and composite production. Additionally, more studies on polymer composites using SCG-filled matrices, including PU, PLA, and PHA, and investigating the recycling potential of these composites after their end-of-life are needed. Purwanto et al. (2021) discusses the utilization of coffee waste from "Jos" coffee shops in Yogyakarta, Indonesia, for composite production. "Jos" coffee, popular among students and artists, generates 4-6 kg of waste nightly in some shops. Coffee grounds were combined with water, gauze fibre, coconut coir fibre, alginate, glycerol, and gelatine in laboratory studies. The tensile and tear strength, flexibility, and surface texture of the composites were examined. When compared to composites reinforced with gauze fibres, those made using coconut coir fibres exhibited inferior mechanical qualities and surface roughness. The best-performing composites, which had a smooth surface texture and great elasticity, were appropriate for crafts. They contained 20 grams of coffee and 4 grams of gelatine. Composites reinforced with gauze exhibited better qualities; their tensile strength was the greatest at 15.58 kg/mm² and their tear resistance was 11.51 kg. These results point to the possibility of utilizing "Jos" coffee trash to make strong, flexible composite materials that can be used to produce handicrafts.

2.4.7 Luffa Fibre Reinforced Polymer Composites

Halashi et al. (2024) investigated the possibility of using luffa fibres as an affordable, eco-friendly material for sound absorption and thermal insulation in buildings. luffa panels were created in a range of densities, thicknesses, and binder compositions, and their thermal and acoustical properties were examined. The panels' effective thermal conductivity (K_{eff}) and sound absorption average (SAA) ranged from 0.033 to 0.054 W/(mK) and 0.16 to 0.68, respectively. The inherent hollow and sponge-like nature of luffa fibre was credited with the panels' promising thermal and acoustical performance. It was found that thickness and density had a substantial impact on both SAA and K_{eff} , whereas binder content did not significantly affect either of them. The ideal parameters for creating panels were found to be 40 mm of thickness, 225 kg/m³ of density, and 7.5% of binder content. The acoustic properties of the optimized panels in a conference room were examined using Odeon software both before and after acoustic treatment. The acoustic treatment involved two distinct scenarios. The results showed that the acoustic qualities of the hall significantly improved when sound-absorbing luffa panels were installed across 65% of the side walls and 30% of the ceiling. There was a noticeable drop in the average reverberation time, which went from 4 s to 0.7 s.

Premalatha et al. (2019) investigated the effects of various chemical treatments on the chemical and physical characteristics of luffa cylindrica fibres (LCFs). To resolve the issue caused by the hydrophilic character of natural fibres clashing with the hydrophobicity of polymers in composite materials, LCFs were first treated individually with stearic acid, potassium permanganate, and benzoyl peroxide in an ideal alkali solution. By reducing their hydrophobicity, these treatments aimed to make LCFs more appropriate as reinforcement materials in composites for a range of semi-structural applications, including home goods,

building materials, and automobile interior components. Thermogravimetric analysis (TGA) and X-ray diffraction (XRD) were used in the study to evaluate the physicochemical characteristics of chemically modified LCFs. The results showed an improvement in crystallinity and thermal stability for all modified LCFs. The stearic acid treatment stood out for having better thermal stability. The various chemical modifications led to notable changes in crystal structure and thermal stability, as shown by Thermogravimetric analysis, which primarily attributed the modified LCFs' higher kinetic degradation activation energy and improved thermal stability to structural changes in cellulose. Furthermore, the increase in CI values after treatment indicated that the fibres' cellulose content had increased. According to the results, treated Stearic acid-treated LCF has comparatively better qualities than the modified LCFs, and all the treatments help to improve permeability, which is necessary to create strong adhesion bonds in polymer matrices.

A thorough mechanical evaluation of carbon-luffa hybrid composites was carried out by Natrayan & Kaliappan (2023) to determine their suitability for use in automobile environments. There is a chance to improve the performance of automobile components by utilizing the strength and stiffness of carbon fibres along with the lightweight and eco-friendly qualities of luffa fibres. Tensile, flexural, and impact tests were among the experimental tests used to evaluate the mechanical properties. The results were compared with standard materials that are often used in the automobile sector. The composite with 15% carbon fibres and 85% epoxy had the maximum tensile strength (168.58 MPa), while the mixture with 7.5% carbon fibres, 85% epoxy, and 7.5% luffa had the highest bending strength (110.25 MPa). The B-type specimens stood out for their low moisture absorption and small void content of 0.72%. These findings provide vital insights into the potential of carbon-luffa hybrid composites as lightweight, high-performance alternatives for a variety

of automotive applications, helping to further environmentally conscious automobile design and manufacture.

Vigneshkumar et al., (2022) investigated on the matrix phase which consisted of an epoxy-based polymer resin and two different types of fibres, one synthetic and the other natural. Using five distinct sequencing techniques, S-glass and luffa fibres were coupled with the epoxy matrix to create a unique composite through compression moulding. The goal was to evaluate the effect of this hybridization on composite laminate. The specimen with luffa stacked in the middle (SL4) showed the maximum mechanical strength, with tensile, compression, and flexural characteristics of 253 MPa, 234 MPa, and 237 MPa, respectively. Tensile, flexural, and compression strength of the composite material were also assessed. When compared to the specimen that had the next-highest values across all characteristics, this indicated a 20% increase. The findings showed that the innermost layer of the composite, which contained luffa fibre layers, was responsible for the gradual improvements in every mechanical property that was examined. Using a compression moulding machine, five distinct S-glass/luffa fibre sequences were stacked inside an epoxy resin-based polymer matrix to create hybrid polymer composite plates. The impact of the fibre sequence was then examined. The results showed that the hybridized composite samples' mechanical properties were greatly influenced by the fibre stacking sequences. Among the combinations tested, sample SL4 showed the best mechanical characteristics, especially when the luffa fibre layers were placed in the innermost part of the composites. The composite was shown to have improvements in tensile, compressive, and flexural characteristics of 19.34%, 23.81%, and 17.33%, respectively, in comparison to only S-glass fibre composites, which had the next highest values in all attributes. Thus, the study concludes that when S-glass/luffa fibres

are employed in epoxy-based hybrid polymer composites, the mechanical parameters are significantly influenced by the fibre stacking sequence.

Luffas are widely grown and widely accessible throughout Asia and Africa, where they provide a valuable supply of natural fibres for the manufacturing of composites (Adeyanju et al., 2020). This paper reviews the research findings related to luffa fibres and their composites, assessing the developments, significant findings, present patterns, areas of uncertainty, and potential future directions in the field. A chemical analysis of luffa fibres showed that they are typically composed of 57–74% cellulose, 14–30% hemicellulose, 1–22% lignin, and up to 12.8% additional substances. The most frequent method of extraction for luffa fibres is drying, and the most common modification method is alkali mercerization. Epoxy resins are popular because they are used as the basis polymer for luffa fibre-reinforced composites in 53% of research studies. Compression moulding is the most common curing process, used in around 63% of research investigations, while manual mixing and layup are the usual methods of composite manufacture. The mechanical, thermal, crystallographic, and other properties of the composites are also considered in this review. Future studies should investigate the effects of drying, carry out further experiments including luffa, and examine the application of multi-resin ternary systems. In summary, because of its advantageous qualities, luffa shows a great deal of potential for the development of composites and is likely to continue playing a major role in the industry.

Luffa is a multipurpose biomaterial that is well-known for its availability, affordability, non-toxicity, porosity, and effectiveness in removing pollutants from the environment (Khadir et al., 2021). This study examines the critical factors, such as temperature, adsorbent dosage, pollutant concentration, pH, and contact time, that affect luffa's efficacy in eliminating pollutants. According to the study, luffa-based composites

have potential for decontaminating water since their adsorption kinetics and equilibrium frequently follow pseudo-second order and Langmuir/Freundlich models. Luffa is a good option for a bio-adsorbent due to its bio-nature, availability, and cost. Thermodynamic studies indicate both exothermic and endothermic reactions in the adsorption process, highlighting the importance of temperature, pH, contact time, and initial pollutant concentration. Although different luffa composites have been employed to eliminate pollutants, more study is required to maximize their synthesis and suitability. Because of their great removal efficiency and adsorption capacity, which make them appropriate for a range of adsorption processes, luffa fibres are often regarded as promising biomaterials.

2.4.8 Durian Fibre Reinforced Polymer Composites

The mechanical properties of glass-carbon fibre and durian skin fibre (DSF)-reinforced polylactic acid (PLA) hybrid composite was studied by Nadondu et al. in 2022. Tensile strength, impact strength, and hardness were the main areas of study. They used response surface methodology (RSM) and mixture design response surface methodology to develop mathematical connections between component proportions and intended responses. The ideal component proportions were found by multi-objective optimization. The results of validation testing indicated that the actual and anticipated values agreed well. The study proposes statistical approaches for composite optimization, highlights the promising mechanical properties of DSF derived from waste natural fibres, and uses scanning electron microscopy to identify fracture surface morphologies, thereby exposing adhesion and dispersion mechanisms. It also mentions the different adhesive capabilities of DSF, with mechanical testing revealing good adherence in 10% of cases and poor adhesion in 20% of cases.

Humaira Alias et al. (2023) investigated the use of durian waste as a reinforcing material in the fabrication of inexpensive insulating boards. They examined the effects on the boards' mechanical, morphological, thermal, and physical characteristics of varying percentages of polymeric methane diphenyl diisocyanate (PMDI) resin (0, 6, 8, and 10%). Results showed that 6% PMDI resin content improved thermal and mechanical performance. Better fibre cross-linking was responsible for the increased static bending. The best formulation in terms of thermal stability and conductivity was produced by incorporating 6% PMDI resin. According to the study, using durian trash provides an affordable way to produce insulating boards that still has the desired qualities for use in architecture and construction while solving waste management issues.

Biopolymers provide renewable and biodegradable alternatives to petroleum-based polymers, helping to minimize environmental challenges (Anuar et al., 2021). To solve this issue, durian skin fibre (DSF) reinforced polylactic acid (PLA) biocomposites containing epoxidized palm oil (EPO) were produced. Life cycle assessments (LCA) using GaBi software found that PLA/DSF biocomposites have considerable global warming potential (GWP) and acidification potential (AP), with values of 199.37 kg CO₂ equiv. GWP and 0.58 kg SO₂ equiv. AP, respectively. Incorporating EPO minimized negative consequences by increasing workability and processability, leading in lower energy requirements. Despite their significant environmental effect, plasticized PLA/DSF biocomposites show promise as biodegradable food packaging materials, with favourable characteristics and low waste output.

Nandiyanto et al. (2021) investigated the impact of particle size and material composition on resin-based brake pads. Experiments were conducted using mixes of 75% UPR with durian peel and banana midribs fibres at different ratios (1/1, 3/2, 2/3) and particle

sizes (104 μm , 250 μm). The results show that reducing particle size improves mechanical characteristics while increasing wear and decreasing friction coefficient. Increased banana midrib fibre % improves brake pad performance. A comparison to commercial brake pads demonstrates the possibility of agricultural waste as an alternative. The 2/3 ratio at 104 μm provides the optimum overall performance. This study highlights the potential of biomass waste as a safer substitute to asbestos brake pads.

A study looks at the influence of adding durian skin fibre (DSF) with thermoplastic cassava starch (TPCS) to create biodegradable products (Ridhwan Jumaidin et al., 2022). Composites were made using a hot press technique, and the effects of DSF (0-50 wt.%) on the matrix were evaluated using a variety of assays such as water absorption, water solubility, thickness swelling, moisture content, biodegradation, and density. The results show that DSF inclusion reduces water absorption while increasing thickness swelling, implying improved environmental qualities. Water solubility falls as the DSF level increases. Morphological study shows strong fibre-matrix attachment, indicating compatibility. Density is unaffected by fibre inclusion. DSF shows potential in improving the functional properties of TPCS as a green material, including increased moisture resistance and water affinity. This biodegradable substance provides an eco-friendly alternative to petroleum-based plastics.

Putra et al. (2022) investigate the sound absorption properties of acoustic absorbers constructed from natural durian husk fibres, which are commonly regarded as agricultural waste. The impedance tube method was used to examine samples of variable fibre density and thickness. The results show that durian husk fibres can attain absorption coefficients greater than 0.5 above 1 kHz when optimum parameters are established using the Johnson-Champoux-Allard (JCA) model. The study shows that these fibres outperform commercial rockwool at certain frequencies, with room for improvement at lower frequencies by altering

density. The inverse method with the JCA model produces precise predictions of absorption coefficients. Durian husk fibres show promise as natural sound absorbers, but more research into durability, fungi resistance, and fire retardancy is required for practical use.

The solution casting approach was used to successfully generate a polyvinyl alcohol (PVA)-based biocomposite film including cellulose from durian peel. Cellulose fibres acquired by alkalization and bleaching procedures were incorporated into the PVA matrix at concentrations of 2%, 4%, 6%, and 8%. Tensile testing and moisture resistance assessments were carried out, and it was discovered that adding 6% cellulose fibre increased tensile strength by 54% (to 37 MPa) when compared to pure PVA film (24 MPa), albeit at the sacrifice of elongation at break. The addition of cellulose fibre increased moisture resistance qualities, which can be attributed to homogenous dispersion within the PVA matrix. Mahardika et al. (2021) showed that adding durian peel fibres (DPF) increased tensile strength and moisture resistance. The SEM analysis indicated improved compatibility between polymer chains, resulting in enhanced properties compared to pure PVA film, suggesting potential for food packaging materials. Future research should focus on biodegradation and thermal stability characterization to further explore the environmental impact of these biocomposites.

2.5 Testing and Methods

Composites have been proposed to be used in several situations such as automotive parts, furniture, prosthetic implants, protection devices, sports equipment, etc. Thus, characterisation of composites is important as it determines the materials worth especially when it comes to utilisation in the industry. Hence, in terms of mechanical engineering, fabricated composites shall be put under testing and observation as it is important financially

and physically, such as safety. In this section, testing and characterisation of polymer composites will be discussed to further understand the lengths taken to benefit society, and efforts to shed light on the recent advances on composites.

2.5.1 Tensile Tests

Tensile testing is a fundamental destructive test to find out the materials response to tensile (or pulling) stress. Common tensile testing provides data on tensile strength, tensile modulus, tensile strain, elongation, and percent elongation at yield. This is crucial as it is important to ensure new materials or products can withstand the mechanical forces it will encounter during use. For example, Alabtah et al. (2021) reviewed that the utilisation of glass fibre, carbon fibre, aramid fibre, etc., in either single or hybrid fibre arrangements can help withstand corrosion effects of underground steel pipes and increase the maximum allowable operating pressure significantly. The analytical analysis of carbon fibre reinforced polymer composites was also carried out by Xiong et al. (2014) where it was proposed to be used for cable stayed bridges. This study concluded that it can be a great substitute for conventional steel cable-stayed bridges, particularly for those with extremely long spans. This is because it is anticipated that the benefits of utilizing CFRP components will increase as bridge span lengths continue to be extended and the cost of CFRP materials continues to decline. Apart from its significance in the research and development phase, tensile testing is employed by quality control units to verify that final product batches satisfy the necessary standards for tensile characteristics. This is crucial for both safety and business reasons, since faulty goods can endanger consumers and seriously hurt firms by delaying new products, costing them money, and damaging their brands.

The definition of the ultimate tensile strength, or usually referred to as tensile strength, is the ability of a material to withstand pulling, stretching or any sort of stress or strain before fracture failure (Mubarak et al., 2023). When a stress is lower than its tensile strength, the material will revert to its original shape and size. Many researchers utilise different methods in testing a composites tensile strength either by machine testing or simulation. Tensile testing of composites is generally in the form of basic tension or flat-sandwich tension testing in accordance with standards such as ISO 527-4, ISO 527-5, ASTM D638, ASTM D3039, and ASTM C297 (Saba et al., 2019). The testing samples will be done by using a universal testing machine and will be in accordance with respective standards. Test samples are placed in the grips at specified grip separation and pulled until failure. The grips used to hold sample samples must be made sure to provide a sufficiently strong and even pressure to prevent the specimen from slipping during testing. This test will produce a stress-strain diagram, which is used to determine tensile modulus. Figure 2.21 below is a simple schematic diagram of the universal testing machine. Equation 2.1 and Equation 2.2 are used to calculate the stress and strain of samples.

$$Stress, \sigma = \frac{applied\ force(N)}{area(mm^2)} \quad \text{Equation 2.1}$$

$$Strain, \varepsilon = \frac{length\ changed(mm)}{initial\ length(mm)} \quad \text{Equation 2.2}$$

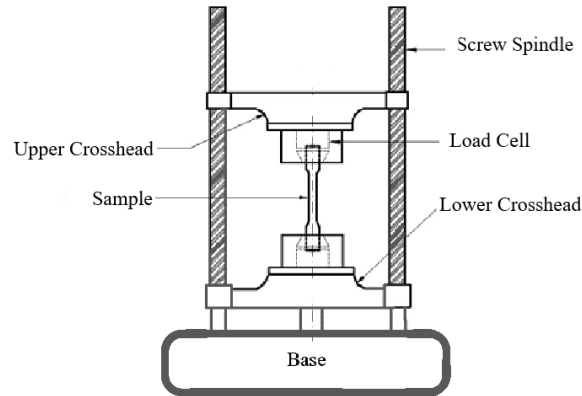


Figure 2.21: Simple schematic of a universal testing machine

2.5.2 Impact Tests

Impact tests are performed to examine a materials toughness, which is the capacity of a material to absorb energy during plastic deformation. Usually, brittle materials such as glass or porcelain break easily when in impact, hence is purported to have poor toughness, and vice versa for ductile materials. It is also noted that temperature can also affect a materials impact value. In general, a materials impact energy decreases as temperature drops (Körbelin et al., 2018). When determining a material's fitness for a given application and projecting its projected service life, test results can be highly helpful. The Charpy impact test, Izod impact test, and falling weight impact test are examples of common impact tests.

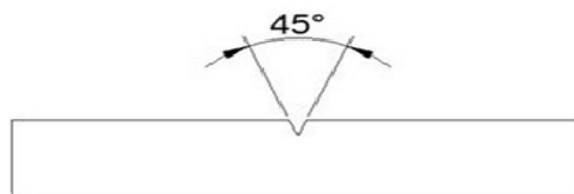


Figure 2.22: Charpy and Izod notched sample diagram

The standardized Charpy impact test, often called the Charpy V-notch test, measures the energy received by a material—typically metals—during fracture. A weighted pendulum

that is dropped from a predetermined height to contact the specimen makes up the test device. By comparing the height of the pendulum before and after the fracture, one may determine the amount of energy that was transmitted to the material. A measurement of a material's notch toughness is called absorbed energy. Because it is simple to conduct and prepare, and because findings can be achieved fast and affordably, it is frequently utilized in industry (Safri et al., 2018). The usual standards to follow for the Charpy impact test on plastics are ASTM D6110-18 and ISO 179/92. A Charpy test specimen, which is placed horizontally into the machine, is typically a 55 mm x 10 mm x 10 mm bar with a notch machined into one of the faces. This notch, which can be either V-shaped (Ashter, 2014), as in Figure 2.22, or U-shaped, and is placed facing away from the pendulum and helps to concentrate the stress and encourage fracture.

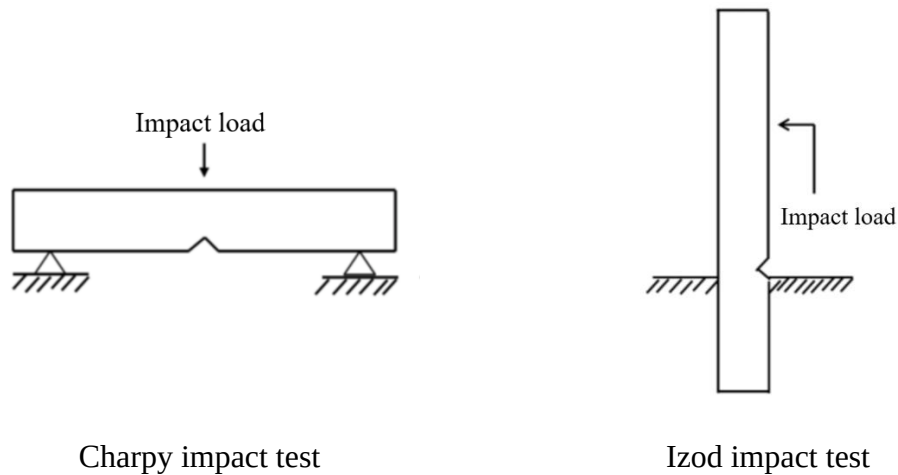


Figure 2.23: Charpy and Izod notched sample (Haque et al., 2021)

Although there are some significant variations, the Izod impact test equipment and specimen design are largely comparable to the Charpy impact test. One such difference is the specimen orientation, which is as follows: it is secured into the apparatus vertically with the notch facing the pendulum, as shown in Figure 2.23. After that, the sample is affected by the pendulum at a designated spot above the notch. Izod impact testing is primarily distinct

from Charpy impact testing in that it can be carried out on metallic or plastic specimens. According to Abdin et al. (2019), plastic samples are normally 64 x 12.7 x 3.2 mm bars with a machined V-shaped notch. Typical Izod impact test techniques are ISO 180, ASTM D256, and ASTM E23.

