Sustainable Materials for Roofing Applications: Mechanical Properties of Recycled PET and Coir Composite

by

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Abstract

One of the most effective ways to manage post-consumer PET waste is through recycling, significantly reducing its environmental impact. By repurposing recycled PET as an alternative material in construction, we not only address environmental pollution but also contribute to producing cost-effective construction materials. This dual benefit underscores the importance of our research in the context of sustainable materials and construction technologies.

Composite materials have long been effective substitutes for conventional materials in various applications. Fiber-reinforced polymer composites stand out for their high strength-to-weight ratio and modulus. This study further explores the potential of coir, a natural fiber, as a recycled PET matrix reinforcement. Such a composite could pave the way for more sustainable and cost-effective construction materials.

The objective is to study the mechanical properties of the coir-reinforced recycled PET composite. The coir fibers were treated with distilled hot water before being incorporated into the recycled PET matrix. The composite was fabricated using compression molding with varying fiber-to-matrix ratios of randomly oriented fiber at 90-10 weight %, 80-20 weight %, and 70-30 weight %, respectively.

The study employs analysis using SEM imaging, Fourier-transform infrared (FTIR) spectroscopy, and tensile testing to understand the composite's physical structure, chemical composition, and mechanical behavior. Morphological examinations reveal the interaction between coconut fiber and PET, shedding light on their compatibility and potential for reinforcement.

Adding fiber improved mechanical properties like tensile strength and elongation at break. The amount of fiber in the composite's total weight exhibited different mechanical properties. FTIR analysis elucidates the composite's chemical composition, highlighting the influence of coconut fiber, rPET, and processing conditions.

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List of Abbreviations

PET	Polyethylene Terephthalate
rPET	Recycled Polyethylene Terephthalate
HDPE	High Density Polyethylene
TGA	Thermogravimetric Analysis
SEM	Scanning Electron Microscopy
FTIR	Fourier-transform infrared spectroscopy
TGA	Thermogravimetric Analysis
PMC	Polymer Matrix Composite
NaOH	Sodium Hydroxide
RTM	Resin Transfer Molding
PLA	Polylactic Acid
BHET	bis(2-hydroxyethyl) terephthalate
TBD	1,5,7-triazabicyclo [4.4.0] dec-5-ene
MFI	Melt Flow Index
NRPC	Natural Fiber-Reinforced Polymer Composite
CRPC	Coir-reinforced recycled PET Composite
Kpa	kilopascal
MPa	Megapascal
PSI	Pounds per Square Inch

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1. Introduction

1.1. Background

The construction industry, one of the world's largest and most resource-intensive sectors, has a significant environmental impact. This impact spans from the extraction of raw materials to the construction process and, ultimately, to the disposal of building materials at the end of their service life. Such practices often lead to excessive waste generation, resource depletion, and environmental degradation. These concerns are only exacerbated by global urbanization trends. The United Nations predicts that approximately 68% of the world's population will reside in urban areas by 2050 (DESA, 2018).

Countries like Ghana, with a population of 30.8 million (World Bank., 2024)., face a critical challenge in providing adequate housing. The UN Human Rights Council (UNHRC) estimated in 2018 that Ghana's housing deficit was 2.4 million (UNHRC, 2018). This deficit is partly due to the high cost of building materials (Danso & Manu, 2013), which account for 50% of total construction costs in the country (Ofori, 2020). The country's over-reliance on imported raw materials for buildings, which could be replaced with local substitutes (Ofori, 2020), further exacerbates these costs.

These challenges underscore the urgent need to reevaluate conventional practices, particularly considering their adverse environmental impacts and economic implications. However, as the detrimental effects of linear economies become increasingly apparent, there is a growing call for alternative materials and practices. These alternatives promise to promote environmental sustainability and align with the goals of a circular economy, offering a glimmer of hope in the face of these pressing issues.

In this context, materials science research is producing innovative construction materials to address these global challenges. Roofing materials, vital for protection, insulation, and aesthetics in building construction, are a key area of focus. However, conventional roofing materials such as metal, clay, concrete, and asphalt have several significant drawbacks. These include high cost, weight, low durability, high maintenance, and a significant environmental impact. For instance, installing metal roofing for a 1,700-square-foot roof costs approximately

$13,200 (Forbes, 2024). These escalating costs present financial challenges for homeowners and construction projects, underscoring the need for more sustainable alternatives.

The initial investment in metal roofing and its installation can be prohibitively high (Smith, 2023). The high temperatures in areas like Ghana can cause thermal expansion and contraction of roofing materials, resulting in cracking and other damages. The ongoing maintenance and repair costs of metal roofing can further strain finances.

The production process of corrugated metal roofing materials has notable environmental effects, especially concerning energy use and emissions. This process is divided into stages: raw material extraction, transportation to manufacturers, and manufacturing. The initial carbon emissions associated with corrugated metal roofing are primarily concentrated at these stages, underscoring the importance of thoroughly studying the cradle-to-gate impact (Le et al., 2019).