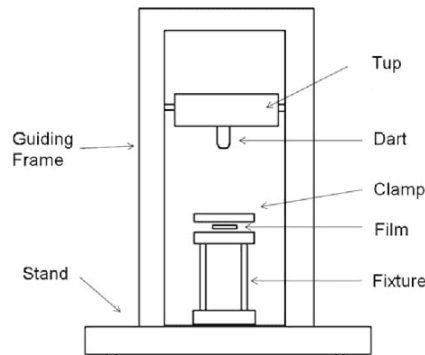


Figure 2.24: Falling weight impact apparatus schematic (Mezghani & Furquan, 2012)

Figure 2.24 is the falling weight impact test or may be known as the drop-weight test for polymers, follows several standards such as, ASTM-D1709, ASTM-D302, ASTM-D4272, ASTM-D3763, and ASTM-D2463 (Warnet & Reed, 1999). The specimen used for the test is commonly a flat plate, either specially moulded or cut from a larger component. A vertically descending dart strikes its centre, supporting it at its edges. The ability of polymeric components to absorb energy from the system when they are struck, either through deformation or damage development, is known as its impact performance (Elchalakani et al., 2023).

2.5.3 Flexural Tests of Polymer Composites

The elasticity of a material does not entirely mean the material to be flexible. This is because flexural strength is a measure of a materials resistance to bending stress, while

flexural modulus and stiffness are measures of the materials ability to resist deformation under bending loads. In simpler terms, the flexural strength is the materials ability to resist attempts of any bending, while elasticity is the ability of the material to reform back to its original structure before application of force. In theory, the modulus of flexure and the modulus of elasticity is equivalent, as both are defined as the ratio of stress to strain (Yılmaz & Arifuzzaman Khan, 2019), however this may not always be the case during true experimentation and testing (Brantley et al., 2017). Seen in Figure 2.25 is some common flexure tests.

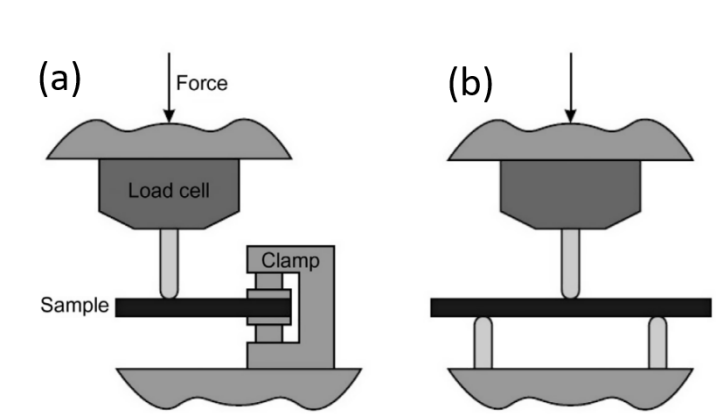


Figure 2.25: Flexural testing schematics. (a) The cantilever beam. (b) Three-point bending (Shrivastava, 2018)

Some of the more popular standards to be followed to be carried out for flexural tests are ASTM D6272, ASTM D7264, ASTM D790, ASTM C393, ISO 178:2010, and ASTM D7249 respectively.

The general equation for flexural stress is the general stress equation as seen in Equation 2.3. However, practically for a rectangular sample with volume under three-point bending setup, the thickness and depth of the material inclusive with its width and length of support must be considered, hence Equation 2.4 is derived.

$$\text{Stress, } \sigma = \frac{\text{applied force}(N)}{\text{area}(\text{mm}^2)} \quad \text{Equation 2.3}$$

$$\text{Flexure Stress, } \sigma_f = \frac{3 \cdot \text{applied force}(N) \cdot \text{support span}(L)}{2 \cdot \text{width}(b) \cdot \text{thickness}^2(d^2)} \quad \text{Equation 2.4}$$

2.5.4 Water Absorption of Polymer Composites

The amount of water a material absorbs is known as its water absorption, and it is measured as the weight of the water absorbed divided by the weight of the dry material (Siddique et al., 2020). The amount of water absorbed by polymeric materials is crucial, especially in marine applications where polymers are frequently utilized as coatings to protect against the corrosion of metallic structures (Derradji et al., 2018). Other than that, it was also found that the mechanical properties of FRP can deviate based on the amount of water absorbed. In contrast to the polymer matrix reinforced with natural fibre, which lost tensile strength by 27% and tensile modulus by 15 to 35% after being submerged in water for a month, Ramesh Kumar et al. (2022) reported that the hybridisation of FRP composites enhanced the water absorption limit and concluded that banana/glass fibre absorbs more water than kenaf/glass fibre composites, which could be caused by many probable reasons. There are three major mechanisms of water absorption in fibre reinforced polymer composites: diffusion, capillary, and transport of water molecules, respectively. Within the microscopic spaces between the polymer chains, a diffusion mechanism takes place. If the impregnation of the reinforcement with the matrix was incomplete during the production process, capillary transport mechanisms develop in the spaces at the fibre-matrix interface space. Due to the expansion of the fibre, the transport of water molecules through the matrix's potential microcracks is particularly crucial in natural fibre composites (Muñoz & García-

Manrique, 2015). Additionally, Sanjeevi et al. (2021) concluded that the mechanical characteristics of the hybrid composites under wet conditions were poorer than those under dry conditions because the interfacial bonding was weakened by water penetration inside the fibre, resulting in weaker composites. As one of the hopes that one day FRP can be used to replace construction materials, water absorption of these advanced materials must be taken seriously.

Simply enough, the testing of polymeric materials, especially composites, can be done by immersing the samples in a body of water for certain time periods, and then comparing the weight during the dry material condition and wet material condition. For polymeric composites, the standard to follow is ASTM D570. Hence, Equation 2.5 is the formula to find the increase in water absorption.

$$Final\ weight, \% = \frac{wet\ weight - dry\ weight}{dry\ weight} \times 100 \quad \text{Equation 2.5}$$

2.5.5 Chemical Treatment of Natural Fibres in Composites

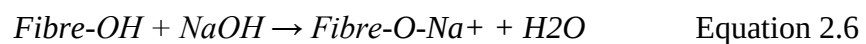
Polymers can exist as hydrophilic or hydrophobic, depending on whether it is composed of natural or petrochemical origins (Finch, 1987), such as the incompatibility of hydrophobic and hydrophilic polymers such as the hydrophobic polymer, polytetrafluoroethylene (PTFE) and hydrophilic polymer polyvinyl alcohol (PVA) (Meng et al., 2020). Despite that, most thermoplastics and thermosets have petrochemical origins, therefore it is safe to say that thermoplastics and thermosets majorly have hydrophobic attributes.

The use of natural fibres in polymer composites has several benefits, including cheap cost and density as well as biodegradability. Nevertheless, because natural fibres are hydrophilic and polymer matrices are hydrophobic, the primary drawbacks of using natural fibres in composites are their poor compatibility with the matrix and their relatively high moisture absorption. As a result, chemical treatments are considered when changing the characteristics of the fibre surface (Kabir et al., 2012).

Thus, natural fibres can be chemically treated to increase the adhesive force between the hydrophilic fibre surface and the hydrophobic polymer matrix. Researchers use a variety of chemical treatments, including malleated coupling agents, acetylation of natural fibres, acrylation and acrylonitrile grafting, permanganate treatment, peroxide treatment, isocyanate treatment, and many more, to improve fibre-matrix lamination (Elfaleh et al., 2023).

Alkaline Treatment

Alkaline treatment, also known as mercerization, is one of the most popular chemical treatments for natural fibres, according to Ferreira et al. (2019). The most important change brought on by alkaline treatment is the disruption of hydrogen bonds in the network structure, which raises surface roughness. A certain amount of lignin, wax, and oils are removed from the outside surface of the fibre cell wall by this treatment. The chemical equation for the fibre and NaOH reaction is found in equation 2.6.



The effect of NaOH concentration can further be supported with research of NaOH treated ground coffee waste (GCW) fibre, reinforcing Oxo-biodegradable HDPE (Tan et al., 2017). This is demonstrated by the removal of unwanted impurities, which enhanced the

composites thermal stability and crystallinity, as well as its water resistance and mechanical properties.

Silane Treatment

A group of silicon-based alkane replacements known as silanes are composed of several silicon atoms bonded together to form the primary chain, which is then linked to hydrogen atoms or other chemical components (Yin et al., 2020). The inclusion of amino-functional silanes such as epoxies and urethane silanes in the silane coupling agents has been thought to give the surface hydrophilic characteristics. For reactive polymers, these silanes serve as primers. More amine functionality can be provided by these primers, which react with the resin during the interphase (Aravind et al., 2022). In short, the use of silane coupling agents can act as the bridge between fibre and matrix as it improves the surface functionality of fibres; enables the fibres to bond chemically. The treatment provides better wetting and dispersion of fibres in the matrix. Figure 2.26 shows the silane reaction on the fibre surface.

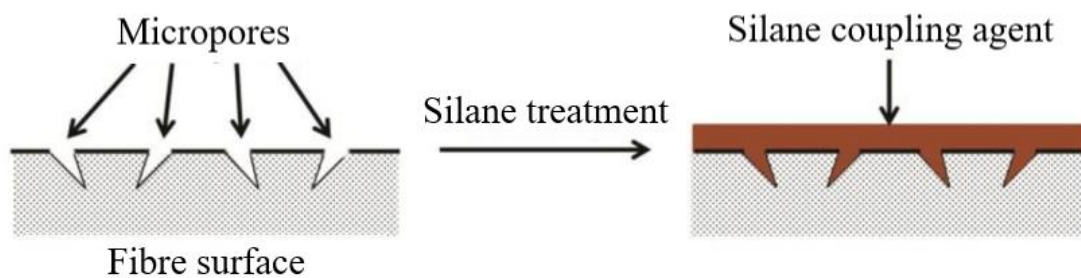


Figure 2.26: Silane treatment on fibre, where the silane coupling agent coats the fibre surface

However, the drawbacks of using silane are in its raw form it is a highly inflammable, pyrophoric, and reactive gas that constitutes a significant fire and explosion hazard. Its

inhalation can cause respiratory tract irritation. Contact can severely irritate and burn the skin and eyes. High exposure can cause headache, nausea, and dizziness (López et al., 2014).

Acetylation

Acetylation is a chemical process that involves grafting and placing acetyl groups onto the cellulose structure at these initially hydrogenated sites. The process eliminates hydrogen atoms from the hydrophilic hydroxyl branches of cellulose molecules by using a suitable catalyst, most commonly acetic acid. To graft acetyl groups onto the cellulose structure, natural fibres can be acetylated either with or without an acid catalyst. Acetylation contributes to a decrease in natural fibres' propensity to absorb moisture, enhancing the resulting fibre-reinforced composite's dimensional stability and resilience to environmental deterioration of the reinforcement fibres (Oladele et al., 2020).

In their investigation into the effects of acetylation on banana fibre-reinforced polypropylene composites, Zaman and Khan (2019) found that treated banana fibre composites exhibited improved tensile strength, tensile modulus, moisture absorption, and impact strength. It was discovered that acetylating flax fibres in polypropylene composites increased the tensile strength up to 18% of the total and thereafter lowered it. It was discovered that when acetylation increased, composites' Charpy impact strengths decreased (Bledzki et al., 2008).

2.5.6 Fabrication Methods of Composites

Fabrication methods for polymer composites involve combining polymers with reinforcing materials to create stronger, more durable materials. Common techniques include hand lay-up, compression moulding, and filament winding. These methods allow for the customization of composites with varying properties, making them versatile for numerous applications in industries like aerospace, automotive, and construction.

Hot compression

Hot compression is a method, usually used to fabricate polymer composites. It utilizes heat and pressure to assimilate the fibres into the matrix, forming the composite. The temperature and pressure are predetermined before the fabrication is carried out, as the type of polymer, type of fibre, and type of composite fabricated must be taken into consideration before compression. Unlike cold compression, where it is usually used for metal composites or woodworking, hot compression utilizes heat as the main medium to melt the matrix for polymer composites. Much past research has used hot compression to fabricate polymer composites, as this method is easy and very simple. The matrix can come in different shapes and sizes, like pellets or sheets, as the mould used are usually machined out from blocks of metals like aluminium and stainless steel, which the matrix is easily placed into. This can be seen in Figure 2.27.

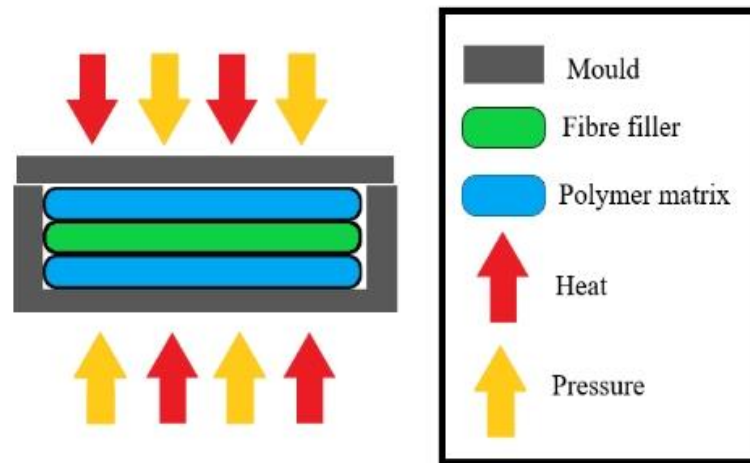


Figure 2.27: Simple schematic visualization of a polymer composite hot-pressed

Friedrich (2021) reviewed the physical and mechanical behaviours of Wood-Polymer Composites, thus concluded that by hot compression method, the composites have increased mechanical properties, and would be advantageous in various applications. This method however has its disadvantages such as it is not the most affordable option, transparent products are not possible, and surface imperfections are expected (Park & Lee, 2012). Furthermore, in practical fabrication of polymer composites, it is difficult to predict the outcome of the specimens as only after the fabrication is complete, only then we can determine the samples to be without defects.

Hot Screw Extrusion

Single screw and multiscrew extruders are the two types of screw extruders. The main reasons why single screw extruders are so well-liked are their affordability, simplicity, toughness, and dependability. Solid conveying, homogenous melting, or plasticizing, and melt pumping are the three major mechanisms in an extrusion process (Shrivastava, 2018).

The revolving screw feeds the polymer in the hopper into the heated barrel through the feed mouth. Shear heating and barrel heating of the screw turn the polymer into a melt that is then driven through the filter screen, into the die, and out. Usually, the die opening reflects the shape of the intended part. Subsequently, the extrudate undergoes a consistent cooling process to solidify and maintain the die's formed shape. When it comes to achieving uniform mixing of different components, such as additives, fillers, and liquids, twin screw extruders outperform single screw extruders (Cegla & Engell, 2020). The single screw extruder's mixing efficiency could be improved by using mixing elements, but it would still not be as good as twin-screw extruders. It is also proven that the utilisation of twin-screw extrusion method is just as effective as other fabrication methods and may be better in terms of fibre dispersion in both synthetic fibre (Kaushal & Singh, 2020) and natural fibre (Sui et al., 2009) polymer composites. Figure 2.28 is the schematic visualization of the twin screw extrusion.

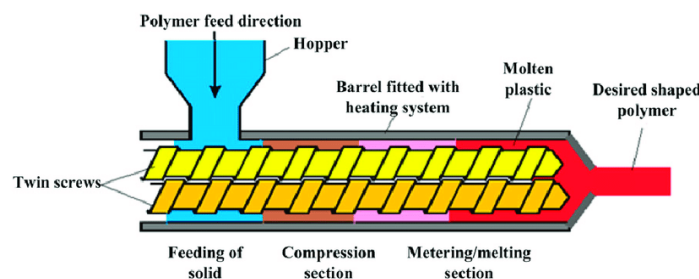


Figure 2.28: Schematic visualization of a polymer in twin screw extrusion (Mishra et al., 2022)

Additive Manufacturing of FRP

The method of creating a real thing from a three-dimensional (3D) digital model is called additive manufacturing (AM), or 3D printing (Yeung & Subburaj, 2023). Typically, this is done by layering and bonding numerous successively thin layers of materials. In recent

research, AM has gained attention as it is utilised as one of the methods in creating FRP composites. Figure 2.29 is the simple schematic of 3D printing.

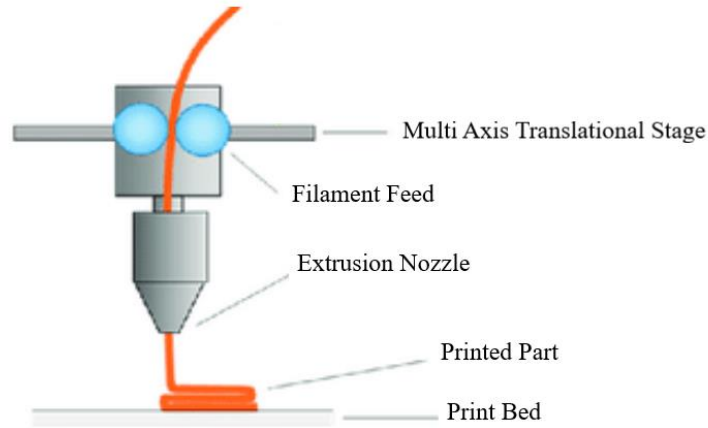


Figure 2.29: Schematic visualization of a polymer in 3D printing (Kjar & Huang, 2019)

From tooling to post-processing, additive manufacturing (AM) can assist with the creation of composite parts along the entire process chain. Integrated positioning and fixation components, layup and handling aids, structural curing aids, and post processing aids are the main AM design concepts that enhance the processing of FRP. In comparison to an aluminium reference panel, the integration of positioning and fixation features might reduce the number of parts by 50% and the number of work steps to install an interface by up to 55%, as demonstrated by the example of an airplane instrument panel created by AM and CFRP (Türk et al., 2017). This demonstrates that if key processing concepts are considered during design, additive manufacturing (AM) can have a positive impact on both the part's performance and construction. The primary goal of current CFRP-AM material design research is to improve mechanical performance by mixing several standard thermoplastic or thermoset matrix materials. Studies on the pre-processing and chemical or physical alteration of the reinforcing materials and matrix, however, are still rare (Liu et al., 2021).

2.6 Sustainable Development Goal 12 (SDG-12) in Asia

In our increasingly environmentally conscious world, sustainability has become a paramount concern, and the recyclability of plastics stands at the forefront of this global endeavour. Sustainable Development Goal 12 (SDG-12) focuses on responsible consumption and production, addressing the urgent need to harmonize economic growth with environmental preservation (Hales & Birdthistle, 2023). The challenge lies in the management of plastics, a material that has revolutionized modern life while posing grave environmental concerns. Asia, with its diverse cultures, rapid urbanization, and economic growth, has become a critical focal point for discussions on sustainability (Roberts, 2006), particularly in the context of waste management and the pursuit of SDG-12.

Plastics have long been a staple of modern life, offering unparalleled convenience and versatility. However, their presence has come at a significant environmental cost. SDG-12, part of the United Nations' Sustainable Development Goals, explicitly focuses on responsible consumption and production, which is a goal that is indirectly linked to the plastics industry. Recyclability is a crucial factor in determining progress in the sustainable management of plastics, which involves many different issues. The solution for addressing the problem is to create plastics that can be recycled effectively, lowering their environmental impact (Vanapalli et al., 2021). This includes not only the materials themselves but also the entire lifecycle of plastics, from production to disposal. Asia's expanding population and economic growth have caused consumption to soar and, as a result, waste generation. In recent years, innovative approaches to plastics recycling have emerged, giving hope to the prospect of achieving SDG-12. These methods span mechanical recycling, chemical recycling, and biodegradable plastics.

Mechanical recycling is a traditional method that involves collecting and reprocessing plastics into new products (Vollmer et al., 2020). While it is a crucial part of the recycling ecosystem, it faces challenges related to the degradation of plastic during its use and limitations on the number of times plastics can be recycled. Chemical recycling is a groundbreaking approach that breaks plastics down into their constituent chemicals, allowing for the creation of virgin-like plastics (Knauer et al., 2023). Although it holds promise, challenges such as scalability and cost must be addressed to make it a sustainable solution. One notable development is the increasing use of biodegradable packaging materials across Asia. Countries like Japan and South Korea have made significant strides in adopting biodegradable alternatives for single-use plastics, aligning with SDG-12's emphasis on sustainable consumption. Derived from natural sources like cornstarch and sugarcane, these materials offer a potential solution to the mounting plastic waste crisis (Sidek et al., 2019). These plastics are designed to break down naturally, reducing the burden of plastic waste. However, their efficacy depends on various factors, including disposal methods and environmental conditions. In the pursuit of sustainable plastics, natural fibres have emerged as an alternative material that aligns with SDG-12. Natural fibres, derived from sources like hemp, jute, and flax, offer several advantages. They are renewable, biodegradable, and often possess impressive strength and durability characteristics. Integrating these fibres into plastic composites creates a more sustainable material that can be used in various applications, from automotive parts to packaging. The use of natural fibres in plastics reduces the reliance on non-renewable resources and mitigates the environmental impact of production and disposal. Moreover, these fibres can enhance the mechanical properties of plastics, making them a viable alternative in industries that demand strength and resilience. While sustainability and recyclability in plastics have made notable strides,

challenges persist. Balancing the economic feasibility of sustainable plastics with their environmental benefits remains a delicate task. Education and awareness regarding responsible consumption and recycling are essential components of achieving SDG-12. Asian countries have demonstrated their capacity for innovation and adaptation, as seen in the adoption of biodegradable materials and advanced recycling technologies. To effectively address biodegradability, recycling, and waste management, a holistic approach is required. Governments, industries, and civil society must work collaboratively to develop and implement sustainable practices in line with SDG-12. Additionally, international cooperation can facilitate knowledge sharing and resource allocation, enabling Asian nations to make significant strides toward achieving responsible consumption and production patterns. SDG-12 challenges us to rethink our relationship with plastics and envision a world where their use aligns with sustainability. Plastics are not inherently evil; their environmental impact is a result of our choices. Sustainability and recyclability in plastics are intrinsically connected to SDG-12, highlighting the need for responsible consumption and production patterns. Innovations in recycling methods and the integration of natural fibres into plastics offer promising avenues toward a more sustainable future. Asia's journey towards sustainable consumption and production, as encapsulated in SDG-12, is complex and multifaceted. While challenges exist, Asia's diversity and dynamism offer a wealth of opportunities for innovation and transformation. Biodegradability, recycling, and waste management initiatives are crucial steps forward, signalling the region's commitment to a more sustainable future, aligned with the global pursuit of SDG-12.

CHAPTER 3

METHODOLOGY

3.1 Flowchart

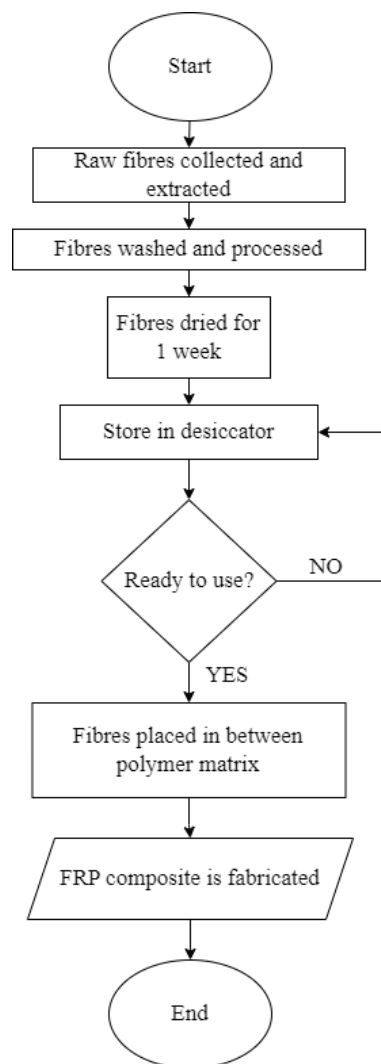


Figure 3.1: Flowchart of current research methodology

A flowchart is utilised to ensure fabrication of composite is carried out properly. Figure 3.1 is the flowchart which shows the flow from when the fibres are not extracted yet, to its infusion into the PE matrix.

Table 3.1: Raw materials to fabricate the hybrid FRP composite.

Materials	Specification
Polymer matrix	HDPE sheets
Fibre 1	Luffa dried fibre
Fibre 2	Ground coffee waste fibre
Fibre 3	Durian peel fibre

The method to fabricate the composite is by hot compression machine located in Metallurgy Lab, Faculty of Engineering, UNIMAS, Sarawak. The fibres will be placed in between the polymer matrix, then will be heat pressed until fabrication is complete. PE films were cut to 260 mm × 260 mm size to fit into the mould. The fibres will be cut and distributed evenly across the PE films. The composite will be produced at 5 MPa and 170 °C for the upper heating plate and 180°C for the lower heating plate by hot compression after approximately 30 minutes. A total of five sets of composite samples will be prepared for each hybrid samples, following ASTM D3039 “Tensile Testing of Composite Laminates”, where one of it will be the control test, consisting of neat PE laminate, while the other four samples will be 10%, 15%, 25%, and 35% volume fraction of hybrid fibre respectively. The reasoning behind the choice of volume fractions can be observed through past research on luffa, durian, and GCW composites, the composites are seen to start deteriorating in mechanical properties at approximately 40% volume fraction of luffa fibres, 20% volume fraction of GCW fibres, and 10% of durian fibre, against polymer matrix. Figure 3.2 is the heat press machine utilised to fabricate the composites. From this point forward, it must be noted that hybrid Luffa/GCW/PE composite will be referred to as CLPE while Luffa/Durian/PE composite will be referred to as DLPE.



Figure 3.2: Hot press machine

Table 3.2 and Table 3.3 is the volume fraction of the respective hybrid composites proposed. The luffa fibre volume is remained constant. Density of fibres are 1.288 g/cm^3 , 0.87 g/cm^3 , and 0.435 g/cm^3 for durian fibre, luffa fibre, and coffee fibre respectively. These

Table 3.2: Composition of Luffa/GCW/HDPE composites.

Laminate	Luffa Volume Fraction, V_{f1} (%)	GCW Volume Fraction, V_{f2} (%)	Matrix Volume Fraction, V_m (%)	Composition Luffa/GCW/HDPE
L0	0	0	100	0/0/100
L1	7	3	90	7/3/90
L2	7	8	85	7/8/85
L3	7	18	75	7/18/75
L4	7	28	65	7/28/65

Table 3.3: Composition of Luffa/Durian/HDPE composites.

Laminate	Luffa Volume Fraction, V_{f1} (%)	Durian Volume Fraction, V_{f2} (%)	Matrix Volume Fraction, V_m (%)	Composition Luffa/Durian/HDPE
R0	0	0	100	0/0/100
R1	7	3	90	7/3/90
R2	7	8	85	7/8/85
R3	7	18	75	7/18/75
R4	7	28	65	7/28/65

Figure 3.3 is the hybrid fibre orientation visualization. The coffee is scattered evenly between the luffa fibres and will cover the gaps between the luffa fibre strands, while the durian fibre will act as a mat, covering the gaps between the luffa fibre strands as well.

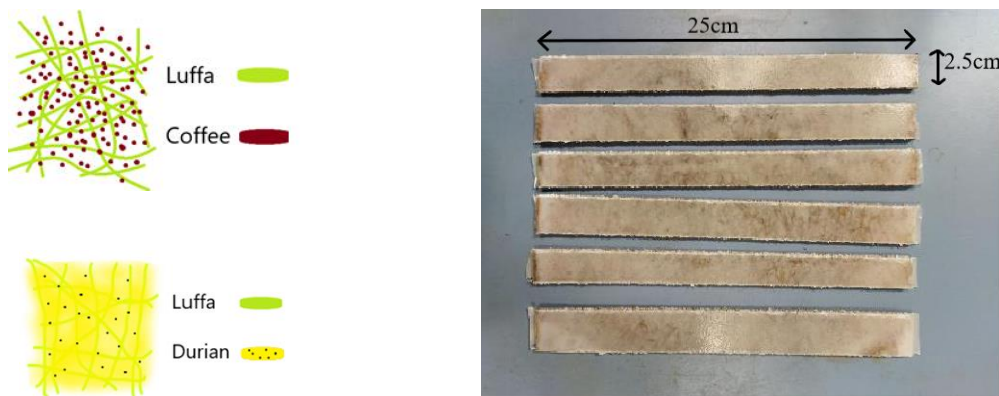


Figure 3.3: Proposed hybrid fibre orientation visualization (left) and actual samples fabricated (right)

3.2 Tensile Testing

The tensile testing of the composite will be done by using the Shimadzu universal testing machine model AG-300K IS MS and will be in accordance with the ASTM D3039 standards. The crosshead displacement rate will be set at 5 mm/min and the test samples will be prepared in dimensions of 260 mm × 260 mm. The minimum required gauge length of the respective hybrid composite is 150 mm. The composites samples are placed in the grips at specified grip separation and pulled until failure. The grips used to hold composite samples must be made sure to provide a sufficiently strong and even pressure to prevent the specimen from slipping during testing. This will be done for each respective hybrid composite volume fraction samples. Ambient temperature and humidity should be maintained as constant as possible through the duration of this test. Equation 3.1, 3.2, and 3.3 are the important equations in a tensile test.

$$\text{Stress, } \sigma = \frac{\text{force applied (N)}}{\text{cross section area (mm)}} \quad \text{Equation 3.1}$$

$$\text{Strain, } \varepsilon = \frac{\text{change of length (mm)}}{\text{initial length (mm)}} \quad \text{Equation 3.2}$$

$$\text{Young's Modulus, } E = \frac{\text{Stress, } \sigma}{\text{Strain, } \varepsilon} \quad \text{Equation 3.3}$$

3.3 Fourier Transform Infrared (FTIR)

The durian, GCW, and luffa fibres is analysed using (FTIR) using an IRAffinity-1 from Shimadzu. The fibre samples were prepared by extraction from the fibre clump, then cleaned thoroughly by soaking and drying. Each sample will be subjected to 48 scans in the range of 600– 4000 cm⁻¹. By creating an infrared absorption spectrum, FTIR detects chemical bonds in a molecule. The spectra provide a sample profile, which is a unique

chemical fingerprint that may be used to screen and scan samples for a variety of components.

3.4 Scanning Electron Microscopy (SEM)

The SEM analysis is carried out to analyse the surface adhesion between the fibre and PE matrix, and the surface morphology of the composite. The Hitachi TM3030 Tabletop Microscope model is used. A sample of cross section of the composite are cut into the dimension of the aluminium plate to be fixed on. Then, this cut sample of the composite will be coated with a 10 nm layer of conductive material, which is gold, as the tested sample is non-conductive. The SEM analysis will be carried out and the results will be documented, however, only the required samples will be analysed using this method depending on the tensile testing.

3.5 Water Absorption Testing

ASTM D570-98 is used to conduct the water absorption test. The test specimens are prepared into 76.2 mm x 25.4 mm in dimension, and completely submerged in distilled water at a temperature of 23±1°C. After 2 hours, the specimens are weighed. The process will be repeated every 24 hours. One by one, the specimens must be taken out of the water. All the samples will be cleaned and dried and weighed to the closest 0.001 g. The water absorption percentage is then calculated.

$$\text{Water Absorbed Percentage, \%} = \frac{w_{final} - W_{initial}}{w_{initial}} \times 100\% \quad \text{Equation 3.4}$$

In Equation 3.4, W_{final} is the final weight at certain immersion period and $W_{initial}$ is the initial weight of the sample before immersion.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter will be focused on the results gathered from several testing of the composite samples. Tensile testing, FTIR, water absorption, and SEM analysis shall be carried out and discussed on.

4.2 Tensile Strength and Modulus of Composites

The ASTM D3039 tensile testing technique was used when conducting the tensile tests. Every polymer sample was divided into 25 mm broad, 150 mm gauge length, and 3 mm thick samples. A 5 mm/min crosshead displacement rate was used to test the samples.

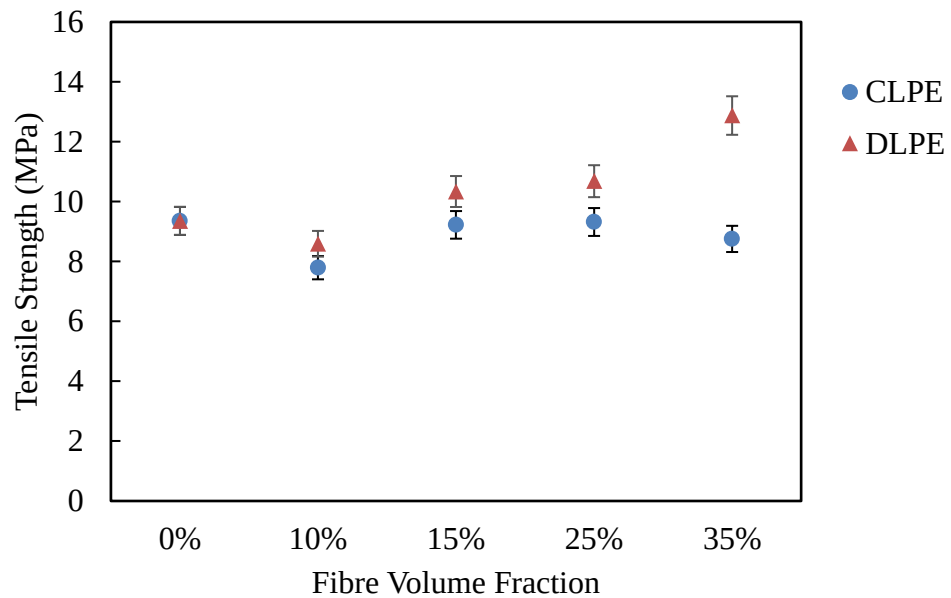


Figure 4.1: Tensile strength of CLPE and DLPE against increasing fibre volume fraction

The tensile strength of DLPE and CLPE versus an increasing fibre volume fraction is shown in Figure 4.1. When measured against the 10% CLPE and DLPE composites, the plain PE has the highest tensile strength value. On the other hand, the trend indicates a positive increasing trend for CLPE's tensile strength from 10% to 25%. The trend for the DLPE is rising, from 10% to 35%. 10% fibre volume fraction has the lowest tensile strength among the composites made of both CLPE and DLPE, at 7.79 MPa and 8.59 MPa, respectively. The maximum tensile strength of 9.32 MPa is reached by the CLPE at 25%, and it falls to 8.75 MPa at 35%. This indicates that between 25% and 35% of CLPE fibre volume fraction is the ideal range for tensile strength. Even at 35% fibre volume fraction, the DLPE shows a trend of rising tensile strength, which may point to a very good bond between the durian/luffa fibres and the PE. In general, the tensile strength characteristics of both CLPE and DLPE are good. At 25%, the tensile strength of CLPE is close to that of pure PE, while at 35%, the tensile strength of DLPE is 12.87 MPa, which is 27% higher than that of neat PE.

Tensile strength for CLPE exhibits a declining trend as the fibre volume fraction increases from 25% to 35%. The increase in fibre volume above its optimum value may be the cause of the decrease in tensile strength. This, in turn, leads to an uneven distribution of stress throughout the composite and, most likely, to agglomerated rather than homogeneously distributed GCW fibres, which create voids between the GCW and matrix (Nicholas Kuan et al., 2022). The adhesion between the fibres and matrix reaches its highest level at low fibre particle volume content, which prevents crack growth and ultimately improves the tensile strength, while adverse effects are seen when the composite has a high fibre particle volume content (Thongchom et al., 2021).

The DLPE shows an increasing trend in tensile strength with an increase of fibre volume. Both the durian fibres and the luffa fibres complement each other in the composite, in which both the fibres control each other's crack propagation. However, it must be noted that for an increased durian fibre content, the fibres are more closely spaced. This gives a higher bonding area between the matrix and the fibres (Larsen & Thorstensen, 2020).

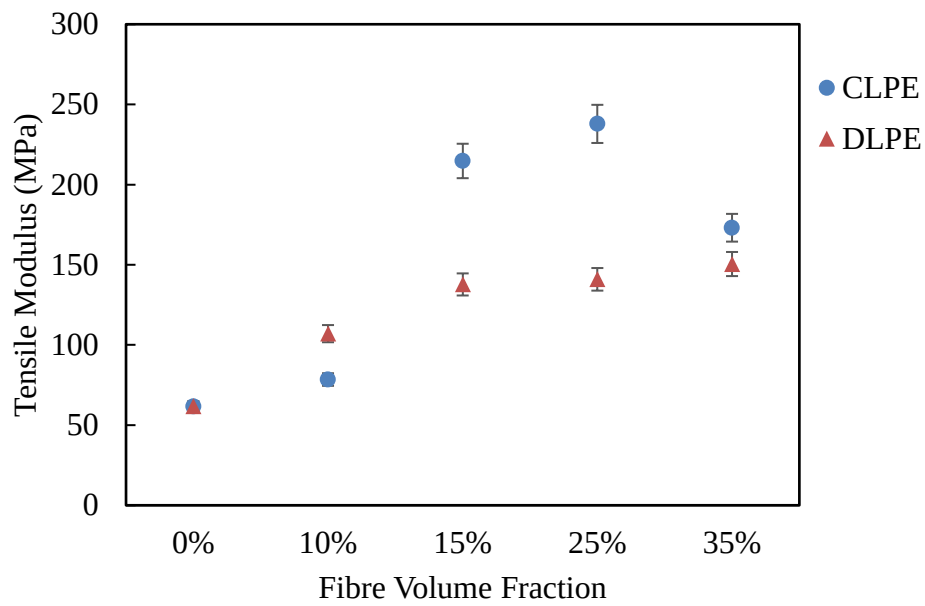


Figure 4.2: Tensile modulus of CLPE and DLPE against increasing fibre volume

From Figure 4.2, the tensile modulus of both hybrid fibre composites is greater than neat PE laminates. For the CLPE, its tensile modulus has an increasing trend up to 25% fibre volume fraction with a 237.85 MPa peak. This is an increase of 74% of tensile modulus compared to the neat PE laminate. However, a decrease is seen after the peak, which is most likely due to the composite already reaching its optimum fibre volume. For the DLPE, an increase is seen up to 35% of fibre volume fraction. Yet, the DLPE only peaks with a tensile modulus of 150.45 MPa at 35% fibre volume fraction, which is less than the peak of CLPE, but still greater than neat PE laminates by 58% in terms of tensile modulus.

Tensile modulus, compressive modulus, and elastic modulus has the same definition, which is the ratio of stress-to-strain, however, may come with different meanings in different contexts. It is also understood that a material with low modulus value is more elastic, while a high modulus value means the material is rigid (Jones & Ashby, 2019). For the DLPE and CLPE, it can be determined that with the inclusion of fibres, the rigidity of the materials increase. Furthermore, an increase of fibre volume fraction, or up to its optimum fibre volume fraction, increases its tensile modulus (Qiao et al., 2022). The CLPE of 15% fibre volume fraction and greater can be observed to be more rigid than both neat PE laminates and DLPE samples. The tensile modulus is affected by many different factors such as fibre morphology, fibre orientation, fibre type, etc (Asim et al., 2020). The reason behind CLPE having a higher tensile modulus at equivalent fibre volume fraction compared to DLPE, even when mean length of GCW fibres being less than durian peel fibres, is probably because of the wettability of the different fibres to the matrix (Ahmad et al., 2019), or the different dispersion of the fibres in these hybrid composites (Kureemun et al., 2018).

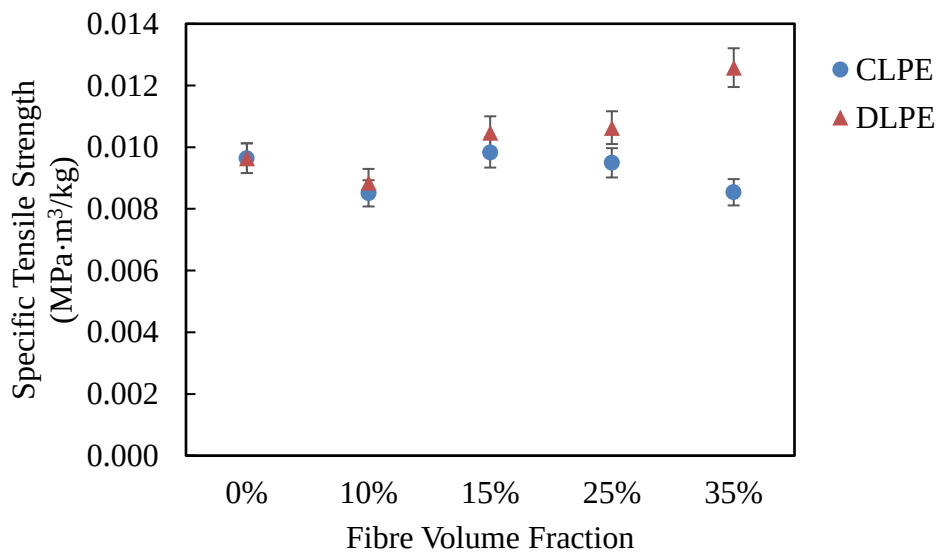


Figure 4.3: Specific tensile strength of CLPE and DLPE against increasing fibre volume

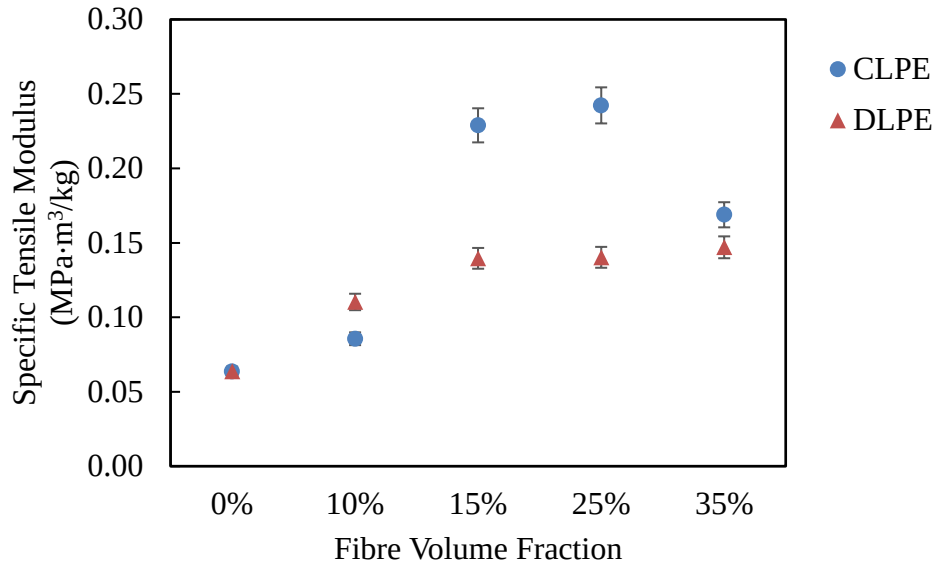


Figure 4.4: Specific tensile modulus of CLPE and DLPE against increasing fibre volume

Figure 4.3 and Figure 4.4 displays the strength-to-weight ratio and modulus-to-weight ratio, or better known as the specific tensile strength and specific tensile modulus respectively. It can be seen in Figure 4.3 that the DLPE performs better than the CLPE in terms of specific tensile strength. At 35% fibre volume fraction, the DLPE has a specific tensile strength greater than CLPE by 32%. It must be noted however, that the CLPE at 25% has a greater specific tensile strength than neat PE. In Figure 4.4, the CLPE specific tensile modulus values have greater values at 15% and 25% fibre volume fraction compared to DLPE. The CLPE values is seen to decrease at 35% fibre volume fraction. Nonetheless, these values are still greater than neat PE sample values. This proves that the inclusion of natural fibres does in fact enhance the properties of PE, especially in weight reduction, cost reduction, and biodegradation (Ahmad et al., 2014). Furthermore, the co-synthesis of these fibres may bring greater benefits rather than the utilisation of a single type of natural fibres in polymer composites.