1.2. Problem Statement

Corrugated metal roofing has been associated with adverse environmental and economic impacts, mainly caused by the extraction and processing of non-renewable materials like steel and aluminum. Resource depletion, habitat destruction, and greenhouse gas emissions have raised concerns about climate change and environmental degradation (Parker, 2024). Furthermore, the disposal of these materials at the end of their lifespan has led to landfill accumulation and environmental pollution.

The high costs of conventional roofing materials, particularly metal roofing, pose significant financial challenges for homeowners, contributing to the housing deficit (Ofori, 2020). The initial costs of purchasing and installing metal roofing can be prohibitive for many individuals and organizations (Smith, 2023), limiting the availability of durable and weather-resistant roofing options. Additionally, the ongoing costs of maintaining and repairing metal roofing, like managing corrosion and replacing fasteners, can further strain finances over time.

Sustainable and cost-effective alternatives should be developed to address the challenges posed by conventional roofing materials. These alternatives should prioritize using renewable resources, minimize environmental impacts throughout their lifecycle, and be competitively priced compared to traditional options. Opting for sustainable roofing materials can help homeowners and construction professionals reduce their ecological footprint and achieve long-term cost savings due to reduced maintenance and energy expenses. Promoting sustainable roofing alternatives can also contribute to wider sustainability objectives, such as climate change mitigation, natural resource conservation, and promoting resilient communities and sustainable development.

Composite materials have emerged as a sustainable solution, offering efficient energy and material use due to their unique chemical and mechanical properties. Composites are materials formed by combining two or more materials with significantly different physical or chemical properties. These materials combine to endow the composite with unique properties (Ngo, 2020). Composites are known for their long lifespan, high corrosion resistance, low maintenance, high strength-to-weight ratio, high stiffness (Zabihi et al., 2020), and design flexibility. They have become a part of our daily lives, finding applications in various sectors, including construction and transportation.

1.3. Aims and Objectives

The inception of this work stems from a critical recognition of two overarching global issues: the persistent concerns surrounding waste management practices and the burgeoning demand for sustainable building materials. As global urbanization continues to surge, so does the volume of waste generated, further exacerbating the existing waste management crisis. The proliferation of non-biodegradable materials, such as PET, within urban waste streams adds a layer of complexity to this issue, necessitating innovative solutions.

The aim is to create a sustainable material by developing a natural fiber-reinforced polymer composite consisting of recycled PET and coir while exploring its mechanical, chemical, and morphological properties. The project also seeks to assess the composite material's feasibility and viability for real-life applications while reducing plastic and coconut waste and promoting the circular economy through material repurposing initiatives.

1. The primary objective is to develop a sustainable composite material that combines a recycled Polyethylene Terephthalate (PET) matrix and coconut fiber reinforcement.
2. The research aims to optimize the mechanical properties of the composite.

   To achieve the stated objectives, we will undertake the following steps as part of the research process:

1. Material Preparation: Collect and prepare the recycled PET and coconut fibers. The PET will be cleaned, shredded, and melted, while the coir fibers will be treated to improve their compatibility with the PET.

2. Composite Fabrication: Combine the PET and coir fibers in a ratio of 90-10 weight %, 80-20 weight %, and 70-30 weight %, respectively, using compression molding to form the composite material.

3. Property Testing: We will employ several methods for the composite's property testing, each serving a specific purpose. A tensile test will evaluate the composite's strength and flexibility. Fourier Transform Infrared (FTIR) spectroscopy will analyze the chemical composition and identify functional groups. Lastly, Scanning Electron Microscopy (SEM) will examine the composite's morphology and composition. These tests collectively will provide a comprehensive understanding of the composite's properties.

4. Data Analysis and Reporting: Analyze the data collected during the testing and assessment stages and compile the results into a comprehensive report.

These objectives will help develop a natural fiber-reinforced polymer composite containing recycled PET and coconut fiber to produce a sustainable material. This study assesses this composite's properties to determine its feasibility and viability for real-world applications. All while helping to reduce plastic and coconut waste and promote the circular economy through material repurposing initiatives.

1.4 Scope of Study

Specifically, the research will investigate the composite material's fabrication process, mechanical and chemical properties, and morphology. The study will also explore the feasibility of utilizing recycled PET and coconut fibers as raw materials in composite manufacturing.

However, it is important to acknowledge the aspects that fall outside the scope of this research. The study will not delve into the detailed chemical analysis of the constituents or the exhaustive examination of every possible application of the composite material. Furthermore, while the research will assess the mechanical characteristics of the composite, it will not cover topics such as long-term durability testing or large-scale production feasibility. The research will not include an environmental impact assessment, and a market analysis or consumer study, this is beyond the scope of this research. The study aims to clarify the specific focus areas and objectives while acknowledging the limitations inherent in the research scope.

1.5. Significance of the Study

This study addresses pressing environmental concerns by exploring sustainable alternatives to conventional roofing materials. The research helps reduce reliance on non-renewable resources and mitigates environmental degradation associated with traditional roofing materials by repurposing waste materials such as PET and coconut husks.

Furthermore, this research has significant implications for the field of sustainable materials. The study advances sustainable materials knowledge by investigating the fabrication process, mechanical and chemical properties, and morphology. It provides valuable insights into the feasibility and efficacy of utilizing recycled PET and coconut fibers in composite fabrication, paving the way for developing eco-friendly building materials.