4.3 Water Absorption

The water absorption tests were conducted in a duration of 30 days. Figure 4.5 and Figure 4.6 is presented as the percentage weight gain by water absorption of respective CLPE and DLPE composites as a function of the square root of time in seconds. It can be seen from Figure 4.5 and Figure 4.6 that regardless of the volume fraction of the natural fibres present, an increase in water absorption is apparent as time increases.

Comparing between the greatest CLPE and DLPE water absorption percentage, the DLPE has a greater water absorption by 27%. This may be caused by the aspect ratio of the fibres, as an increase in fibre aspect ratio (more fibres) increases the absorption of moisture (Ratna Kumari et al., 2021). As the fibres absorb water which causes swelling, this causes a degradation of the fibre-matrix interface along with a change in dimensions of the composites. This may lead to microcracks in the matrix which further weakens the composite, and thus further allowing more absorption of water to the fibres (Sahu & Gupta, 2020). It must be noted that the hydrophilic nature of the fibres does not have excellent interfacial adhesion with the hydrophobic matrix, which promotes a gap at the interface area, and encourages water penetration to the internal segments of the material (Youssef et al., 2015).

To reduce the water absorption of these composites, various strategies can be employed. One approach involves treating the surface of natural fibres through chemical treatments like silane coupling or acetylation, creating hydrophobic properties. Additionally, the use of nanomaterials in the matrix, heat treatment of fibres, optimizing processing conditions, controlling fibre length, and applying post-treatments such as coatings are effective methods to enhance water resistance.

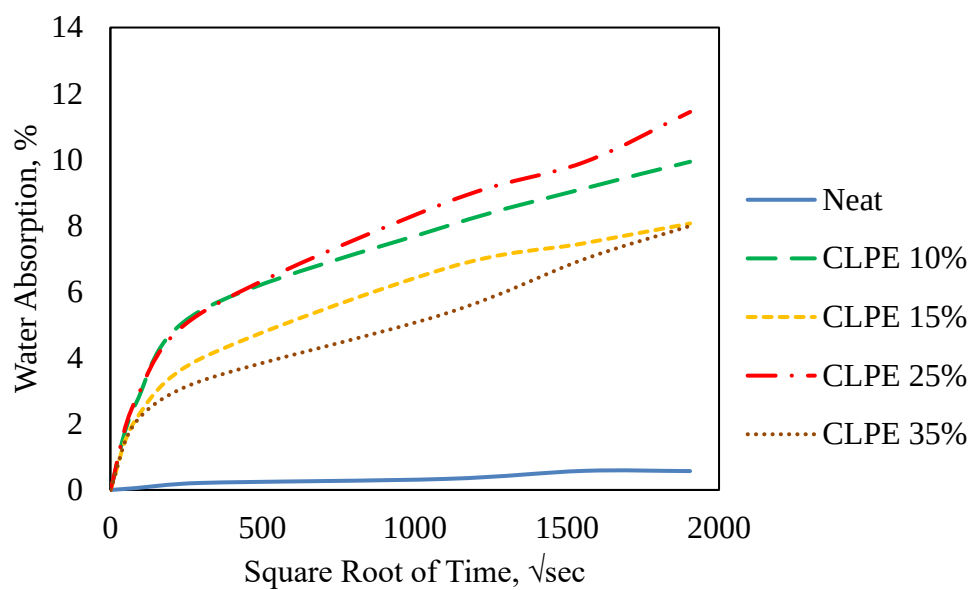


Figure 4.5: Water absorption of the CLPE as a function of the square root of time

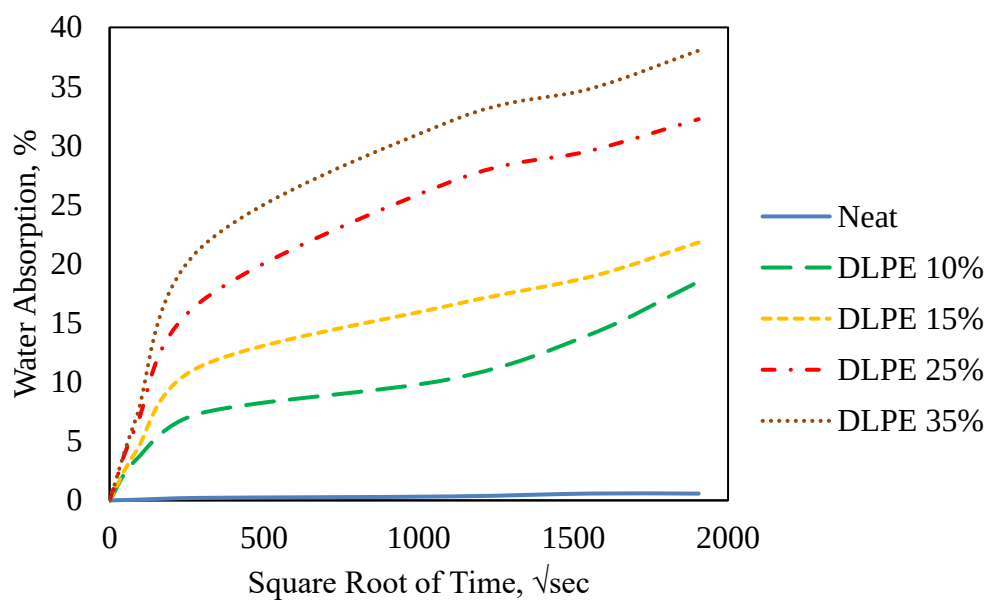
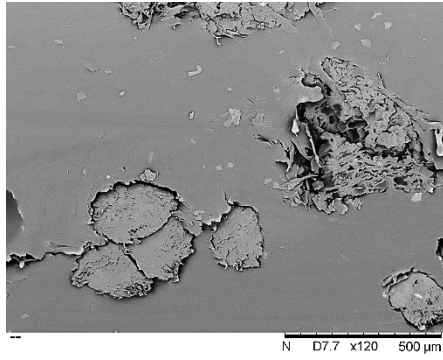


Figure 4.6: Water absorption of the DLPE as a function of the square root of time

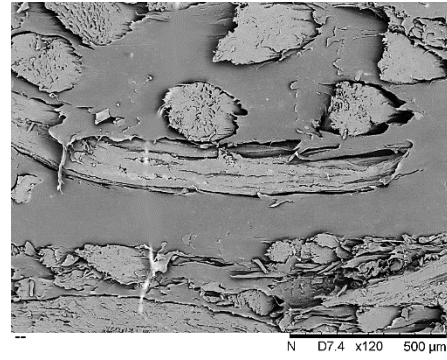
4.4 Scanning Electron Microscopy (SEM) Analysis

The surface morphology of the composite as well as the surface adhesion between the fibre and PE matrix were examined using SEM analysis. A fair integration of luffa/GCW fibre with the PE matrix is revealed by SEM examination. On the other hand, Figure 4.7(c) and (e) show that adhesion between the luffa fibres, GCW fibres, and matrix is not entirely merged in some locations due to gaps. Pectin, waxes, lignin, and other contaminants could be the cause of this. Similar gaps can be detected between the luffa fibres and matrix of the DLPE composites, as shown in (d). In (f) however, the durian fibres and matrix have meagre gaps between them, signalling that the integration of durian and PE matrix is satisfactory. In Figure 4.7, the circled areas are the interfacial gaps between fibre and matrix.

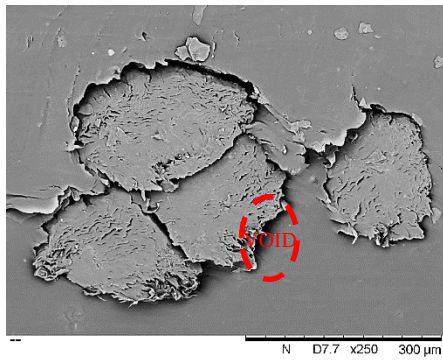
It can also be seen that the durian fibres occupy a large area in the composite as seen in (f), which proves why the DLPE composites have a greater composite strength compared to CLPE, as the stress is better distributed along the durian fibres, compared to GCW microfibrils. It must be noted that in an ambient surrounding, DLPE can have a greater tensile strength compared to CLPE due to the aspect ratio of the fibres (more fibres), however DLPE can be at a greater disadvantage when exposed to moisture compared to CLPE. Key factors influencing interfacial adhesion include chemical compatibility between the fibre surface and the polymer matrix, surface energy matching, mechanical interlocking through proper fibre orientation, and the use of bonding agents or coupling agents. Additionally, surface treatments, such as plasma or chemical modifications, are employed to enhance wettability, while the selection of an appropriate polymer matrix also contributes to adhesion (Zhou et al., 2016). It can be suggested that the interfacial adhesion of the composites must be taken into as a critical aspect that influences the overall performance and properties of the material.



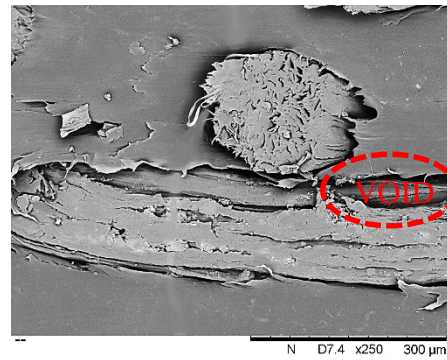
(a) 120x magnification of CLPE



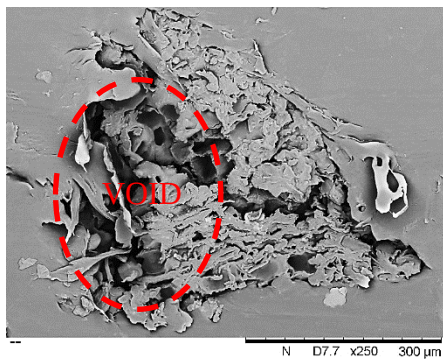
(b) 120x magnification of DLPE



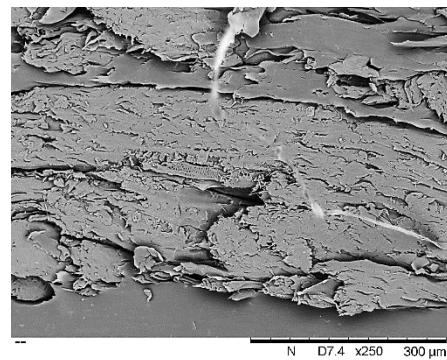
(c) 250x magnification of luffa in CLPE



(d) 250x magnification of luffa in DLPE



(e) 250x magnification of GCW



(f) 250x magnification of durian fibre

Figure 4.7: SEM images of 25% fibre volume fraction of CLPE and DLPE at (a)(b) 120 magnification, and (c)(d) 250 magnification of luffa fibre in respective composites, and 250 magnifications of (e) GCW microfibre and (f) durian fibre in respective composites

4.5 Fourier-transform Infrared (FTIR) Spectroscopy

Given that hemicellulose, lipid, lignin, and cellulose constitute the primary components of each natural fibre, the FTIR spectra of these fibres exhibit minimal variations as seen in Figure 4.8. The absorptions in the range of 3800 - 3300 cm^{-1} , attributed to the stretching of the O-H group, result from intramolecular and intermolecular hydrogen bonding in polymeric compounds like alcohols, phenols, and carboxylic acids found in lignin, pectin, and cellulose (Nandiyanto et al., 2022).

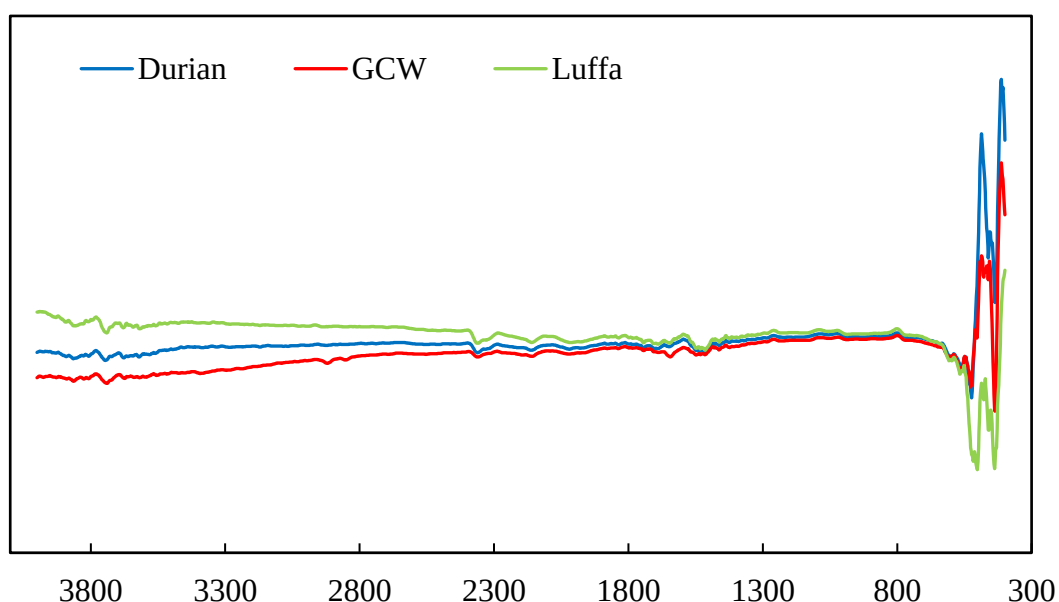


Figure 4.8: FTIR spectra of durian fibre, GCW microfibre, and luffa fibre

The O-H stretching vibrations reveal a diverse range of frequencies, indicating the presence of both bound O-H bands and free hydroxyl groups in carboxylic acids. The peaks within the 2923 to 2859 cm^{-1} range signify symmetric or asymmetric C-H stretching vibrations associated with aliphatic fragments generated from cellulose lipids (Lubis et al., 2019). The presence of alkyne is identified by peaks in the 2260 - 2100 cm^{-1} band, as observed in various sources like plants, algae, fungi, and bacteria (Back et al., 2022). The

peaks identified in 1733 and 1650 cm^{-1} are associated with the carboxyl group, $-\text{COOH}$, derived from xanthine derivatives such as caffeine (Kesraoui et al., 2018; Chou et al., 2012). The absorption in the range of 1650 - 1440 cm^{-1} may be attributed to the presence of lignin, specifically referring to $\text{C}=\text{C}$ double bonds in aromatic rings. Additionally, a peak detected at 1600 - 1254 cm^{-1} corresponds to the carboxylic acid present in hemicelluloses and lignin (Nandiyanto et al., 2022). Material analysis using FTIR spectroscopy reveals a unique region known as the fingerprint region for each compound, which is rarely discussed due to its complexity arising from the multitude of signals (Ramírez-Hernández et al., 2019). In this context, it is determined to be within the 1100 - 600 cm^{-1} range. Numerous peaks in this range have been assigned to cellulose, hemicellulose, lignin, holocellulose, carbohydrates (Javier-Astete et al., 2021). Observing Table 4.1, GCW microfibres having greater presence of lipid, hemicellulose, and pectin-wax, which might be the cause for the decrease of mechanical properties.

Table 4.1: FTIR results of durian fibre, GCW microfibre, and luffa fibre.

Band wavelength (cm^{-1})	Associated chemical group	Durian fibre	GCW microfibre	Luffa fibre
3800 - 3300	-OH intensity	High	High	High
2923 - 2859	Lipid peak	Reduced	Present	Reduced
2260 - 2100	Alkyne peak	Present	Present	Present
1733 - 1650	Carboxyl group peak	Reduced	Present	Reduced
1600 - 1254	Lignin, Hemicellulose peak	Present	Present	Present
1100 - 600	-OH intensity	High	High	High

4.6 Discussion and Summary

From Table 4.2, the tensile strength, tensile modulus, and water absorption of CLPE and DLPE composites is summarized. In terms of tensile strength and tensile modulus, it is evident that an increase in fibre volume fraction contributes to an increase in these values. However, a decrease is apparent after a certain volume fraction for each respective composite sample. This is probably due to the volume fraction reaching an optimum volume. Hence, the stress is unevenly distributed throughout the composite (Alrawashdeh & Eren, 2022).

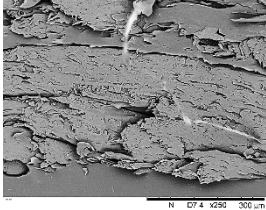
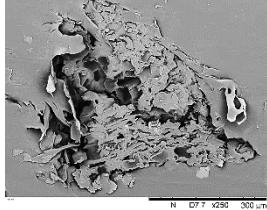
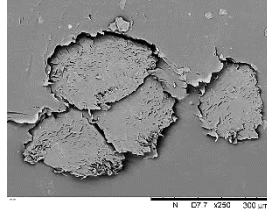
Table 4.2: Summary of CLPE and DLPE tensile strength, tensile modulus, and water absorption at respective volume fractions.

Composite	Testing type	Volume fraction (%)				
		0	10	15	25	35
CLPE	Tensile Strength (MPa)	9.4	7.8	9.2	9.3	8.8
	Tensile Modulus (MPa)	61.7	78.4	241.7	237.9	173.2
	Water Absorption (%)	0.57	9.9	8.1	11.4	7.99
DLPE	Tensile Strength (MPa)	9.4	8.6	10.3	10.7	12.9
	Tensile Modulus (MPa)	61.7	107.0	137.7	140.9	150.4
	Water Absorption (%)	0.57	18.5	21.8	32.2	38.0

Many other reasons may be behind this issue, which includes the methodology of sample preparation, surrounding conditions, type and size of fibre, polymer type, etc. In terms of water absorption, each sample has an increase in water absorption by time. It is understood that the several variables affect the composite's ability to absorb water, such as

temperature, fibre type, diffusivity, void, orientation, interfacial bonding, and volume or weight fraction of the fibre (Hamdan et al., 2019). It is believed, a modification of the surface of natural fibres by chemical treatment may enhance the mechanical properties and water absorption of the composite (Mohammed et al., 2023; Kusmono et al., 2020).

Table 4.3: Summary of SEM imaging and FTIR results of durian fibre, GCW microfibre, and luffa fibre.

Fibre sample	Durian fibre	GCW microfibre	Luffa fibre
SEM image			
-OH intensity	High	High	High
Lipid peak	Reduced	Present	Reduced
Carboxyl group peak	Reduced	Present	Reduced
Lignin, Hemicellulose peak	Present	Present	Present

From this research, DLPE is greater in terms of mechanical strength compared to CLPE. Through SEM and FTIR in Table 4.3 of the fibres, it is rather evident that durian fibre has a greater aspect ratio than GCW microfibre, which promotes stress distribution throughout the composite (He et al., 2021). Furthermore, FTIR proves that GCW microfibres has additional lipids, linking to oils, and carboxyl groups, which is linked to caffeine, that may affect fibre wettability with the matrix.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Characterisation of hybridised natural fibre polyethylene (PE) composites have been carried out successfully. The natural fibres utilised in hybridisation were mixtures of GCW/luffa and durian/luffa fibre hybrids. GCW microfibrils were in powdered form, while the durian fibres were created into sheet form. Fibres were distributed evenly throughout the PE sheets, then hot-pressed to form composite samples. These samples were characterised by an increasing fibre volume fraction (FVF) of 10%, 15%, 25%, 35%, respectively, and the neat PE samples were used as the control. Samples of this hybrid natural fibre PE composites were then subjected to FTIR, SEM, water absorption, and tensile testing for characterisation.

Tensile testing was carried out and it was found that the DLPE and CLPE composites to be structurally sound. This is evident as the tensile strength of both DLPE and CLPE to have an increasing or equal tensile strength when volume of fibres increases. However, in accordance with other researchers, it is still relevant that tensile strength of natural fibre composites increases only up to a certain value as the optimum fibre volume has been achieved. In comparison between DLPE and CLPE, DLPE is greater in terms of tensile strength, with DLPE having the greatest tensile strength at 35% FVF, while CLPE of 25% FVF achieving a tensile strength on par with neat PE. In terms of elasticity, CLPE has a higher tensile modulus compared to DLPE. For the CLPE at 25% FVF, its tensile modulus has an increase of 74% of tensile modulus compared to the neat PE laminate. However, a decrease is seen after the peak, which is most likely due to the composite already reaching its optimum fibre volume. For the DLPE at 35% FVF, an increase in tensile modulus of 58%

is seen, which is less than the peak of CLPE, but still greater than neat PE laminates. Specific tensile strength is where DLPE outperforms against CLPE. The DLPE at 35% fibre volume fraction has a specific tensile strength that is 32% higher than the CLPE. However, it should be mentioned that the specific tensile strength of CLPE at 25% FVF is higher than that of plain PE. In comparison to DLPE, the CLPE specific tensile modulus values are higher at 15% and 25% fibre volume fraction. At 35% fibre volume fraction, a drop in CLPE values is observed. These levels are still higher than the neat PE sample results, though. This indicates that the addition of natural fibres improves PE qualities, particularly regarding weight loss, cost savings, and biodegradation.

For water absorption of DLPE and CLPE, regardless of the volume fraction of the natural fibres present, an increase in water absorption is apparent as time increases. Hybridisation of natural fibres does not enhance water absorption resistance, and furthermore increases as the fibre volume increases. This is accurate since natural fibres are hydrophilic by nature and changing them chemically is the only way to prevent this. It is important to highlight that the hydrophilic fibres poor interfacial adhesion to the hydrophobic matrix creates a breach at the interface and allows water to seep into the material's internal sections. The fibre-matrix interface deteriorates, and the composites dimensions alter because of the fibres absorption of water, which results in swelling. This could result in microcracks in the matrix, which would further weaken the composite and increase the amount of water that can absorb by the fibres.

Utilising SEM analysis allows inspection of the interaction of the natural fibres with the matrix in the composite. The luffa fibres, durian fibres, and the GCW microfibrils do in fact bond with the PE matrix, however, there exists micro gaps between fibre and matrix.

Furthermore, it also can be seen that the aspect ratio of the fibres does influence the stress distribution as the durian fibres can be seen to cover more areas on the composite cross section in comparison to the GCW microfibrils. FTIR analysis further supports the fact why DLPE is greater in withstanding mechanical tensile stress compared to CLPE. FTIR analysis determined that GCW microfibrils contain additional constituents compared to luffa fibres and durian fibres, which in turn decreases the wettability of the matrix to GCW microfibrils. This may be the reason behind CLPE withstands less mechanical stress compared to DLPE. Further investigation and research must be carried out to overcome this issue.

In conclusion, inclusion of natural fibres to be an alternative in place of synthetic fibres is highly recommended, as it is on par with SDG standards. This research proves that hybridisation of fibres is not impossible, but it is beneficial in mechanical strength, environmentally sound, and cost efficient. Furthermore, recycling these natural fibres in composites adds value to it, and reduces production costs. This may be beneficial to several industries such as packaging, gardening, furniture, hardware, automotive, and others.

5.2 Recommendations

Upon completion, several recommendations can be brought forward to further improve topics regarding this research. Different fabrication techniques may be carried out to enhance composites. Chemical treatment of natural fibres, chemical alteration of matrix, and surface modification of both fibres and matrix may benefit the composite in terms of interfacial bonding and wettability. Different hybridisation techniques and different aspect ratios of fibres may be varied to explore more options to further enhance natural fibre composites. Finally, recycling of raw materials may be much more efficient and environmentally friendly, and further strengthens the cause.

REFERENCES

- A Aziz, N., & Mhd Jalil, A. (2019, March 13). Bioactive compounds, nutritional value, and potential health benefits of indigenous durian (*Durio Zibethinus Murr.*): A review. *Foods*, 8(3), 96. <https://doi.org/10.3390/foods8030096>
- Abhilash, S. S., & Lenin Singaravelu, D. (2020). A comparative study of mechanical, dynamic mechanical and morphological characterization of Tampico and coir fibre-reinforced LLDPE processed by Rotational moulding. *Journal of Industrial Textiles*, 51(1_suppl). <https://doi.org/10.1177/1528083720929363>
- Abidin, N. M., Sultan, M. T., Shah, A. U., & Safri, S. N. (2019). Charpy and Izod impact properties of natural fibre composites. *IOP Conference Series: Materials Science and Engineering*, 670(1), 012031. <https://doi.org/10.1088/1757-899x/670/1/012031>
- Adeyanju, C. A., Ogunniyi, S., Ighalo, J. O., Adeniyi, A. G., & Abdulkareem, S. A. (2020). A review on luffa fibres and their polymer composites. *Journal of Materials Science*, 56(4), 2797–2813. <https://doi.org/10.1007/s10853-020-05432-6>
- Adunphatcharaphon, S., Petchkongkaew, A., Greco, D., D'Ascanio, V., Visessanguan, W., & Avantaggiato, G. (2020, February 8). The effectiveness of durian peel as a multi-mycotoxin adsorbent. *Toxins*, 12(2), 108. <https://doi.org/10.3390/toxins12020108>
- Ahmad, F., Choi, H. S., & Park, M. K. (2014). A review: Natural fiber composites selection in view of mechanical, light weight, and economic properties. *Macromolecular Materials and Engineering*, 300(1), 10–24. <https://doi.org/10.1002/mame.201400089>

- Ahmad, M. A. A., Abdul Majid, M. S., Ridzuan, M. J. M., Mazlee, M. N., & Gibson, A. G. (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. <https://doi.org/10.1016/j.conbuildmat.2018.05.227>
- Ahmad, R., Hamid, R., & Osman, S. A. (2019). Physical and chemical modifications of plant fibres for reinforcement in cementitious composites. *Advances in Civil Engineering*, 2019, 1–18. <https://doi.org/10.1155/2019/5185806>
- Alabtah, F. G., Mahdi, E., & Eliyan, F. F. (2021). The use of fiber reinforced polymeric composites in pipelines: A review. *Composite Structures*, 276, 114595. <https://doi.org/10.1016/j.compstruct.2021.114595>
- Alani, A. H., Bunnori, N. M., Noaman, A. T., & Majid, T. A. (2020). Mechanical characteristics of pet fibre-reinforced green ultra-high performance composite concrete. *European Journal of Environmental and Civil Engineering*, 26(7), 2797–2818. <https://doi.org/10.1080/19648189.2020.1772117>
- Alavudeen, A., Rajini, N., Karthikeyan, S., Thiruchitrambalam, M., & Venkateshwaren, N. (2015). Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation. *Materials & Design (1980-2015)*, 66, 246–257. <https://doi.org/10.1016/j.matdes.2014.10.067>
- Alberto, M. (2013). Introduction of Fibre-Reinforced Polymers – Polymers and Composites: Concepts, Properties and Processes. In *Fiber Reinforced Polymers - The Technology Applied for Concrete Repair*. IntechOpen. <https://doi.org/10.5772/54629>

- Alhijazi, M., Safaei, B., Zeeshan, Q., Asmael, M., Eyvazian, A., & Qin, Z. (2020). Recent developments in luffa natural fiber composites: Review. *Sustainability*, 12(18), 7683. <https://doi.org/10.3390/su12187683>
- Alrawashdeh, A., & Eren, O. (2022). Mechanical and physical characterisation of steel fibre reinforced self-compacting concrete: Different aspect ratios and volume fractions of Fibres. *Results in Engineering*, 13, 100335. <https://doi.org/10.1016/j.rineng.2022.100335>
- Amir, S. M., Sultan, M. T. H., Jawaid, M., Ariffin, A. H., Mohd, S., Salleh, K. A., Ishak, M. R., & Shah, A. U. (2019). Nondestructive testing method for Kevlar and natural fiber and their hybrid composites. *Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, 367–388. <https://doi.org/10.1016/b978-0-08-102290-0.00016-7>
- Anuar, H., Abd Rashid, S. M., Mohd. Nordin, N., Ali, F., Buys, Y. F., Thomas, S., Mohd Nasir, N. A., & Mohd Asri, S. E. (2021). Potential of fabrication of durian skin fiber biocomposites for food packaging application through the Electricity Impact Analysis. *IJUM Engineering Journal*, 22(2), 294–305. <https://doi.org/10.31436/iiumej.v22i2.1673>
- Aravind, M. K., Kappen, J., Narayanamoorthi, E., Sanjaykumar, A., Varalakshmi, P., Arockiadoss, T., John, S. A., & Ashokkumar, B. (2022). Bioengineered magnetic graphene oxide microcomposites for bioremediation of chromium in ex situ - a novel strategy for aggrandized recovery by electromagnetic gadgetry. *Environmental Pollution*, 308, 119675. <https://doi.org/10.1016/j.envpol.2022.119675>

- Asaithambi, B., Ganesan, G., & Ananda Kumar, S. (2014). Bio-composites: Development and mechanical characterization of banana/sisal fibre reinforced poly lactic acid (PLA) hybrid composites. *Fibers and Polymers*, 15(4), 847–854. <https://doi.org/10.1007/s12221-014-0847-y>
- Ashothaman, A., Sudha, J., & Senthilkumar, N. (2023). A comprehensive review on biodegradable polylactic acid polymer matrix composite material reinforced with synthetic and natural fibers. *Materials Today: Proceedings*, 80, 2829–2839. <https://doi.org/10.1016/j.matpr.2021.07.047>
- Ashter, S. A. (2014). *Thermoforming of single and Multilayer Laminates*. Elsevier, Inc.
- Asim, M., Jawaaid, 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. <https://doi.org/10.1016/j.jmrt.2020.01.099>
- Asmatulu, E., Twomey, J., & Overcash, M. (2014). Recycling of fibre-reinforced composites and direct structural composite recycling concept. *Journal of Composite Materials*, 48 (5), 593-608.
- Awodi, E., Ishiaku, U. S., Yakubu, M. K., & Abifarin, J. K. (2021). Experimentally predicted optimum processing parameters assisted by numerical analysis on the multi-physicomechanical characteristics of coir fiber reinforced recycled high density polyethylene composites. <https://doi.org/10.21203/rs.3.rs-591200/v1>

- Babu, K., Rhoda Afriyie Mensah, Shanmugam, V., Rashedi, A., Pugazhenthir Athimoolam, J. Ronald Aseer, & Das, O. (2022). Self-reinforced polymer composites: An opportunity to recycle plastic wastes and their future trends. *Journal of Applied Polymer Science*, 139(46), e53143. <https://doi.org/10.1002/app.53143>
- Bacci, L., Di Lonardo, S., Albanese, L., Mastromei, G., & Perito, B. (2010). Effect of different extraction methods on fiber quality of nettle (*Urtica dioica* L.). *Textile Research Journal*, 81(8), 827–837. <https://doi.org/10.1177/0040517510391698>
- Back, D., Shaffer, B. T., Loper, J. E., & Philmus, B. (2022). Untargeted identification of alkyne-containing natural products using ruthenium-catalyzed azide alkyne cycloaddition reactions coupled to LC-MS/MS. *Journal of Natural Products*, 85(1), 105–114. <https://doi.org/10.1021/acs.jnatprod.1c00798>
- Baek, B. S., Park, J. W., Lee, B. H., & Kim, H. J. (2013, April 11). Development and application of green composites: using coffee ground and bamboo flour. *Journal of Polymers and the Environment*, 21(3), 702–709. <https://doi.org/10.1007/s10924-013-0581-3>
- Baeurle, S. A., Hotta, A., & Gusev, A. A. (2006). On the glassy state of multiphase and pure polymer materials. *Polymer*, 47(17), 6243–6253. <https://doi.org/10.1016/j.polymer.2006.05.076>
- Bahari, S. A., & Krause, A. (2016). Utilizing Malaysian bamboo for use in thermoplastic composites. *Journal of Cleaner Production*, 110, 16–24. <https://doi.org/10.1016/j.jclepro.2015.03.052>

- Baskaran, S., & Sathivelu, M. (2022). Bioaugmentation and biostimulation of dumpsites for plastic degradation. *Cost Effective Technologies for Solid Waste and Wastewater Treatment*, 9–23. <https://doi.org/10.1016/b978-0-12-822933-0.00015-2>
- Basu, P., Kumar, R., & Das, M. (2023, July). Natural and manmade fibers as sustainable building materials. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2023.07.222>
- Begum, K. & Islam, Mohammad. (2013). Natural fibre as a substitute to synthetic fibre in polymer composites: A review. *Research Journal of Engineering Sciences*. 2. 46-53.
- BioPak Team. (2022, January 17). *What is Pla?* BioPak Singapore. Retrieved August 19, 2022, from <https://www.biopak.com/sg/resources/what-is-pla>
- Bîrcă, A., Gherasim, O., Grumezescu, V., & Grumezescu, A. M. (2019). Introduction in thermoplastic and thermosetting polymers. *Materials for Biomedical Engineering*, 1–28. <https://doi.org/10.1016/b978-0-12-816874-5.00001-3>
- Bledzki, A. K., Mamun, A. A., Lucka-Gabor, M., & Gutowski, V. S. (2008). The effects of acetylation on properties of flax fibre and its polypropylene composites. *Express Polymer Letters*, 2(6), 413–422. <https://doi.org/10.3144/expresspolymlett.2008.50>
- Bomfim, A., Oliveira, D., Voorwald, H., Benini, K., Dumont, M.-J., & Rodrigue, D. (2022). Valorization of spent coffee grounds as precursors for biopolymers and composite production. *Polymers*, 14(3), 437. <https://doi.org/10.3390/polym14030437>

- Bongarde, U. S., & Shinde, V. D. (2014). Review on natural fibre reinforcement polymer composites. *International Journal of Engineering Science and Innovative Technology*, 3(2), 431-436.
- Bottausci, S., Ungureanu-Comanita, E.-D., Gavrilescu, M., & Bonoli, A. (2021). ENVIRONMENTAL IMPACTS QUANTIFICATION OF PVC PRODUCTION. *Environmental Engineering and Management Journal*, 20(10), 1693–1702. <https://doi.org/10.30638/eemj.2021.158>
- Bradford, A. (2017, October 14). *What is a polymer?* Retrieved November 21, 2020, from <https://www.livescience.com/60682-polymers.html>
- Brantley, W., Berzins, D., Iijima, M., Tufekçi, E., & Cai, Z. (2017). Structure/property relationships in orthodontic alloys. *Orthodontic Applications of Biomaterials*, 3–38. <https://doi.org/10.1016/b978-0-08-100383-1.00001-1>
- BrickAdmin, A. (2020, May 8). *Polyvinyl chloride (PVC): uses, benefits, and safety facts*. ChemicalSafetyFacts.org. Retrieved August 18, 2022, from <https://www.chemicalsafetyfacts.org/polyvinyl-chloride/>
- Britannica, T. Editors of Encyclopaedia (2017, December 6). *Polypropylene*. Encyclopedia Britannica. <https://www.britannica.com/science/polypropylene>
- Britannica, T. Editors of Encyclopaedia (2020, March 5). *Monomer*. Encyclopedia Britannica. <https://www.britannica.com/science/monomer>

- Britannica, T. Editors of Encyclopaedia (2020, May 20). *Polyethylene terephthalate*. Encyclopedia Britannica. <https://www.britannica.com/science/polyethylene-terephthalate>
- BYJUS. (2021, December 1). *Difference between alloy and composite*. Retrieved September 23, 2022, from <https://byjus.com/chemistry/difference-between-alloy-and-composite/>
- Callister, W. D., & Rethwisch, D. G. (2018). *Materials science and engineering: An introduction*. Wiley.
- Capiati, N. J., & Porter, R. S. (1975). The concept of one polymer composites modelled with high density polyethylene. *Journal of Materials Science*, 10(10), 1671–1677. <https://doi.org/10.1007/bf00554928>
- Cegla, M., & Engell, S. (2020). Reliable modelling of twin-screw extruders by integrating the backflow cell methodology into a mechanistic model. *Computer Aided Chemical Engineering*, 175–180. <https://doi.org/10.1016/b978-0-12-823377-1.50030-6>
- Cevahir, A. (2017). Glass fibers. *Fiber Technology for Fiber-Reinforced Composites*, 99–121. <https://doi.org/10.1016/b978-0-08-101871-2.00005-9>
- Chakrawarthy, V., Avudaiappan, S., Amran, M., Dharmar, B., Raj Jesuarulraj, L., Fediuk, R., Aepuru, R., Vatin, N., & Saavedra Flores, E. (2021). Impact resistance of polypropylene fibre-reinforced alkali-activated copper slag concrete. *Materials*, 14(24), 7735. <https://doi.org/10.3390/ma14247735>

- Chawla, K. (2016). Glass fibers. *Reference Module in Materials Science and Materials Engineering*. <https://doi.org/10.1016/b978-0-12-803581-8.02325-0>
- Chou, W. L. (2012). Investigation of indium ions removal from aqueous solutions using spent coffee grounds. *International Journal of Physical Sciences*, 7(16), 2445–2454. <https://doi.org/10.5897/ijps12.192>
- Chua, J. Y., Pen, K. M., Poi, J. V., Ooi, K. M., & Yee, K. F. (2023). Upcycling of biomass waste from durian industry for green and sustainable applications: An analysis review in the Malaysia context. *Energy Nexus*, 10, 100203. <https://doi.org/10.1016/j.nexus.2023.100203>
- Clau, B. (2008). Fibers for ceramic matrix composites. *Ceramic Matrix Composites*, 1–20. <https://doi.org/10.1002/9783527622412.ch1>
- Creative Mechanisms Staff (Ed.). (2016, July 6). *Everything you need to know about PVC plastic*. Everything You Need To Know About PVC Plastic. Retrieved August 18, 2022, from <https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-pvc-plastic>
- Creative Mechanisms Staff. (2016, May 4). *Everything you need to know about polypropylene (PP) plastic*. Everything You Need To Know About Polypropylene (PP) Plastic. Retrieved July 23, 2022, from [https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic#:~:text=Polypropylene%20\(PP\)%20is%20a%20thermoplastic,like%20living%20hinges%2C%20and%20textiles.](https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic#:~:text=Polypropylene%20(PP)%20is%20a%20thermoplastic,like%20living%20hinges%2C%20and%20textiles.)

- Danilenko, V. N., Korznikova, G. F., Zhilyaev, A. P., Sergeev, S. N., Khalikova, G. R., Khisamov, R. K., Nazarov, K. S., Kiekkuzhina, L. U., & Mulyukov, R. R. (2018). Effect of annealing on the structure and phase composition of Al-Cu laminated metal-matrix composites produced by shear deformation under pressure. *IOP Conference Series: Materials Science and Engineering*, 447, 012021. <https://doi.org/10.1088/1757-899x/447/1/012021>
- Dan-mallam, Y., Abdullah, M. Z., & MegatYusoff, P. S. (2012). Predicting the tensile properties of woven kenaf/polyethylene terephthalate (PET) fibre reinforced polyoxymethylene (POM) hybrid laminate composite. *IOSR J Mech Civil Eng*, 2, 6–13.
- Derradji, M., Jun, W., & Wenbin, L. (2018). *Phthalonitrile resins and composites: Properties and applications*. William Andrew.
- Dhakal, S., & Keerthi Gowda, B. S. (2017). An experimental study on mechanical properties of banana polyester composite. *Materials Today: Proceedings*, 4(8), 7592–7598. <https://doi.org/10.1016/j.matpr.2017.07.092>
- Dhanasekar, S., Ganesan, A. T., Rani, T. L., Vinjamuri, V. K., Nageswara Rao, M., Shankar, E., Dharamvir, Kumar, P. S., & Misganaw Golie, W. (2022). A comprehensive study of ceramic matrix composites for space applications. *Advances in Materials Science and Engineering*, 2022, 1–9. <https://doi.org/10.1155/2022/6160591>
- Dhinakaran, V., Vijayakumar, M. D., Muthu, G., Sathish, T., & Bupathi ram, P. M. (2021). Experimental investigation of hybrid fibre reinforced polymer composite material

and its microstructure properties. *Materials Today: Proceedings*, 37, 1799–1803.
<https://doi.org/10.1016/j.matpr.2020.07.394>

Dodiuk, H., & Goodman, S. H. (Eds.). (2013). *Handbook of thermoset plastics*. William Andrew.