Moreover, the findings of this research have the potential to impact the roofing industry positively. Developing sustainable composite materials offers an opportunity to address the industry's environmental footprint while meeting the demand for durable and cost-effective roofing solutions. By offering a viable alternative to traditional roofing materials, the composite material derived from recycled PET and coconut fibers could promote sustainable practices within the roofing industry and contribute to the transition towards more eco-conscious construction practices. This study has the potential to drive innovation, promote sustainability, and foster positive change in the roofing industry and beyond.

1.6. Methodology Overview

The methodology encompasses a multi-step approach involving material selection, composite fabrication, laboratory testing, and data analysis. Initially, post-consumer PET and coconut fibers were selected as the primary raw materials for composite fabrication based on their availability, compatibility, and sustainability considerations.

The subsequent section will outline the fabrication process and detail the procedures for composite fabrication. These procedures include techniques such as compression molding and fiber-matrix assembly, which are essential for achieving optimal blending and distribution of the reinforcing fibers within the PET matrix. Special attention will be given to controlling processing parameters to ensure the consistency and integrity of the composite material.

After the fabrication process, comprehensive laboratory testing will be conducted to evaluate the composite material's mechanical, chemical, and morphological properties. The testing will involve tensile testing, Fourier-transform infrared (FTIR) spectroscopy, and scanning electron microscopy (SEM). These techniques will allow for a thorough characterization of the composite material's performance.

Finally, the collected data will undergo rigorous analysis, employing techniques to discern patterns, correlations, and discrepancies among the tested samples. This analytical phase aims to extract meaningful insights into the relationship between fiber content ratios, processing parameters, and composite properties, informing optimization and refinement of the fabrication process.

1.7. Outline

The thesis is divided into chapters, each concentrating on a different component of the research topic to comprehend the study thoroughly. Chapter 2: Literature Review delves into the existing literature on composite materials, sustainable alternatives such as natural fiber-reinforced composites, and recycled PET and coconut fibers in composite fabrication. This chapter carefully explores major concepts, theories, and preceding research to comprehensively understand the research within the larger academic environment.

The methodology chapter will cover the study's research procedures, such as material selection, fabrication processes, and characterization techniques. It will describe the step-by-step processes used to accomplish the research objectives. The results of the experiments and data analysis will be presented and discussed in the Results and Discussion chapters. The results will be examined within the context of the research objectives and compared with relevant literature to draw meaningful conclusions.

The last chapter will review the study's main findings and analyze their implications for sustainable materials and the roofing industry. It will also emphasize the study's limitations and offer areas for future research to expand knowledge in this field.

2. Literature Review

In this chapter, an in-depth exploration of existing literature on composite materials, sustainable solutions, and the integration of recycled PET, coconut fibers, and composite fabrication is undertaken. Specifically, the chapter seeks to establish a robust foundation for future research within the field by examining key concepts, theories, and prior studies. Through an extensive review of relevant literature, the chapter provides insights into composite materials' evolution, emerging sustainability trends, and the efficacy of incorporating recycled materials in composite fabrication processes. By synthesizing and analyzing existing knowledge, this chapter aims to elucidate the significance of the research topic and identify gaps in current understanding, thereby paving the way for the subsequent research methodology and findings.

2.1. Urbanization and Roofing Materials

The construction industry, a significant global economic driver, is grappling with environmental issues due to rapid urbanization. This growth has escalated the demand for construction materials, intensifying the sector's dependence on natural resources and energy. The 2019 World Economic Forum's Global Competitiveness Report highlights the rising cost of building materials, which adds financial strain to construction projects and impedes efforts to address the global housing crisis.

In Ghana, the construction sector is grappling with the high cost of building materials, largely attributed to the high import rates. This situation has resulted in a significant deficit in the housing supply. To address this deficit, experts advocate using local materials like timber and bamboo, which play a crucial role in Ghana's construction industry (Cardoso et al., 2007).

Approximately 60% of the working population requires housing assistance, and about 35% cannot access it even with government subsidies (Ohene, 2022). Addressing this deficit would mean providing 190,000 to 200,000 housing units over the next decade, costing an estimated US$3.4 billion (Ofori, 2020). Consequently, the government and real estate agencies are keen on developing affordable and sustainable housing.

Today's roofing materials offer many options, from traditional options like clay tiles and slate to modern alternatives like synthetic and metal roofing (Cleland, 2023). Pitched roofs with corrugated metallic sheets are common in Ghana's warm-humid climates. Despite their longevity and natural appeal, metal roofs have challenges, including susceptibility to corrosion and rust, especially in humid regions with high salt content (Calapa, 2022). Temperature fluctuations can also cause metal roofs to expand and contract, leading to loose fasteners and potential leaks, reducing reliability (Duckworth & Hadid, 2024).

Producing metal roofing materials involves extracting and processing non-renewable resources like steel and aluminum. The demand for steel in construction has been rising, with virgin steel production increasing by 5% in 2018 to reach 1817 Mt (IEA, 2018). However, the environmental impact of manufacturing virgin steel is significant, involving energy-intensive processes like sorting, de-galvanizing, and smelting (Roy et al., 2022). Disposing of these materials at the end of their lifespan contributes to landfill accumulation, exacerbating waste management issues.

A circular economy has emerged as a popular model in response to environmental and resource depletion concerns. This shift emphasizes the need for sustainable, affordable, lightweight, durable, and eco-friendly alternative roofing materials. Composite materials offer a promising solution, combining two or more components to create a new material with enhanced properties (Soboyejo, 2002). These materials provide a versatile and sustainable alternative with diverse applications in construction, transport, and sports (Prashanth et al., 2017).

2.2. Composite Materials in Construction

Using natural fibers in construction offers a path to more sustainable building material consumption patterns (Yan et al., 2014). These fibers have many applications, including inside panels, decking, railing, window frames, outdoor furniture, benches, pallets, and boards. Furthermore, using natural fiber-reinforced composites, such as kenaf-reinforced polymers, provides a feasible alternative to unsustainable wood procurement in construction, reducing local environmental degradation (Georgios et al., 2016). For example, composite decking now contains 100% recyclable materials reinforced with bamboo fibers, making it twice as robust and four times harder than traditional alternatives (Anderson & Altan, 2012).

Composites are stronger and lighter than traditional materials such as steel or concrete, enabling innovative architectural ideas. They can also be customized for specific purposes by changing stiffness, thermal conductivity, and corrosion resistance (Ngo, 2020). As a result of this adaptability, architects and engineers can meet various structural and functional requirements. Material properties such as corrosion resistance and long life make composites ideal for harsh environments.

Composites, with their enhanced durability, not only reduce maintenance costs but also extend the lifespan of structures. They offer design flexibility, allowing for complex shapes that are unattainable with traditional materials. Furthermore, their thermal and electrical insulation properties contribute to improved energy efficiency and sustainability of buildings (Carrie, 2017).

One of the most widely used composite materials and potential candidates for sustainable roofing materials is the polymer matrix composite (PMC). Polymer matrix composites are made from either thermosetting polymer, like epoxy resin, which is often used due to their high thermal resistance and reduces the degradation of natural fibers (Keya et al., 2019), or thermoplastic polymers, such as polypropylene (PP), polyethylene (PE), polyurethane, and Polyethylene Terephthalate (PET) which are recyclable and energy efficient during processing.

The recyclability of composite materials can vary depending on their composition, with some formulations posing challenges for end-of-life disposal or recycling. One of the central problems is the production and disposal of non-recyclable polymers (plastics). Waste management of non-biodegradable plastics presents a formidable challenge. Due to their nonbiodegradability and high visibility in the waste stream, plastics have become a severe problem. Inadequate waste management practices, like littering, have brought on additional issues, such as clogged sewers, "plastics-filled" oceans, and problems regarding health and microplastics. When waste plastics are inadequately treated at the end of their life, their presence in the waste stream creates a significant issue.

2.2.1. Polymer Recycling

Synthetic polymers, meticulously designed to fulfill consumer demands, and materials are indispensable components in our consumer demands. The production of these polymers surged to a staggering 311 million tons in 2014 and is projected to triple by the year 2050 (Agenda, I., 2016). Despite their utility, plastics pose a significant challenge due to their linear lifecycle, often leading to single-use applications and subsequent waste accumulation and pollution.

Consequently, plastic waste has become a pressing environmental concern, necessitating a shift towards sustainable practices.

Plastics have permeated every aspect of modern life, serving as ubiquitous packaging materials and consumer goods. Nevertheless, the fate of most plastics lies in landfills or incinerators, contributing to environmental degradation and resource depletion. Current disposal methods, including incineration and landfilling, yield suboptimal outcomes, releasing harmful gases into the atmosphere (Hong & Chen, 2017).