Elchalakani, M., Yang, B., Mao, K., & Pham, T. (2023). Geopolymer concrete material characteristics. *Geopolymer Concrete Structures with Steel and FRP Reinforcements*, 1–74. <https://doi.org/10.1016/b978-0-443-18876-3.00005-0>

Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnier, C. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results in Engineering*, 19, 101271. <https://doi.org/10.1016/j.rineng.2023.101271>

Far, H., & Nejadi, S. (2021). Experimental investigation on flexural behaviour of composite PVC encased macro-synthetic fibre reinforced concrete walls. *Construction and Building Materials*, 273, 121756. <https://doi.org/10.1016/j.conbuildmat.2020.121756>

Feng, H., Shao, Q., Yao, X., Li, L., & Yuan, C. (2022). Investigating the Hybrid Effect of Micro-steel Fibres and Polypropylene Fibre-Reinforced Magnesium Phosphate Cement Mortar. *International Journal of Concrete Structures and Materials*, 16(1), 35. <https://doi.org/10.1186/s40069-022-00528-6>

- Ferreira, D. P., Cruz, J., & Figueiro, R. (2019). Surface modification of natural fibers in polymer composites. *Green Composites for Automotive Applications*, 3–41. <https://doi.org/10.1016/b978-0-08-102177-4.00001-x>
- Finch, C. A. (1987). Hydrophilic polymers. *Specialty Polymers*, 65–82. https://doi.org/10.1007/978-1-4615-7894-9_5
- Friedrich, D. (2021). Thermoplastic moulding of wood-polymer composites (WPC): A review on physical and mechanical behaviour under hot-pressing technique. *Composite Structures*, 262, 113649. <https://doi.org/10.1016/j.compstruct.2021.113649>
- Gaidukova, G., Platnieks, O., Aunins, A., Barkane, A., Ingrao, C., & Gaidukovs, S. (2021). Spent coffee waste as a renewable source for the production of sustainable poly(butylene succinate) biocomposites from a circular economy perspective. *RSC Advances*, 11(30), 18580–18589. <https://doi.org/10.1039/d1ra03203h>
- Gajalakshmi, K., Senthilkumar, N., Mohan, B., & Anbuezhayan, G. (2020). An investigation on microstructure and mechanical behaviour of copper-nickel coated carbon fibre reinforced aluminium composites. *Materials Research Express*, 7(11), 115701. <https://doi.org/10.1088/2053-1591/abcb4c>
- Gokkon, B. (2020, December 2). *Southeast Asian countries pledge to tackle Marine Plastic Waste Crisis*. Mongabay Environmental News. <https://news.mongabay.com/2019/06/southeast-asian-countries-pledge-to-tackle-marine-plastic-waste-crisis/>

- Gotro, J. (2014, March 03). *Thermoset Cure Chemistry 1: Introduction*. Retrieved November 21, 2020, from <https://polymerinnovationblog.com/thermoset-cure-chemistry-1-introduction/>
- Graupner, N., Herrmann, A. S., & Müssig, J. (2009). Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics and application areas. *Composites Part A: Applied Science and Manufacturing*, 40(6-7), 810–821. <https://doi.org/10.1016/j.compositesa.2009.04.003>
- Gupta, M. K., & Srivastava, R. K. (2015). Mechanical properties of hybrid fibers-reinforced polymer composite: A review. *Polymer-Plastics Technology and Engineering*, 55(6), 626–642. <https://doi.org/10.1080/03602559.2015.1098694>
- Halashi, K., Taban, E., Soltani, P., Amininasab, S., Samaei, E., Moghadam, D. N., & Khavanin, A. (2024). Acoustic and thermal performance of Luffa Fiber Panels for sustainable building applications. *Building and Environment*, 247, 111051. <https://doi.org/10.1016/j.buildenv.2023.111051>
- Hales, R., & Birdthistle, N. (2023). The Sustainable Development Goals - SDG#12 responsible consumption and production. *Attaining the 2030 Sustainable Development Goal of Responsible Consumption and Production*, 1–10. <https://doi.org/10.1108/978-1-80455-840-920231001>
- Hamad, A. J. (2017, October). Size and shape effect of specimen on the compressive strength of HPLWFC reinforced with glass fibres. *Journal of King Saud University - Engineering Sciences*, 29(4), 373–380. <https://doi.org/10.1016/j.jksues.2015.09.003>

- Hamdan, M. H., Siregar, J. P., Cionita, T., Jaafar, J., Efriyohadi, A., Junid, R., & Kholil, A. (2019). Water absorption behaviour on the mechanical properties of woven hybrid reinforced polyester composites. *The International Journal of Advanced Manufacturing Technology*, 104(1–4), 1075–1086. <https://doi.org/10.1007/s00170-019-03976-9>
- Haque, S. M., Ardila-Rey, J. A., Umar, Y., Mas'ud, A. A., Muhammad-Sukki, F., Jume, B. H., Rahman, H., & Bani, N. A. (2021). Application and suitability of polymeric materials as insulators in electrical equipment. *Energies*, 14(10), 2758. <https://doi.org/10.3390/en14102758>
- Hasan, M. S., Ahmed, I., Parsons, A. J., Walker, G. S., & Scotchford, C. A. (2013). The influence of coupling agents on mechanical property retention and long-term cytocompatibility of phosphate glass fibre reinforced PLA composites. *Journal of the Mechanical Behavior of Biomedical Materials*, 28, 1–14. <https://doi.org/10.1016/j.jmbbm.2013.07.014>
- He, S., Wang, X., Bai, H., Xu, Z., & Ma, D. (2021). Effect of fiber dispersion, content and aspect ratio on tensile strength of PP fiber reinforced soil. *Journal of Materials Research and Technology*, 15, 1613–1621. <https://doi.org/10.1016/j.jmrt.2021.08.128>
- Henshaw, J. M. (2001). Recycling and disposal of polymer–matrix composites. *ASM Handbook*, 21, 1006-1012.
- Horie, K., Barón, M., Fox, R. B., He, J., Hess, M., Kahovec, J., Kitayama, T., Kubisa, P., Maréchal, E., Mormann, W., Stepto, R. F., Tabak, D., Vohlídal, J., Wilks, E. S., &

- Work, W. J. (2004). Definitions of terms relating to reactions of polymers and to functional polymeric materials (IUPAC recommendations 2003). *Pure and Applied Chemistry*, 76(4), 889–906. <https://doi.org/10.1351/pac200476040889>
- Hu, X., Sun, Z., Zhang, C., Wang, X., & Wu, K. (2018). Microstructure and mechanical properties of bio-inspired CF/Ti/Mg laminated composites. *Journal of Magnesium and Alloys*, 6(2), 164–170. <https://doi.org/10.1016/j.jma.2018.04.005>
- Hulle, A., Kadole, P., & Katkar, P. B. (2015, February 5). *Agave Americana Leaf Fibers*. Fibers; Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/fib3010064>
- Humaira Alias, A., Zainudin, E. S., Mohd Norizan, M. N., & Rushdan, A. I. (2023). Development and characterisation of biocomposite insulator board from durian skin fibres. *Toward Successful Implementation of Circular Economy*, 31(S1), 59–85. <https://doi.org/10.47836/pjst.31.s1.04>
- Inoue, R., Arai, Y., Kubota, Y., Goto, K., & Kogo, Y. (2018). Development of short- and continuous carbon fiber-reinforced Zrb2-sic-ZRC matrix composites for thermal protection systems. *Ceramics International*, 44(13), 15859–15867. <https://doi.org/10.1016/j.ceramint.2018.05.268>
- Islam, M. S., Pickering, K. L., & Foreman, N. J. (2010). Influence of alkali treatment on the interfacial and physico-mechanical properties of industrial hemp fibre reinforced polylactic acid composites. *Composites Part A: Applied Science and Manufacturing*, 41(5), 596–603. <https://doi.org/10.1016/j.compositesa.2010.01.006>

- Jacoby, M. (2021, June 18). *What's that stuff? Fiberglass*. Chemical & Engineering News.
<https://cen.acs.org/materials/inorganic-chemistry/s-fiberglass-does-delicate-material/96/i38>
- Jahan, A., Rahman, M.M., Kabir, H., Kabir, M., Ahmed, F., Hossain, M., & Gafur, M. (2012). Comparative Study of Physical and Elastic Properties of Jute and Glass Fiber Reinforced LDPE Composites. *International Journal of Scientific & Technology Research*. 1. 68-72.
- Jamir, M. R., Majid, M. S., & Khasri, A. (2018). Natural lightweight hybrid composites for aircraft structural applications. *Sustainable Composites for Aerospace Applications*, 155–170. <https://doi.org/10.1016/b978-0-08-102131-6.00008-6>
- Javier-Astete, R., Jimenez-Davalos, J., & Zolla, G. (2021). Determination of hemicellulose, cellulose, holocellulose and lignin content using FTIR in *Calycophyllum spruceanum* (Benth.) K. Schum. and *Guazuma crinita* Lam. *PLOS ONE*, 16(10), e0256559. <https://doi.org/10.1371/journal.pone.0256559>
- Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, 86(1), 1–18. <https://doi.org/10.1016/j.carbpol.2011.04.043>
- Jawaid, M., Khalil, H. P. S. A., Bakar, A. A., & Khanam, P. N. (2011). Chemical resistance, void content and tensile properties of oil palm/jute fibre reinforced polymer hybrid composites. *Materials & Design*, 32(2), 1014–1019. <https://doi.org/10.1016/j.matdes.2010.07.033>

- Jenkins, E. B. (2018). High-performance apparel for outdoor pursuits. 421–449.
<https://doi.org/10.1016/b978-0-08-100904-8.00021-3>
- Jino, R., Pugazhenth, R., Ashok, K. G., Ilango, T., & Chakravarthy, P. R. K. (2017, September 1). Enhancement of mechanical properties of luffa fiber/epoxy composite using B4C. *Journal of Advanced Microscopy Research*, 12(2), 89–91.
<https://doi.org/10.1166/jamr.2017.1324>
- Jones, D. R. H., & Ashby, M. F. (2019). Elastic moduli. *Engineering Materials 1*, 31–47.
<https://doi.org/10.1016/b978-0-08-102051-7.00003-8>
- Kabir, M. M., Wang, H., Lau, K. T., & Cardona, F. (2012). Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. *Composites Part B: Engineering*, 43(7), 2883–2892.
<https://doi.org/10.1016/j.compositesb.2012.04.053>
- Kaushal, A., & Singh, V. (2020). Development of lightweight polypropylene/carbon fiber composites for its application in shielding of electromagnetic interference in X-band. *Journal of Materials Science: Materials in Electronics*, 31(17), 14088–14100.
<https://doi.org/10.1007/s10854-020-03963-x>
- Kesraoui, A., Bouzaabia, S., & Seffen, M. (2018). The combination of luffa cylindrical fibers and metal oxides offers a highly performing hybrid fiber material in water decontamination. *Environmental Science and Pollution Research*, 26(12), 11524–11534. <https://doi.org/10.1007/s11356-018-1507-3>

- Ketsa, S., Wisutiamonkul, A., Palapol, Y., & Paull, R. E. (2019). The durian. *Horticultural Reviews*, 125–211. <https://doi.org/10.1002/9781119625407.ch4>
- Khadir, A., Motamedi, M., Pakzad, E., Sillanpää, M., & Mahajan, S. (2021). The prospective utilization of luffa fibres as a lignocellulosic bio-material for environmental remediation of aqueous media: A review. *Journal of Environmental Chemical Engineering*, 9(1), 104691. <https://doi.org/10.1016/j.jece.2020.104691>
- Khan, R. A., Mahdi, E., & Cabibihan, J.-J. (2021). Effect of fibre orientation on the quasi-static axial crushing behaviour of glass fibre reinforced polyvinyl chloride composite tubes. *Materials*, 14(9), 2235. <https://doi.org/10.3390/ma14092235>
- Kjar, A., & Huang, Y. (2019). Application of micro-scale 3D printing in Pharmaceuticals. *Pharmaceutics*, 11(8), 390. <https://doi.org/10.3390/pharmaceutics11080390>
- Knauer, K., Higginson, C., Liang, Y., & Lee, M. (2023). Circular plastics technologies: depolymerization of polymers into parent monomers. *Physical Sciences Reviews*, 9(7), 2499–2524. <https://doi.org/10.1515/psr-2023-0014>
- Konieczny, M. (2022). Mechanical properties and failure analysis of laminated magnesium-intermetallic composites. *AIMS Materials Science*, 9(4), 572–583. <https://doi.org/10.3934/materci.2022034>
- Körbelin, J., Derra, M., & Fiedler, B. (2018). Influence of temperature and impact energy on low velocity impact damage severity in CFRP. *Composites Part A: Applied Science and Manufacturing*, 115, 76–87. <https://doi.org/10.1016/j.compositesa.2018.09.010>

- Kueh, A. B. (2021). Spent ground coffee - awaking the sustainability prospects. *Environmental and Toxicology Management*, 1(1), 1–6. <https://doi.org/10.33086/etm.v1i1.2016>
- Kueh, A., & Pellegrino, S. (2007). Abd matrix of single-ply triaxial weave fabric composites. *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. <https://doi.org/10.2514/6.2007-2161>
- Kureemun, U., Ravandi, M., Tran, L. Q. N., Teo, W. S., Tay, T. E., & Lee, H. P. (2018). Effects of hybridization and hybrid fibre dispersion on the mechanical properties of woven flax-carbon epoxy at low carbon fibre volume fractions. *Composites Part B: Engineering*, 134, 28–38. <https://doi.org/10.1016/j.compositesb.2017.09.035>
- Kusmono, Hestiawan, H., & Jamasri. (2020). The water absorption, mechanical and thermal properties of chemically treated woven fan palm reinforced polyester composites. *Journal of Materials Research and Technology*, 9(3), 4410–4420. <https://doi.org/10.1016/j.jmrt.2020.02.065>
- L&L Special Furnace Co, Inc. (2022, September 23). *What are ceramic matrix composites?*. L&L Special Furnace Co, Inc. <https://lffurnace.com/blog/what-are-ceramic-matrix-composites/>
- Larsen, I. L., & Thorstensen, R. T. (2020). The influence of steel fibres on compressive and tensile strength of Ultra High Performance Concrete: A review. *Construction and Building Materials*, 256, 119459. <https://doi.org/10.1016/j.conbuildmat.2020.119459>

- Łątka, J. F., Jasiołek, A., Karolak, A., Niewiadomski, P., Noszczyk, P., Klimek, A., Zielińska, S., Misiurka, S., & Jezierska, D. (2022). Properties of paper-based products as a building material in architecture – An interdisciplinary review. *Journal of Building Engineering*, 50, 104135. <https://doi.org/10.1016/j.jobbe.2022.104135>
- Law, K.-Y. (2014). Definitions for hydrophilicity, hydrophobicity, and superhydrophobicity: Getting the basics right. *The Journal of Physical Chemistry Letters*, 5(4), 686–688. <https://doi.org/10.1021/jz402762h>
- Lebreton, L. C. M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, 8(15611), 15611. <https://doi.org/10.1038/ncomms15611>
- Lee, C. H., Khalina, A., Lee, S. H., & Liu, M. (2020, July 13). A comprehensive review on bast fibre retting process for optimal performance in fibre-reinforced polymer composites. *Advances in Materials Science and Engineering*, 2020, 1–27. <https://doi.org/10.1155/2020/6074063>
- Lee, Y.-G., Cho, E.-J., Maskey, S., Nguyen, D.-T., & Bae, H.-J. (2023). Value-added products from coffee waste: A review. *Molecules*, 28(8), 3562. <https://doi.org/10.3390/molecules28083562>
- Leow, Y., Yew, P. Y., Chee, P. L., Loh, X. J., & Kai, D. (2021). Recycling of spent coffee grounds for useful extracts and green composites. *RSC Advances*, 11(5), 2682–2692. <https://doi.org/10.1039/d0ra09379c>

- Li, N., Liu, W., Wang, Y., Zhao, Z., Yan, T., Zhang, G., & Xiong, H. (2021). Laser additive manufacturing on metal matrix composites: A review. *Chinese Journal of Mechanical Engineering*, 34(1), 1–16. <https://doi.org/10.1186/s10033-021-00554-7>
- Lin, G., Peng, Y., Li, Y., Liang, H., Dong, Z., Zhou, Y., Yue, Z., Zhang, J., Xiong, D.-B., & Zhang, D. (2021). Remarkable anisotropic wear resistance with 100-fold discrepancy in a copper matrix laminated composite with only 0.2 vol% graphene. *Acta Materialia*, 215, 117092. <https://doi.org/10.1016/j.actamat.2021.117092>
- Liu, G., Xiong, Y., & Zhou, L. (2021). Additive manufacturing of continuous fiber reinforced polymer composites: Design opportunities and novel applications. *Composites Communications*, 27, 100907. <https://doi.org/10.1016/j.coco.2021.100907>
- López, S., Bergueiro, J., & Fidalgo, J. (2014). Silane. *Encyclopedia of Toxicology*, 261–263. <https://doi.org/10.1016/b978-0-12-386454-3.01180-5>
- Low, I. M. (2018). Advances in ceramic matrix composites. *Advances in Ceramic Matrix Composites*, 1–7. <https://doi.org/10.1016/b978-0-08-102166-8.00001-3>
- Lubis, R., Riyanto, Wirjosentono, B., Eddyanto, & Septevani, A. (2019). Extraction and characterization of cellulose fiber of durian rinds from North Sumatera as the raw material for textile fiber. *Journal of Physics: Conference Series*, 1232(1), 012017. <https://doi.org/10.1088/1742-6596/1232/1/012017>

- Lubis, R., Saragih, S. W., Wirjosentono, B., & Eddyanto, E. (2018). Characterization of durian rinds fiber (*Durio zubinthinus, murr*) from North Sumatera. *AIP Conference Proceedings*. <https://doi.org/10.1063/1.5082474>
- Mahardika, M., Asrofi, M., Amelia, D., Syafri, E., Mavinkere Rangappa, S., & Siengchin, S. (2021). Tensile strength and moisture resistance properties of biocomposite films based on Polyvinyl Alcohol (PVA) with cellulose as reinforcement from durian peel fibers. *E3S Web of Conferences*, 302, 02001. <https://doi.org/10.1051/e3sconf/202130202001>
- Malaysia's Roadmap Towards Zero Single-Use Plastics 2018-2030*. Prime Minister's Office of Malaysia. (2019, July 12). <https://www.pmo.gov.my/2019/07/malaysias-roadmap-towards-zero-single-use-plastics-2018-2030/>
- Małek, M., Łasica, W., Kadela, M., Kluczyński, J., & Dudek, D. (2021). Physical and mechanical properties of polypropylene fibre-reinforced cement-glass composite. *Materials*, 14(3), 637. <https://doi.org/10.3390/ma14030637>
- Manshor, M., Anuar, H., Nur Aimi, M., Ahmad Fitrie, M., Wan Nazri, W., Sapuan, S., El-Shekeil, Y., & Wahit, M. (2014, July). Mechanical, thermal and morphological properties of durian skin fibre reinforced PLA biocomposites. *Materials & Design*, 59, 279–286. <https://doi.org/10.1016/j.matdes.2014.02.062>
- Mendes, J. F., Martins, J. T., Manrich, A., Luchesi, B. R., Dantas, A. P., Vanderlei, R. M., Claro, P. C., Neto, A. R., Mattoso, L. H., & Martins, M. A. (2021). Thermo-physical and mechanical characteristics of composites based on high-density polyethylene

- (HDPE) spent coffee grounds (SCG). *Journal of Polymers and the Environment*, 29(9), 2888–2900. <https://doi.org/10.1007/s10924-021-02090-w>
- Meng, J., Lau, C. H., Xue, Y., Zhang, R., Cao, B., & Li, P. (2020). Compatibilizing hydrophilic and hydrophobic polymers via spray coating for desalination. *Journal of Materials Chemistry A*, 8(17), 8462–8468. <https://doi.org/10.1039/d0ta00871k>
- Mezghani, K., & Furquan, S. (2012). Analysis of dart impact resistance of low-density polyethylene and linear low-density polyethylene blown films via an improved instrumented impact test method. *Journal of Plastic Film & Sheeting*, 28(4), 298–313. <https://doi.org/10.1177/8756087911434184>
- Minnesota Rubber and Plastics. (2019). Thermoset Plastics vs Thermoplastics. Retrieved November 21, 2020, from https://www.mnrubber.com/Design_Guide/5-2.html
- Mirdehghan, S. A. (2021). Fibrous polymeric composites. *Engineered Polymeric Fibrous Materials*, 1–58. <https://doi.org/10.1016/b978-0-12-824381-7.00012-3>
- Mishra, A. A., Momin, A., Strano, M., & Rane, K. (2021). Implementation of viscosity and density models for improved numerical analysis of melt flow dynamics in the nozzle during extrusion-based additive manufacturing. *Progress in Additive Manufacturing*, 7(1), 41–54. <https://doi.org/10.1007/s40964-021-00208-z>
- Mohammed, L., Ansari, M. N., Pua, G., Jawaid, M., & Islam, M. S. (2015). A review on natural fiber reinforced polymer composite and its applications. *International Journal of Polymer Science*, 2015, 1–15. <https://doi.org/10.1155/2015/243947>

- Mohammed, M., Jawad, A. J., Mohammed, A. M., Oleiwi, J. K., Adam, T., Osman, A. F., Dahham, O. S., Betar, B. O., Gopinath, S. C. B., & Jaafar, M. (2023). Challenges and advancement in water absorption of natural fiber-reinforced polymer composites. *Polymer Testing*, 124, 108083. <https://doi.org/10.1016/j.polymertesting.2023.108083>
- Mohan, S. K., Ganesan, A. T., Ramarao, M., Mangrulkar, A. L., Rajesh, S., Al Obaid, S., Alfarraj, S., Sivakumar, S., & Ganesan, M. (2021). Evaluation of mechanical properties of sisal and bamboo fibres reinforced with polymer matrix composites prepared by compression moulding process. *Advances in Materials Science and Engineering*, 2021, 1–8. <https://doi.org/10.1155/2021/2832149>
- Monie, F., Vidil, T., Grignard, B., Cramail, H., & Detrembleur, C. (2021). Self-foaming polymers: Opportunities for the next generation of personal protective equipment. *Materials Science and Engineering: R: Reports*, 145, 100628. <https://doi.org/10.1016/j.mser.2021.100628>
- Mubarak, N. M., Anwar, M., Debnath, S., & Sudin, I. (2023). Mechanical properties and testing. *Fundamentals of Biomaterials*, 67–84. https://doi.org/10.1007/978-981-19-9300-8_7
- Mumthas, A. C. S. I., Wickramasinghe, G. L. D., & Gunasekera, U. S. (2019, January). Effect of physical, chemical and biological extraction methods on the physical behaviour of banana pseudo-stem fibres: Based on fibres extracted from five common Sri Lankan cultivars. *Journal of Engineered Fibers and Fabrics*, 14, 155892501986569. <https://doi.org/10.1177/1558925019865697>