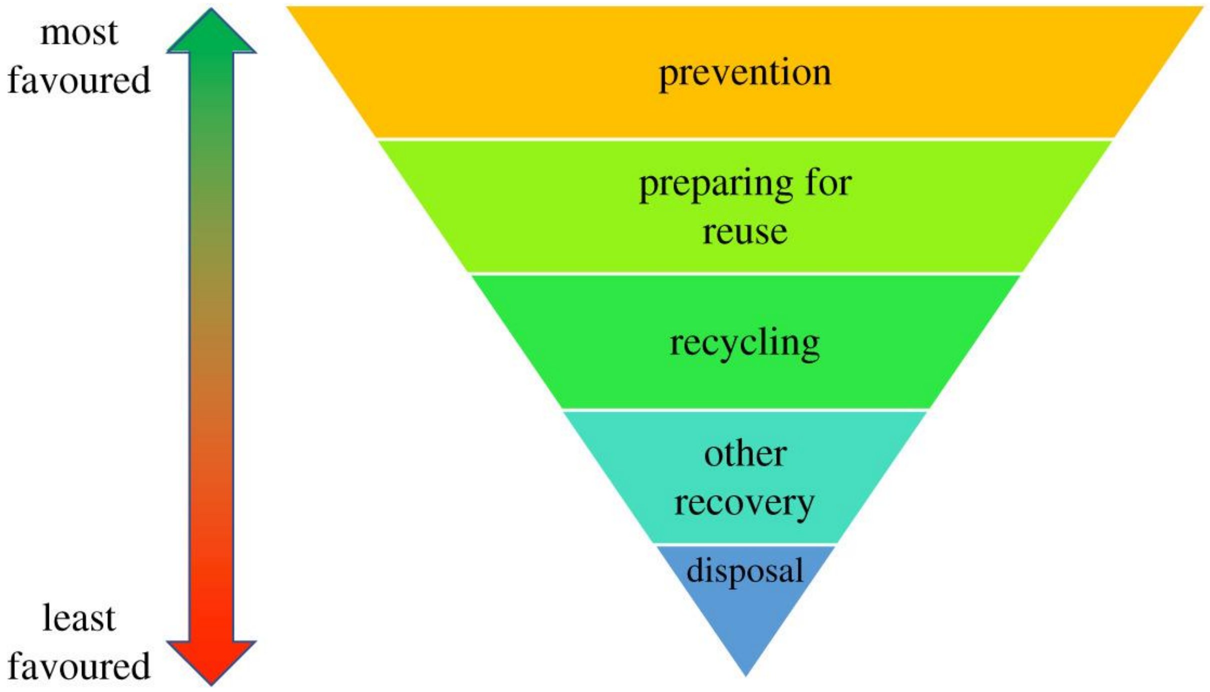


Figure 2.1. Hierarchy of preferred waste management methods from most to least favored (Bucknall, 2020).

Efforts to mitigate plastic waste extend beyond conventional recycling methods to embrace the principles of a circular economy. In this paradigm, plastics are viewed as valuable resources with the potential for multiple lifecycles. Mechanical recycling is a prominent example, although its efficacy is hampered by contamination and degradation. For example, plastic bottles, once discarded, face limited reuse due to contamination, perpetuating the cycle of waste and pollution. Alternatively, chemical recycling, called feedstock recycling, presents a promising avenue for depolymerizing plastics into their constituent monomers, offering higher quality than mechanical recycling (Valerio, 2020).

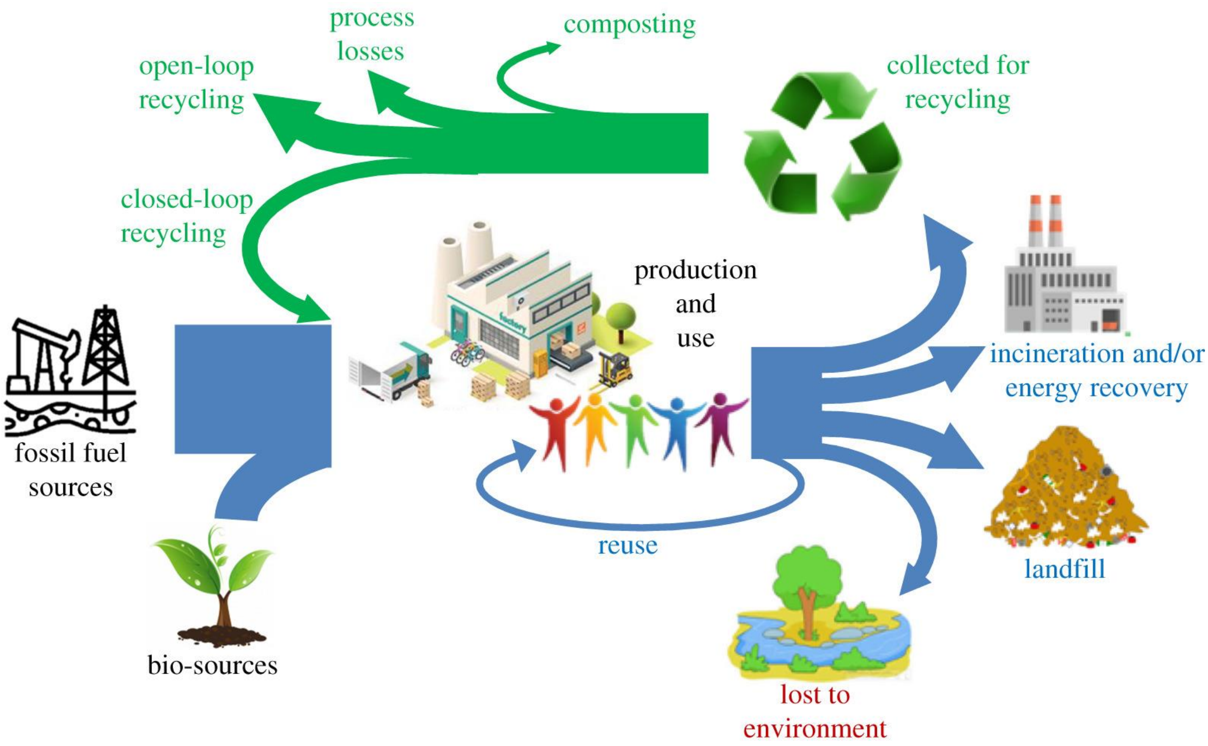


Figure 2.2. Diagram illustrating the life cycle of plastics (Bucknall, 2020).

The transition towards renewable resources is imperative as the world grapples with a rapidly depleting petroleum reserve, the primary source of synthetic polymers (Dale, 2021). However, this transition must be accompanied by comprehensive waste management strategies to address the pervasive issue of polymer waste. By embracing the principles of a circular economy and prioritizing recyclability, we can pave the way for a sustainable future where plastics serve as renewable resources rather than disposable commodities.

Implementing robust waste management strategies is crucial for attaining environmental sustainability and promoting a circular economy. The prevalent issues with the design and disposal of plastics must be addressed to mitigate their long-term impact on landfills and oceans. Many plastics are engineered for durability over biodegradability, leading to persistent environmental accumulation. Life cycle assessment into plastic production is vital to ensure responsible end-of-life management. Presently, the disposal of substantial quantities of plastic waste in landfills exacerbates environmental contamination and squanders resources (Bucknall, 2020). Biodegradable polymers offer a potential solution, with polylactic acid (PLA) emerging as a prominent candidate (Hong & Chen, 2017). However, the slow degradation of PLA via hydrolysis presents challenges in waste management and may contribute to excess waste accumulation.

The widespread adoption of biodegradable polymers emphasizes the necessity for a comprehensive waste management strategy aligned with circular economy principles. Rather than viewing plastics as disposable commodities, we must transition towards a model where plastics serve as renewable resources with multiple lifecycles. Recycling offers a potential for economic growth and plastic waste reduction, which has seen tremendous growth globally. A profit pool of about $60 billion is estimated to emerge from recycling, of which 39% would be derived from mechanical and 61% from chemical recycling (Ragaert et al., 2017).

Open-loop recycling, wherein plastics are recycled into new products, offers a promising avenue for minimizing waste accumulation and maximizing resource utilization. A novel chemical recycling method entails glycolysis of post-consumer PET utilizing surplus ethylene glycol and an organic catalyst, 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD), resulting in the production of bis(2-hydroxyethyl) terephthalate (BHET). Under glycolysis conditions at 190 °C for 3.5 hours, BHET is synthesized with a 78% isolated yield alongside minor impurities (Fukushima et al., 2011)

Mechanical recycling, though considered a remedy, involves sorting, washing, drying, and melting consumer polymer products. However, the presence of residual moisture and contaminants compromises the quality of recycled polymers, impeding their effectiveness. For example, recycling PET bottles back to new PET bottles is preferred. However, the remaining contamination that mechanical recycling cannot eliminate is a significant factor holding this back.

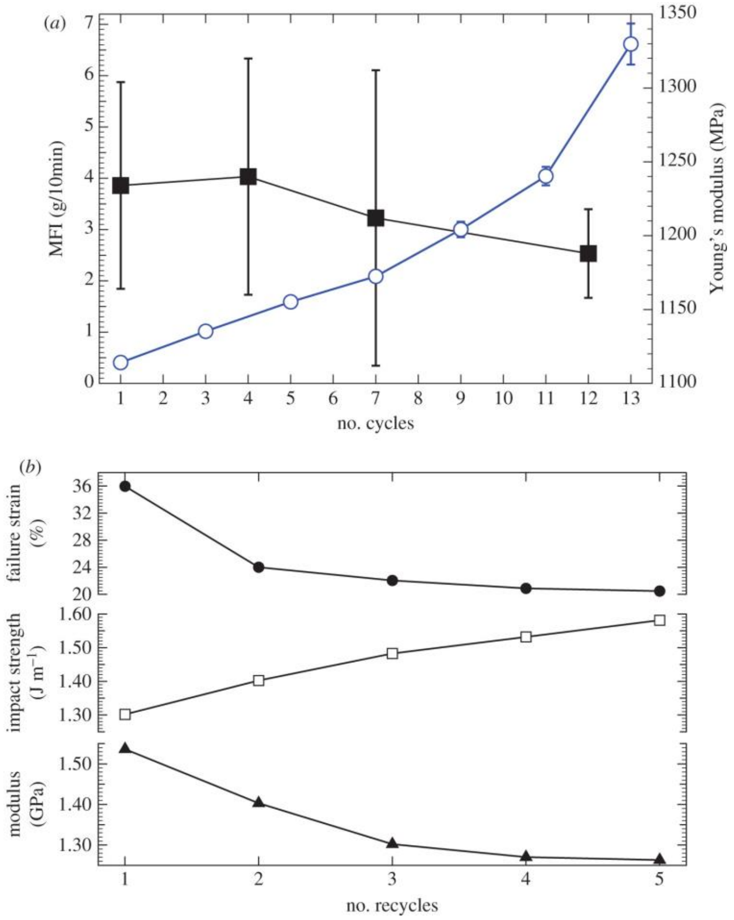


Figure 2.3 The change of properties with respect to thermal processing cycles for PP and thermo-mechanical processing cycles (Delva et al., 2014) and (La Mantia & Vinci, 1994), respectively. The graph in (a) shows how MFI (open circles) and Young's modulus (closed squares) change with PP. Meanwhile, (b) shows the variations in PET's modulus (closed triangles), impact strength (open squares), and strain to failure (closed circles).