- Muñoz, E., & García-Manrique, J. A. (2015). Water absorption behaviour and its effect on the mechanical properties of flax fibre reinforced Bioepoxy composites. *International Journal of Polymer Science*, 2015, 1–10. <https://doi.org/10.1155/2015/390275>
- Nadondu, B., Surin, P., & Deeying, J. (2022). Multi-objective optimization on mechanical properties of glass-carbon and durian skin fiber reinforced poly(lactic acid) hybrid composites using the extreme mixture design response surface methodology. *Case Studies in Construction Materials*, 17. <https://doi.org/10.1016/j.cscm.2022.e01675>
- Nandiyanto, A. B., Oktiani, R., & Ragadhita, R. (2019). How to read and interpret FTIR spectroscopy of organic material. *Indonesian Journal of Science and Technology*, 4(1), 97. <https://doi.org/10.17509/ijost.v4i1.15806>
- Nandiyanto, A. B., Ragadhita, R., & Fiandini, M. (2022). Interpretation of Fourier Transform Infrared Spectra (FTIR): A practical approach in the polymer/plastic thermal decomposition. *Indonesian Journal of Science and Technology*, 8(1), 113–126. <https://doi.org/10.17509/ijost.v8i1.53297>
- Nandiyanto, A. B., Simbara, A. T., & Girsang, G. C. (2021). Effects of particle size and composite composition of durian peels and banana midribs' as reinforcement components on resin-based brake pad performance. *Journal of Engineering Research*, 1-15. <https://doi.org/10.36909/jer.asseee.16029>
- Naser, M. Z., Hawileh, R. A., & Abdalla, J. (2021). Modeling strategies of finite element simulation of reinforced concrete beams strengthened with FRP: A review. *Journal of Composites Science*, 5(1), 19. <https://doi.org/10.3390/jcs5010019>

- Natrayan, L., & Kaliappan, S. (2023). Mechanical assessment of carbon-luffa hybrid composites for automotive applications. *SAE Technical Paper Series*.
<https://doi.org/10.4271/2023-01-5070>
- Ngo, T.-D. (2020). Introduction to Composite Materials. In *Composite and Nanocomposite Materials - From Knowledge to Industrial Applications*. IntechOpen.
<https://doi.org/10.5772/intechopen.91285>
- Nicholas Kuan, H. T. (2018, September 30). Characterisation of *Artocarpus Heterophyllus* fibre reinforced composite. *Journal of Applied Science & Process Engineering*, 5(2), 304–309. <https://doi.org/10.33736/jaspe.948.2018>
- Nicholas Kuan, H. T., Tan, M. Y., Hassan, M. Z., & Zuhri, M. Y. (2022). Evaluation of physico-mechanical properties on oil extracted ground coffee waste reinforced polyethylene composite. *Polymers*, 14(21), 4678.
<https://doi.org/10.3390/polym14214678>
- Noorunnisa Khanam, P., Mohan Reddy, M., Raghu, K., John, K., & Venkata Naidu, S. (2007). Tensile, flexural and compressive properties of Sisal/silk hybrid composites. *Journal of Reinforced Plastics and Composites*, 26(10), 1065–1070.
<https://doi.org/10.1177/0731684407079347>
- Norfarhana, A. S., Ilyas, R. A., Ngadi, N., Sharma, S., Sayed, M. M., El-Shafay, A. S., & Nordin, A. H. (2022). Natural fiber-reinforced thermoplastic ENR/PVC composites as potential membrane technology in industrial wastewater treatment: A review. *Polymers*, 14(12), 2432. <https://doi.org/10.3390/polym14122432>

- O'Connell, J. (2022, May 31). *PLA plastic / material – the ultimate guide*. All3DP. Retrieved August 19, 2022, from <https://all3dp.com/2/what-is-pla-plastic-material-properties/>
- Ojha, S., Raghavendra, G., & Acharya, S. K. (2012). Fabrication and study of mechanical properties of orange peel reinforced polymer composite. *Cellulose*, 13, 0–6.
- Oladele, I. O., Michael, O. S., Adediran, A. A., Balogun, O. P., & Ajagbe, F. O. (2020). Acetylation treatment for the batch processing of natural fibers: Effects on constituents, tensile properties and surface morphology of selected plant stem fibers. *Fibers*, 8(12), 73. <https://doi.org/10.3390/fib8120073>
- Ovalı, S., & Sancak, E. (2020). Investigation of mechanical properties of jute fiber reinforced low density polyethylene composites. *Journal of Natural Fibers*, 19(8), 3109–3126. <https://doi.org/10.1080/15440478.2020.1838999>
- Pakdel, E., Kashi, S., Varley, R., & Wang, X. (2021, March). Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. *Resources, Conservation and Recycling*, 166, 105340. <https://doi.org/10.1016/j.resconrec.2020.105340>
- Park, C. H., & Lee, W. I. (2012). Compression molding in polymer matrix composites. *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, 47–94. <https://doi.org/10.1533/9780857096258.1.47>
- Payus, C., Refdin, M., Zahari, N., Rimba, A., Geetha, M., Saroj, C., Gasparatos, A., Fukushi, K., & Alvin Oliver, P. (2021). Durian husk wastes as low-cost adsorbent for physical

- pollutants removal: Groundwater supply. *Materials Today: Proceedings*, 42, 80–87.
<https://doi.org/10.1016/j.matpr.2020.10.006>
- Pearson, A., Liao, W., Kazemi, Y., Duncan, M., Slingerland, E., Kakroodi, A., Heydrich, M., Hammami, A., & Naguib, H. E. (2022). Fiber-matrix adhesion between high-density polyethylene and carbon fiber. *Polymer Testing*, 105, 107423.
<https://doi.org/10.1016/j.polymertesting.2021.107423>
- Perkins, S. (2020, April 22). *Explainer: What are polymers?* Retrieved November 21, 2020, from <https://www.sciencenewsforstudents.org/article/explainer-what-are-polymers>
- Perrin, F. X., & Oueiny, C. (2017). Polyaniline thermoset blends and composites. *Reactive and Functional Polymers*, 114, 86–103.
<https://doi.org/10.1016/j.reactfunctpolym.2017.03.009>
- polymer. (2011) *American Heritage Dictionary of the English Language, Fifth Edition*. (2011). Retrieved July 9, 2022, from <https://www.thefreedictionary.com/polymer>.
- Polymers - Classification, Types, Uses, Properties, Polymerization*. (2020, November 03). Retrieved November 21, 2020, from <https://byjus.com/jee/polymers>
- Premalatha, N., Saravanakumar, S. S., Sanjay, M. R., Siengchin, S., & Khan, A. (2019). Structural and thermal properties of chemically modified *luffa cylindrica* fibers. *Journal of Natural Fibers*, 18(7), 1037–1043.
<https://doi.org/10.1080/15440478.2019.1678546>
- Priyanka, P., Mali, H. S., & Dixit, A. (2020). Dynamic mechanical behaviour of Kevlar and carbon-kevlar hybrid fibre reinforced polymer composites. *Proceedings of the*

Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235(19), 4181–4193. <https://doi.org/10.1177/0954406220970600>

Pujol, D., Liu, C., Gominho, J., Olivella, M., Fiol, N., Villaescusa, I., & Pereira, H. (2013, October). The chemical composition of exhausted coffee waste. *Industrial Crops and Products*, 50, 423–429. <https://doi.org/10.1016/j.indcrop.2013.07.056>

Purwanto, Prihatmo, G., & Diasmara, G. (2021). Waste composite of “jos” coffee waste and gauze as alternative basic material for manufacturing craft products. *Journal of Physics: Conference Series*, 1760(1), 012056. <https://doi.org/10.1088/1742-6596/1760/1/012056>

Pusch, J., & Wohlmann, B. (2018). Carbon Fibers. *Inorganic and Composite Fibers*, 31–51. <https://doi.org/10.1016/b978-0-08-102228-3.00002-5>

Putra, A., Othman, M. N., Oliveira, T., Souli, M., Kassim, D. H., Irianto, & Herawan, S. (2022). Waste durian husk fibers as natural sound absorber: Performance and acoustic characterization. *Buildings*, 12(8), 1112. <https://doi.org/10.3390/buildings12081112>

Qiao, J., Zhang, Q., Wu, C., Wu, G., & Li, L. (2022). Effects of fiber volume fraction and length on the mechanical properties of milled glass fiber/polyurea composites. *Polymers*, 14(15), 3080. <https://doi.org/10.3390/polym14153080>

Qiao, Y., Fring, L. D., Pallaka, M. R., & Simmons, K. L. (2022). A review of the fabrication methods and mechanical behavior of continuous thermoplastic polymer fiber-

- thermoplastic polymer matrix composites. *Polymer Composites*, 44(2), 694–733.
<https://doi.org/10.1002/pc.27139>
- Qin, Y. (2016). A brief description of textile fibers. *Medical Textile Materials*, 23–42.
<https://doi.org/10.1016/b978-0-08-100618-4.00003-0>
- Rahman, R., & Zhafer Firdaus Syed Putra, S. (2019). Tensile properties of natural and synthetic fiber-reinforced polymer composites. *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, 81–102.
<https://doi.org/10.1016/b978-0-08-102292-4.00005-9>
- Rajak, D., Pagar, D., Menezes, P., & Linul, E. (2019). Fiber-reinforced polymer composites: Manufacturing, properties, and applications. *Polymers*, 11(10), 1667.
<https://doi.org/10.3390/polym11101667>
- Rajan, S., Marimuthu, K., Balaji Ayyanar, C., Khan, A., Siengchin, S., & Mavinkere Rangappa, S. (2022). In-vitro cytotoxicity of zinc oxide, graphene oxide, and calcium carbonate nano particulates reinforced high-density polyethylene composite. *Journal of Materials Research and Technology*, 18, 921–930.
<https://doi.org/10.1016/j.jmrt.2022.03.012>
- Rajeshkumar, G., Arvinth Seshadri, S., Devnani, G. L., Sanjay, M. R., Siengchin, S., Prakash Maran, J., Al-Dhabi, N. A., Karuppiyah, P., Mariadhas, V. A., Sivarajasekar, N., & Ronaldo Anuf, A. (2021). Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites – A comprehensive review. *Journal of Cleaner Production*, 310, 127483.
<https://doi.org/10.1016/j.jclepro.2021.127483>

- Ramesh Kumar, S. C., Kaviti, R. V., Mahesh, L., & Mohan Babu, B. M. (2022). Water absorption behavior of hybrid natural fiber reinforced composites. *Materials Today: Proceedings*, 54, 187–190. <https://doi.org/10.1016/j.matpr.2021.08.281>
- Ramírez-Hernández, A., Aguilar-Flores, C., & Aparicio-Saguilán, A. (2019). Fingerprint analysis of FTIR spectra of polymers containing vinyl acetate. *DYNA*, 86(209), 198–205. <https://doi.org/10.15446/dyna.v86n209.77513>
- Ratna Kumari, Y., Ramanaiah, K., Ratna Prasad, A. V., Hemachandra Reddy, K., Prasad Sanaka, S., & Kalyan Prudhvi, A. (2021). Experimental investigation of water absorption behaviour of sisal fiber reinforced polyester and sisal fiber reinforced polylactic acid composites. *Materials Today: Proceedings*, 44, 935–940. <https://doi.org/10.1016/j.matpr.2020.11.002>
- Ratna, D. (2009). *Handbook of Thermoset Resins*. Shrewsbury: ISmithers Rapra Publishing.
- Ratnam, C. T., Raju, G., Ibrahim, N. A., Ab Rahman, M. Z., & Wan Yunus, W. M. Z. (2008). Characterization of oil palm empty fruit bunch (OPEFB) fiber reinforced PVC/ENR blend. *Journal of Composite Materials*, 42(20), 2195–2204. <https://doi.org/10.1177/0021998308094555>
- Ridhwan, J., Jowel, W., Alia Ruzanna, A., Meysam, K., Tuan Suhaimi, S., Rushdan Ahmad, I., Fudhail, A. M., Mastura, M. T., Nadlene, R., Abdul Rafeq, S., Ahmad Fuad, A. G., Nuzaimah, M., Nazri Huzaimi, Z., Mohd Adrinata, S., Syahibudil Ikhwan, A. K., & Mohd Yuhazri, Y. (2022). Water absorption and environmental properties of thermoplastic cassava starch reinforced with durian skin fiber. *Journal*

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 96(2), 115–121. <https://doi.org/10.37934/arfmts.96.2.115121>

Roberts, B. (2006). *Urbanization and sustainability in asia: Case studies of good practice*. Asian Development Bank.

Rogers, T. (2015, October 7). *Everything you need to know about polylactic acid (PLA)*. Everything You Need To Know About Polylactic Acid (PLA). Retrieved August 19, 2022, from <https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes>

Saba, N., Jawaid, M., & Sultan, M. T. H. (2019). An overview of mechanical and physical testing of composite materials. *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, 1–12. <https://doi.org/10.1016/b978-0-08-102292-4.00001-1>

Saeki, Y., & Emura, T. (2002). Technical progresses for PVC production. *Progress in Polymer Science*, 27(10), 2055–2131. [https://doi.org/10.1016/s0079-6700\(02\)00039-4](https://doi.org/10.1016/s0079-6700(02)00039-4)

Safri, S. N., Sultan, M. T., Jawaid, M., & Jayakrishna, K. (2018). Impact behaviour of hybrid composites for structural applications: A review. *Composites Part B: Engineering*, 133, 112–121. <https://doi.org/10.1016/j.compositesb.2017.09.008>

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

- Sahu, P., & Gupta, M. (2020). Water absorption behavior of cellulosic fibres polymer composites: A review on its effects and remedies. *Journal of Industrial Textiles*, 51(5_suppl). <https://doi.org/10.1177/1528083720974424>
- Sakthivel, M., Vijayakumar, S., & Ramesh, S. (2014). Production and characterization of luffa/coir reinforced polypropylene composite. *Procedia Materials Science*, 5, 739–745. <https://doi.org/10.1016/j.mspro.2014.07.323>
- Sam, S. T., Nuradibah, M. A., Ismail, H., Noriman, N. Z., & Ragunathan, S. (2014). Recent advances in polyolefins/natural polymer blends used for packaging application. *Polymer-Plastics Technology and Engineering*, 53(6), 631–644. <https://doi.org/10.1080/03602559.2013.866247>
- Sanjeevi, S., Shanmugam, V., Kumar, S., Ganesan, V., Sas, G., Johnson, D. J., Shanmugam, M., Ayyanar, A., Naresh, K., Neisiany, R. E., & Das, O. (2021). Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. *Scientific Reports*, 11(1), 13385. <https://doi.org/10.1038/s41598-021-92457-9>
- Santos, R. A. M., Gorbatiikh, L., & Swolfs, Y. (2021). Commercial self-reinforced composites: A comparative study. *Composites Part B: Engineering*, 223, 109108. <https://doi.org/10.1016/j.compositesb.2021.109108>
- Sathishkumar, T., Naveen, J., Navaneethakrishnan, P., Satheeshkumar, S., & Rajini, N. (2016). Characterization of sisal/cotton fibre woven mat reinforced polymer hybrid composites. *Journal of Industrial Textiles*, 47(4), 429–452. <https://doi.org/10.1177/1528083716648764>

- Schluttenhofer, C., & Yuan, L. (2017, November). Challenges towards revitalizing hemp: A multifaceted crop. *Trends in Plant Science*, 22(11), 917–929. <https://doi.org/10.1016/j.tplants.2017.08.004>
- Schneider, C., Kazemahvazi, S., Åkermo, M., & Zenkert, D. (2013). Compression and tensile properties of self-reinforced poly(ethylene terephthalate)-composites. *Polymer Testing*, 32(2), 221–230. <https://doi.org/10.1016/j.polymertesting.2012.11.002>
- Shahinur, S., & Hasan, M. (2020). Natural fiber and synthetic fiber composites: Comparison of properties, performance, cost and environmental benefits. *Encyclopedia of Renewable and Sustainable Materials*, 794–802. <https://doi.org/10.1016/b978-0-12-803581-8.10994-4>
- Shinde, A., Veer, S., Shinde, T., & Kamble, D. P. (2018, May 11). A review on extraction of bamboo fibers and banana fibers. *International Journal of Recent Trends in Engineering and Research*, 4(5), 7–12. <https://doi.org/10.23883/ijrter.2018.4283.itjsj>
- Shrivastava, A. (2018). Introduction to Plastics Engineering. Introduction to Plastics Engineering, 1–16. <https://doi.org/10.1016/b978-0-323-39500-7.00001-0>
- Shrivastava, A. (2018). *Introduction to plastics engineering*. William Andrew, an imprint of Elsevier.
- Siddique, S., Naqi, A., & Jang, J. G. (2020). Influence of water to cement ratio on CO₂ uptake capacity of belite-rich cement upon exposure to carbonation curing. *Cement*

and Concrete Composites, 111, 103616.
<https://doi.org/10.1016/j.cemconcomp.2020.103616>

Sidek, I. S., Draman, S. F., Abdullah, S. R., & Anuar, N. (2019). Current development on bioplastics and its future prospects: An introductory review. *INWASCON Technology Magazine*, 03–08. <https://doi.org/10.26480/itechmag.01.2019.03.08>

Siqueira, R. L., Yoshida, I. V., Pardini, L. C., & Schiavon, M. A. (2007). Poly(borosiloxanes) as precursors for carbon fiber ceramic matrix composites. *Materials Research*, 10(2), 147–151. <https://doi.org/10.1590/s1516-14392007000200009>

Stelea, L., Filip, I., Lisa, G., Ichim, M., Droboță, M., Sava, C., & Mureșan, A. (2022). Characterisation of hemp fibres reinforced composites using thermoplastic polymers as matrices. *Polymers*, 14(3), 481. <https://doi.org/10.3390/polym14030481>

Strong, A. B. (2008). *Fundamentals of Composites Manufacturing: Materials, methods and applications*. Society of Manufacturing Engineers.

Sudoł, E., Kozikowska, E., & Choińska, E. (2022). The utility of recycled rice husk-reinforced PVC composite profiles for façade cladding. *Materials*, 15(10), 3418. <https://doi.org/10.3390/ma15103418>

Sui, G., Fuqua, M. A., Ulven, C. A., & Zhong, W. H. (2009). A plant fiber reinforced polymer composite prepared by a twin-screw extruder. *Bioresource Technology*, 100(3), 1246–1251. <https://doi.org/10.1016/j.biortech.2008.03.065>

- Suresh, S. K., Thirumalai, S. K., Velmurugan, G., Perumal, A., Sekar, S., & Uthayakumar, M. (2022). Physical and mechanical properties of various Metal Matrix Composites: A review. *Materials Today: Proceedings*, 50, 1022–1031. <https://doi.org/10.1016/j.matpr.2021.07.354>
- Suriani, M. J., Zainudin, H. A., Ilyas, R. A., Petru, M., Sapuan, S. M., Ruzaidi, C. M., & Mustapha, R. (2021). Kenaf fiber/pet yarn reinforced epoxy hybrid polymer composites: Morphological, tensile, and flammability properties. *Polymers*, 13(9), 1532. <https://doi.org/10.3390/polym13091532>
- Tan, M. Y., Nicholas Kuan, H. T., & Lee, M. C. (2017). Characterization of alkaline treatment and fiber content on the physical, thermal, and mechanical properties of ground coffee waste/oxobiodegradable HDPE biocomposites. *International Journal of Polymer Science*, 2017, 1–12. <https://doi.org/10.1155/2017/6258151>
- Tapangnoi, P., Sae-Oui, P., Naebetch, W., & Siriwong, C. (2022). Preparation of purified spent coffee ground and its reinforcement in natural rubber composite. *Arabian Journal of Chemistry*, 15(7), 103917. <https://doi.org/10.1016/j.arabjc.2022.103917>
- Taraghi, I., Fereidoon, A., & Taheri-Behrooz, F. (2014). Low-velocity impact response of woven kevlar/epoxy laminated composites reinforced with multi-walled carbon nanotubes at ambient and low temperatures. *Materials Design*, 53, 152–158. <https://doi.org/10.1016/j.matdes.2013.06.051>
- Technotes, Boeing Environmental. (2003). *Composite Recycling and Disposal: An Environmental R&D Issue*. Boeing Environmental Technotes, 8, 1-4.

- Thongchom, C., Refahati, N., Roodgar Saffari, P., Roudgar Saffari, P., Niyaraki, M. N., Sirimontree, S., & Keawsawasvong, S. (2021). An experimental study on the effect of nanomaterials and fibers on the mechanical properties of polymer composites. *Buildings*, 12(1), 7. <https://doi.org/10.3390/buildings12010007>
- Thongpin, C., Srimuk, J., hipkam, N., & Wachirapong, P. (2015). Effect of natural fiber types and sodium silicate coated on natural fiber mat/PLA composites: Tensile properties and rate of fire propagation. *IOP Conference Series: Materials Science and Engineering*, 87, 012078. <https://doi.org/10.1088/1757-899x/87/1/012078>
- Thyavihalli Girijappa, Y. G., Mavinkere Rangappa, S., Parameswaranpillai, J., & Siengchin, S. (2019). Natural fibers as sustainable and renewable resource for development of eco-friendly composites: A comprehensive review. *Frontiers in Materials*, 6, 226. <https://doi.org/10.3389/fmats.2019.00226>
- Tokimoto, T., Kawasaki, N., Nakamura, T., Akutagawa, J., & Tanada, S. (2005). Removal of lead ions in drinking water by coffee grounds as vegetable biomass. *Journal of Colloid and Interface Science*, 281(1), 56–61. <https://doi.org/10.1016/j.jcis.2004.08.083>
- Torres-León, C., Ramírez-Guzman, N., Londoño-Hernandez, L., Martinez-Medina, G. A., Díaz-Herrera, R., Navarro-Macias, V., Alvarez-Pérez, O. B., Picazo, B., Villarreal-Vázquez, M., Ascacio-Valdes, J., & Aguilar, C. N. (2018). Food waste and byproducts: An opportunity to minimize malnutrition and hunger in developing countries. *Frontiers in Sustainable Food Systems*, 2, 57. <https://doi.org/10.3389/fsufs.2018.00052>

- Tuloup, C., Harizi, W., Aboura, Z., & Meyer, Y. (2020). Integration of piezoelectric transducers (PZT and PVDF) within polymer-matrix composites for Structural Health Monitoring Applications: New success and challenges. *International Journal of Smart and Nano Materials*, 11(4), 343–369. <https://doi.org/10.1080/19475411.2020.1830196>
- Türk, D.-A., Kussmaul, R., Zogg, M., Klahn, C., Leutenecker-Twelsiek, B., & Meboldt, M. (2017). Composites part production with Additive Manufacturing Technologies. *Procedia CIRP*, 66, 306–311. <https://doi.org/10.1016/j.procir.2017.03.359>
- Valvez, S., Santos, P., Parente, J. M., Silva, M. P., & Reis, P. N. B. (2020). 3D printed continuous carbon fiber reinforced PLA Composites: A short review. *Procedia Structural Integrity*, 25, 394–399. <https://doi.org/10.1016/j.prostr.2020.04.056>
- Vanapalli, K. R., Sharma, H. B., Ranjan, V. P., Samal, B., Bhattacharya, J., Dubey, B. K., & Goel, S. (2021). Challenges and strategies for effective plastic waste management during and post covid-19 pandemic. *Science of The Total Environment*, 750, 141514. <https://doi.org/10.1016/j.scitotenv.2020.141514>
- Veerendra, V. (2023, May 8). *Different Types Of Natural Fibres And Their Uses*. A Plus Topper. Retrieved September 19, 2023, from <https://www.aplustopper.com/types-of-natural-fibres-uses/>
- Vieira, L. M., Dobah, Y., dos Santos, J. C., Panzera, T. H., Campos Rubio, J. C., & Scarpa, F. (2022). Impact properties of novel natural fibre metal laminated composite materials. *Applied Sciences*, 12(4), 1869. <https://doi.org/10.3390/app12041869>

- Vigneshkumar, N., Harikannan, N., Selvakumar, S., Manoj Kumar, P., Subbiah, R., & Saravanakumar, P. T. (2022). Investigating mechanical properties of hybrid polymer composite reinforced with S-glass and luffa fibres. *Journal of Physics: Conference Series*, 2272(1), 012024. <https://doi.org/10.1088/1742-6596/2272/1/012024>
- Vollmer, I., Jenks, M. J., Roelands, M. C., White, R. J., van Harmelen, T., de Wild, P., van der Laan, G. P., Meirer, F., Keurentjes, J. T., & Weckhuysen, B. M. (2020). Beyond mechanical recycling: Giving new life to plastic waste. *Angewandte Chemie International Edition*, 59(36), 15402–15423. <https://doi.org/10.1002/anie.201915651>
- Vuba, K. K., Etakula, N., & Uttaravalli, A. N. (2023). Preparation of polypropylene copolymer (PPCP) based composites with improved properties in presence of MWCNT and MAGPP fillers. *Materials Today: Proceedings*, 80, 1096–1100. <https://doi.org/10.1016/j.matpr.2022.12.002>
- Wang, G., Yu, D., Kelkar, A. D., & Zhang, L. (2017). Electrospun nanofiber: Emerging reinforcing filler in polymer matrix composite materials. *Progress in Polymer Science*, 75, 73–107. <https://doi.org/10.1016/j.progpolymsci.2017.08.002>
- Wang, J., Zhang, Q., Cheng, Y., Song, F., Ding, Y., & Shao, M. (2022). Self-reinforced composites based on polypropylene fiber and graphene nano-platelets/polypropylene film. *Carbon*, 189, 586–595. <https://doi.org/10.1016/j.carbon.2021.12.098>
- Warnet, L., & Reed, P. E. (1999). Falling weight impact testing principles. *Polymer Science and Technology Series*, 66–70. https://doi.org/10.1007/978-94-015-9231-4_17

- Wolela, A. D. (2019, July 21). Extraction and characterization of natural cellulose fibers from *Sanseveria Trifasciata* plant. *Trends in Textile Engineering & Fashion Technology*, 5(2), 630-634. <https://doi.org/10.31031/tteft.2019.05.000609>
- Xiong, J., Zhang, M., Stocchi, A., Hu, H., Ma, L., Wu, L., & Zhang, Z. (2014). Mechanical behaviors of carbon fiber composite sandwich columns with three dimensional honeycomb cores under in-plane compression. *Composites Part B: Engineering*, 60, 350–358. <https://doi.org/10.1016/j.compositesb.2013.12.049>
- Yan, B., Chen, Z., Zhu, J., Zhang, J., & Jiang, Y. (2009). Effects of ablation at different regions in three-dimensional orthogonal C/SIC composites ablated by oxyacetylene torch at 1800°C. *Journal of Materials Processing Technology*, 209(7), 3438–3443. <https://doi.org/10.1016/j.jmatprotec.2008.08.002>
- Yang, W., Song, L., Hu, Y., Lu, H., & Yuen, R. K. K. (2011). Enhancement of fire retardancy performance of glass-fibre reinforced poly(ethylene terephthalate) composites with the incorporation of aluminum hypophosphite and melamine cyanurate. *Composites Part B: Engineering*, 42(5), 1057–1065. <https://doi.org/10.1016/j.compositesb.2011.03.019>
- Yashoda. (2016, November 27). *Difference between HDPE and LDPE: Physical and chemical properties, uses*. Pediaa.Com. Retrieved September 3, 2022, from <https://pediaa.com/difference-between-hdpe-and-ldpe/>
- Yeung, L. Y., & Subburaj, K. (2023). 3D-printed orthotics for pediatric lower limb deformities correction. *3D Printing in Podiatric Medicine*, 51–81. <https://doi.org/10.1016/b978-0-323-91911-1.00003-1>

- Yilmaz, N. D., & Arifuzzaman Khan, G. M. (2019). Flexural behavior of textile-reinforced polymer composites. *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, 13–42. <https://doi.org/10.1016/b978-0-08-102292-4.00002-3>
- Yin, Z.-Z., Qi, W.-C., Zeng, R.-C., Chen, X.-B., Gu, C.-D., Guan, S.-K., & Zheng, Y.-F. (2020). Advances in coatings on biodegradable magnesium alloys. *Journal of Magnesium and Alloys*, 8(1), 42–65. <https://doi.org/10.1016/j.jma.2019.09.008>
- Youssef, A. M., El-Gendy, A., & Kamel, S. (2015). Evaluation of corn husk fibers reinforced recycled low density polyethylene composites. *Materials Chemistry and Physics*, 152, 26–33. <https://doi.org/10.1016/j.matchemphys.2014.12.004>
- Zaman, H. U., & Khan, R. A. (2019). Acetylation used for natural fiber/polymer composites. *Journal of Thermoplastic Composite Materials*, 34(1), 3–23. <https://doi.org/10.1177/0892705719838000>
- Zhang, M., Tian, X., & Li, D. (2021). Interfacial transcrystallization and mechanical performance of 3D-printed fully recyclable continuous fiber self-reinforced composites. *Polymers*, 13(18), 3176. <https://doi.org/10.3390/polym13183176>
- Zherebtsov, D., Chukov, D., Statnik, E., & Torokhov, V. (2020). Hybrid self-reinforced composite materials based on ultra-high molecular weight polyethylene. *Materials*, 13(7), 1739. <https://doi.org/10.3390/ma13071739>

Zhou, Y., Fan, M., & Chen, L. (2016). Interface and bonding mechanisms of plant fibre composites: An overview. *Composites Part B: Engineering*, 101, 31–45.
<https://doi.org/10.1016/j.compositesb.2016.06.055>

APPENDICES

Appendix A: Journal Publications

1. **Afiq, M. K.**, Nicholas, T., & Indor, C. J. (2025). Mechanical Properties of Durian/Luffa Fiber Reinforced Polymer Composite. *Key Engineering Materials*, 1007, 9–15. <https://doi.org/10.4028/p-gv0c48>
2. Nicholas Kuan, H. T., Yong Lee, Y., Nee Ting, S., Khoon Ng, C., & **Afiq, M. K.** (2024). Mechanical properties of virgin and recycled polymer for construction pile application. *Pertanika Journal of Science and Technology*, 32(2), 819–838. <https://doi.org/10.47836/pjst.32.2.18>
3. Kuan, H. T., **Afiq, M. K.**, & Lumpong, S. J. (2024). Mechanical properties of luffa fiber reinforced recycled polymer composite. *Defect and Diffusion Forum*, 432, 63–68. <https://doi.org/10.4028/p-jrgi9s>
4. **Afiq, M. K.**, Kuan, H. T., & Hassan, M. Z. (2023). Tensile properties characterisation of hybrid luffa/GCW fiber reinforced polymer composite. *Materials Science Forum*, 1111, 77–82. <https://doi.org/10.4028/p-tw3ujj>
5. Indor, C. J., Kuan, H. T., San Yeo, F. K., & **Afiq, M. K.** (2023). Tensile properties of luffa acutangula reinforced polymer composite. *International Journal of Integrated Engineering*, 15(5). <https://doi.org/10.30880/ijie.2023.15.05.001>

Mechanical Properties of Virgin and Recycled Polymer for Construction Pile Application

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ABSTRACT

Annual polymer waste generated in Malaysia has increased significantly to more than 1 million tonnes. The prolonged degradation periods required by diverse industrial polymer waste streams are a matter of significant concern, with some taking up to 1000 years to fully degrade. Pursuing a similar environmental concern, the use of bakau piles as supports for lightweight structures in Sarawak, including drainage systems, roads, sewerage, and other water-related structures, has become a matter of concern due to the deforestation of mangrove forests. Both bakau deforestation and polymer waste issues are significant environmental and global concerns. The idea of mitigating mangrove degradation and the non-biodegradable nature of polymer waste has led to the conceptualization of an alternative solution whereby recyclable thermoplastic polymer piles are utilized to supplant bakau piles in providing support for lightweight structures during civil engineering construction projects. Therefore, the study of polymer piles is conducted to examine their mechanical properties in the form of virgin (V) and recycled (R) thermoplastic polymers. In this

study, high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC) are considered, and the possibility of being utilized in pile application has been discussed. Based on the results, all virgin types of thermoplastic polymers (HDPE, PP, and PVC), 50%V:50%R for PP, PP(R), and PVC(R), respectively, exceed the bakau ultimate tensile strength. Thermoplastic polymer piles showed great potential to be

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Tensile Properties of Luffa Acutangula Reinforced Polymer Composite

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Abstract: In recent years, there has been a growing trend in the popularity of natural fiber-reinforced polymer composites (NFRPC). Numerous researchers have put forward various alternatives to synthetic fibers. Luffa is one of the many natural fibers can be integrated into NFRPCs. Luffa with its unique interconnecting branch (mat/mesh) is suitable for NFRPCs. In this study, luffa reinforced high-density polyethylene (Luffa/HDPE) composite was fabricated using compression molding machine. In the preparation of the fiber, Luffa were cylindrically cut-out and opened into sheets form. The fiber was then laminated with high-density polyethylene (HDPE) film using compression molding method. The proposed fabricated composite consisting of a fiber volume fraction (FVF) of 7%, 14%, 21%, 27% and 30%. Tensile properties of the Luffa/HDPE composite were determined. SEM was used to study the interlamination and delamination of the composite. Tensile test shows that the increase of FVF enhanced the tensile strength of Luffa/HDPE composite. Tensile strength has gradually increased from 7 % to 21 % FVF. Though, tensile strength declines after 21% FVF.

Keywords: Natural fiber, tensile, Luffa, NFRP

1. Introduction

In this study, Luffa was used as fiber reinforcement in the natural fiber reinforced polymer composite (NFRPC). Current trends in the composite industry suggest the replacement of synthetic fibers for natural fiber as it is safer for human health and environment. The cost to produce NFRPC is far economical compared to synthetic fibers. A study carried out in 2013 shows that when synthetic cotton was manufactured, the synthetic fiber cause irritations and in the long term induce lungs and skin cancer to the workers [1]. Plastic waste is a problem to the environment. Since 2018, 3,300 metric tons were dumped on daily basis in this country. The waste consists of 45 % organic and food waste, while plastic took up 13 % of the statistics. Despite the recycling awareness, only 17.5 % of citizens recycled their waste [2].

Luffa acutangula or *Luffa cylindrica* has been known to be a type of vegetable, it has been more of a remedy for gastric and diabetes for some cases [3]. It can be grown in all-warm weather countries and mostly found in Asia. Some other warm weather countries have been commercializing luffa and mostly used for replacing dish washing sponge, bath scrub and shoe insole. Currently, studies have made on chemical constituents, aging and, structural and mechanical properties [4-6]. A tensile test study was done on luffa fiber itself ranges between 10 MPa to 50 MPa. Due to the high specific strength of luffa, it can be used as a good fiber reinforcement material [7,8]. The aim of this study is to investigate the tensile properties of Luffa/HDPE composite.

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Tensile Properties Characterisation of Hybrid Luffa/GCW Fiber Reinforced Polymer Composite

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Abstract. Extensive research has been conducted on fiber reinforced polymer (FRP) composites, which have demonstrated superior mechanical properties compared to their individual components. In order to add on to current research trends, the use of ground coffee waste (GCW) and Luffa fibers reinforced polyethylene (PE) composites were fabricated to produce a hybrid natural FRP composite. Tensile testing of the composite indicates that the optimum fiber volume to be between 15% and 35%, as the tensile strength exhibited 9.32 MPa and 8.75 MPa, respectively. Similarly, the tensile modulus of the fabricated composite peaked at 25% with 238 MPa, then declined to 173 MPa at 35%. This indicates that the fibers effectively reinforce the polymer matrix, but once the composite reaches its optimal fiber volume, a decrease in both tensile strength and tensile modulus is observed. The reduction in tensile properties can be attributed to an uneven distribution of load-bearing capacity throughout the composite, as the fibers are no longer able to fully support the matrix once the optimal fiber volume is reached. The specific tensile strength and specific tensile modulus also shows that with the inclusion of Luffa fiber and GCW microfiber contributed to a lighter weight composite. In a nutshell, the hybrid composite fabricated using 25% fiber volume exhibited a tensile strength almost similar to its neat matrix counterpart, though has a noteworthy value in terms of its tensile modulus. The hybrid composite can be as strong in terms of tensile strength, but far more significant in its rigidity, in comparison to the neat polyethylene laminate. Therefore, it showed that the hybrid natural Luffa/GCW FRP has the potential in the engineering industry, such as lightweight furniture, household appliances, automotive parts, and other composite engineering applications.

Introduction

In the past two decades, much research has been done in regards with fiber reinforced polymer (FRP) composites. This comes to no shock as some FRP composites deliberately enhances material strength, stiffness, density, and economical value in the fields of construction, mechanical, automobile, aerospace, biomedical, and marine [1], where a conventional single pure polymer would not [2]. In fact, composite materials are highly sought after due to the versatility of their properties which enables them to be applied into various fields. Composite materials have superior properties than those of the individual components when used alone depending on the type of materials being combined [3]. Some composites may also have better resistance towards corrosion and chemicals. However, the requirement of improving these properties must be linearly improved against sustainability of sources [1]. The concept behind composite materials is the combination of two or more materials in creating a new engineered material [4]. It is a multiphase material that is artificially made, as opposed to one that occurs or forms naturally [5]. In general, composite materials are composed of two phases: matrix and reinforcement. This means in regards of FRP composites, it consists of natural or synthetic fibers acting as load-carrying reinforcements, providing strength and rigidity, embedded in polymer matrices that maintains the fibers position and orientation while protecting them against any possible damage [2]. These various individual materials in the composite work together to give the composite unique properties such as being lightweight while rigid [3].

Mechanical Properties of Luffa Fiber Reinforced Recycled Polymer Composite

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Abstract. Environmental issues over the eventual fate of post-consumer polymers can be dealt with in two separate ways which is recycling or using biodegradable polymers. However, it is evident that recycling polymers from post-consumer polymers can decrease the mechanical properties over time. Hence, to strengthen the recycled polymers, integrating fibers, such as luffa, into the High-Density Polyethylene (HDPE) matrix, was carried out to produce a fiber reinforced recycled polymer (FRrP) composite. The tensile testing of the FRrP composite shows that the 10% fiber volume fraction (FVF) composite exhibits a higher tensile strength of 3.9% than the neat recycled HDPE (RHDPE). In terms of Young's Modulus, the 5% FVF of FRrP is shown to have a higher value than the neat RHDPE by 54%. The low density of luffa fibers also contributes to the composites lightweight character. The impact testing shows that the FRrP enhances the impact properties when compared to the neat RHDPE. The peak load, perforation energy, and the total energy absorbed by the FRrP indicate an increasing trend when luffa, of up to 15% FVF, is added as the reinforcement. Thus, the addition of luffa as reinforcement in RHDPE shows significant potential as a high-performance, sustainable, and environmentally friendly material, such as automotive parts and protective gear.

Introduction

With the rise of polymer production, ensuring a sustainable supply of raw materials has become more critical than ever. To address the environmental impact of post-consumer polymers, two measures can be taken which are recycling and the use of biodegradable polymers. Recycling of polymers refers to activities that aim to recover materials and energy from post-consumer polymers. This process can involve mechanical recycling, energy recovery, or chemical recycling, among other methods. Polymers, also known as plastics, is defined as large molecules made by bonding (chemical linking) a series of blocks [1]. A molecule called polymer has long winded repeating monomer units [2]. Nowadays, High-Density Polyethylene (HDPE), which is one of the primary types of polymers, is currently the most widely utilized polymer in commercial and industrial products. HDPE is a highly versatile plastic material that finds application in various products like detergent bottles, plastic bottles, pipes, and cutting boards. It has impacted daily life as their use is rising, and their annual production is predicted to surpass 300 million tons. Yet, excessive, and unsupervised plastics consumption and manufacturing leads to wastage that may result in losses for certain businesses and environmental pollution. The major downside of plastics is the process of decaying them. Practical solutions must be sought for the issues brought on by expanding the use of plastics as it is difficult to stop plastic use. Hence, techniques for recycling and methodologies to assess these recyclable plastics must be developed. In order to minimize the effect of pollution on the environment, efforts were made to recycle the post-consumer plastic. It is well known that recycled materials have varied mechanical properties from their original materials. The objective of this study is to investigate the tensile and impact properties of the fabricated luffa fiber reinforced RHDPE composite and to evaluate the suitability of luffa plant as reinforcing material based on its tensile and impact properties.

Luffa acutangula / Luffa cylindrica. Luffa, one of the *Cucurbitaceae* species [3], is very popular amongst researchers, as its fibrous network can be easily obtained and is very affordable. Potential for

Mechanical Properties of Durian/Luffa Fiber Reinforced Polymer Composite

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Keywords: FRP, hybrid fiber, tensile testing, mechanical, advanced materials.

Abstract. This research explores the development of advanced materials known as natural fiber reinforced polymer (FRP) composites with the aim of enhancing overall quality of life. Hybrid fibers derived from durian/luffa fibers were integrated into Polyethylene (PE) matrices to fabricate hybrid natural fiber PE composites. The study involves a comprehensive examination of these composites through tensile testing, scanning electron microscopy (SEM), and Fourier-Transform Infrared (FTIR) analysis. Results indicate that the tensile strength of the durian/luffa PE (DLPE) composite surpasses that of neat PE laminates, highlighting its superior stress tolerance. Overall, the composites exhibit specific tensile strength and modulus, contributing to the creation of lightweight materials compared to neat PE. SEM analysis indicates satisfactory fiber-to-matrix bonding with room for improvement, as observed gaps between fibers and matrix are present. FTIR analysis uncovers constituents in the chemical composition of durian and luffa fibers. The inclusion of natural fibers as an alternative to synthetic counterparts aligns with Sustainable Development Goals (SDG) standards. This research underscores the feasibility and benefits of fiber hybridization, emphasizing improved mechanical strength, environmental sustainability, and cost efficiency.

Introduction

Integration of reinforcing fillers, such as fibers, within a polymer matrix, synergistic mechanical properties that cannot be achieved by either component alone, results in a multi-phase material called a polymer composite [1] or also known as fiber-reinforced polymer (FRP) composite. Many applications in major fields such as construction, mechanical, automobile, aerospace, biomedical, and marine, utilizes composite polymers with addition of natural or synthetic fibers in its fabrication, as the durability of FRPs are proven to be better than conventional materials alone [2]. Synthetic fibers common in FRPs are usually glass, carbon, or aramid [3], which is not natural nor biodegradable [4], thus possessing a threat to the environment in relation to accumulation of plastic waste [5]. In order to combat this issue, research in alternatives for both matrix and filler, such as natural fibers, biopolymers, and chemical treatments, are constantly being engineered, as the world's non-renewable resources are depleted by the second [6]. The utilization of natural fibers such as coir, jute, bagasse, cotton, bamboo, and hemp [7] exist as lightweight, durable, renewable, cheap, and biodegradable substitutes for synthetic fibers in FRPs. The properties of the hybrid composite may reveal peculiar results in comparison with the individual components of the FRP composites.

Luffa acutangula / Luffa cylindrica. Seen in Figure 1 is luffa and its fiber. Luffa, also known as sponge gourd, is a *Cucurbitaceae* (cucumber) family plant that grows from south Asia through east and central Asia. Its fruit, a gourd, is green and cylindrical in shape, and it climbs on other solid physical surfaces. Its mature fruit is consumed like vegetables, but its immature fruits are used as natural cleaning sponges. Luffa fibers have substantial toughness, strength, and stiffness, like those found in metals of similar density [8]. The chemical makeup of luffa is mostly made up of lignin and hemicellulose/cellulose, but it also contains inorganic components such as glycosides, polypeptides, amino acids, proteins, and other compounds [9].

Durio zibenthinus. Seen in Figure 2 is durian and its fiber. It is a tropical fruit termed as the “King of Fruits” and is popular in southeast Asia. Morphology of durian is armed with sharp thorns on the