Recycling engineering plastics such as Polyethylene terephthalate (PET) holds immense potential for advancing the circular economy. Mechanical recycling of PET is a prominent example, but chemical recycling provides a more comprehensive solution by depolymerizing plastics into their constituent monomers, resulting in a higher-quality output. The mechanical recycling of PET resin is a prominent example; however, contaminants cause the molecular weight and strength to be diminished. For example, a mechanically recycled PET bottle exhibits less than 10% elongation at break (Torres et al., 2000).

The potential benefits of efficient recycling are vast, including the conservation of resources and mitigation of environmental impact. For instance, it could help save 7.5 billion cubic yards of landfill space, reduce 17 trillion tons of CO_2 emissions, and conserve 4.2 trillion gallons of water (Quartinello et al., 2018). However, achieving a circular economy is not a task for a single entity. It requires a joint effort from industry, government, and society. Plastics can be transformed from environmental liabilities to valuable resources if we prioritize recyclability, implement innovative recycling technologies, and foster a culture of sustainability.

Waste recycling offers significant environmental benefits. It reduces the degradation caused by the exploitation of raw materials, saves energy, reduces pollution, and even creates jobs. A case in point is Polyethylene Terephthalate (PET), a versatile polymer used in various applications such as beverage containers and packaging. Despite its recyclability, PET often becomes litter on our streets, landfills, or the ocean, contributing to environmental pollution and resource wastage. There is a growing interest in developing composite materials from renewable, biodegradable, and waste-based sources, such as agricultural residues, natural fibers, and polymer waste (Shanmugam et al., 2021).

With open-loop recycling, we are offered a promising avenue for minimizing waste accumulation and maximizing resource utilization, highlighting the potential for sustainable alternatives such as polymer matrix materials in composites. For example, polyethylene terephthalate (PET) can be recycled as a polymer matrix due to its good mechanical, thermal, and chemical resistance. High temperatures and UV rays also cause it to yellow and degrade (Edge et al., 1996). Therefore, PET can be modified or blended with other additives or reinforcements to improve its stability and performance (Hasan et al., 2021) in roofing applications.

2.3. Sustainable Composite Materials

Composite properties are also controlled by selecting the appropriate constituents with preferred mechanical, chemical, and physical properties (Soboyejo, 2002). The reinforcement of fiber upon polymeric matrix, as illustrated in Figure 2.4, brings about significant improvements in the properties of the polymer, like excellent weathering stabilities (Kendall, 2010). Composite reinforcement can engineer a variety of essential mechanical and physical qualities, making them highly valuable. Multiple types of fibers with different polymers are required to achieve tailor-made qualities for specific applications, with the fiber contributing to the final composites' properties (Prashanth et al., 2017).

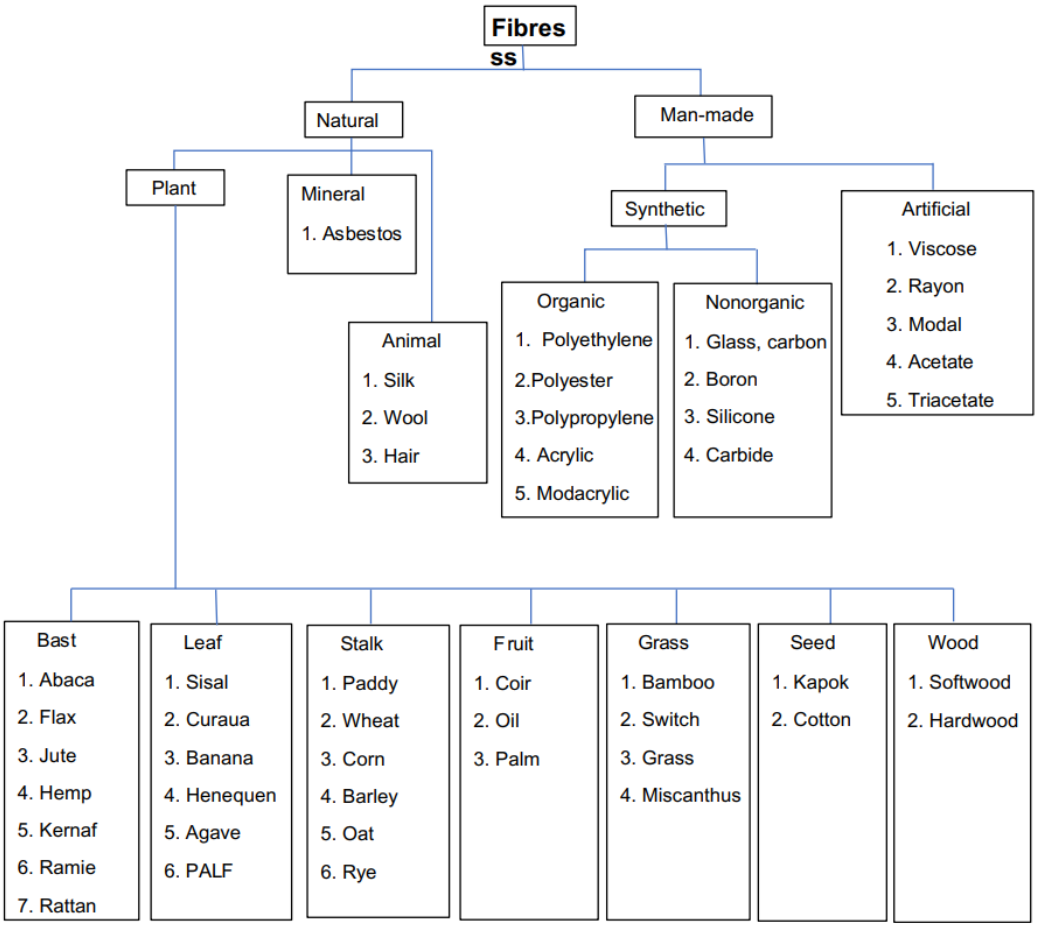


Figure 2.4. Classification of fiber reinforcements (Ahmad et al., 2019).

Composite materials have efficiently used fibers in various configurations, including mats, woven structures, and chopped forms, to meet specific performance requirements. Fibers are complex because they contain thousands of filaments, each with a unique arrangement. Short or discontinuous fibers with lengths of a few millimeters produce isotropic tendencies in the composite material (Soboyejo, 2002). On the other hand, fibers are oriented along two perpendicular directions: one warps and the other wefts. The weft passes over and under the warp yarns. (Gay et al., 2003, p 41).

The interfacial adhesion between fibers and matrix, matrix stress transmission capacity, and a composite's properties can be controlled by controlling the interfacial properties (Soboyejo, 2002). Excellent properties like the strength-to-weight ratio of composites result from low fiber densities. Fibers like carbon, Kevlar, glass, and natural fibers are the most used in construction, transport, and sports. Natural fibers have become common in boat construction and other equipment due to their lightweight, good relative mechanical properties, and lower cost when compared to fiberglass (Shalwan & Yousif, 2013). Fiberglass and some synthetic fibers are costly, highly impact the ecosystem, and cross into occupational health and safety concerns (Mohammed et al., 2015). Natural composite reinforcements include cellulosic fibers such as sisal, jute, hemp, coir, bamboo, wood, banana, oil palm, and kenaf (Mehdikhani et al., 2019).

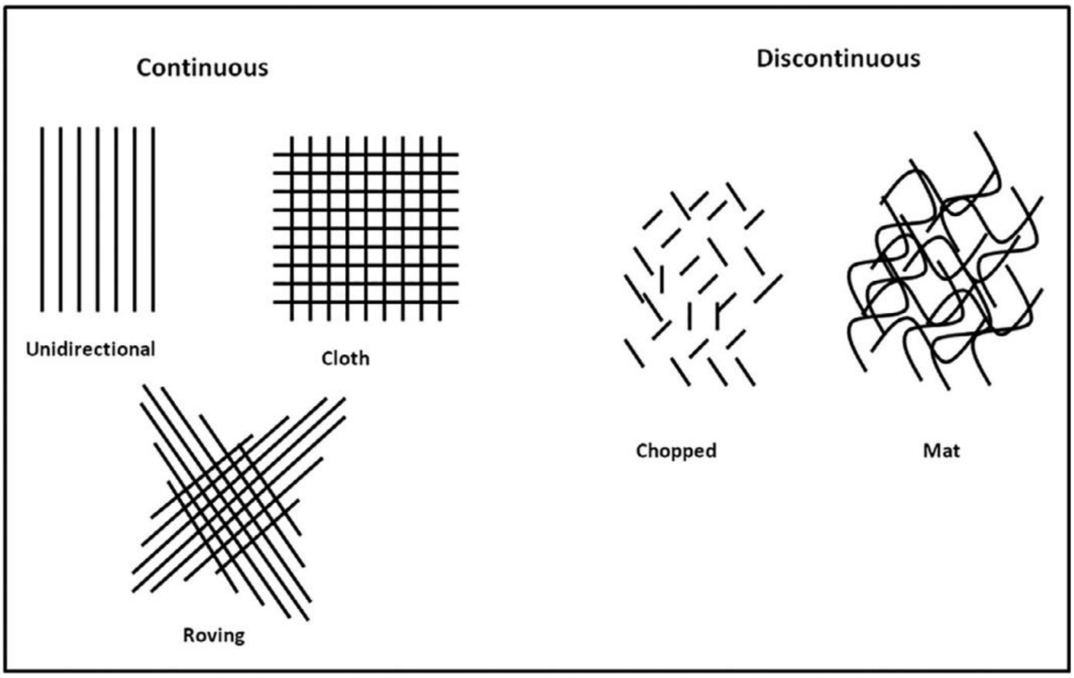


Figure 2.5. Typical fiber reinforcement types (Jayan et al., 2021).

There is a growing interest in developing composite materials from renewable, biodegradable, and waste-based sources, such as agricultural residues and natural fibers (Shanmugam et al., 2021). Various synthetic fibers, such as glass, carbon, boron, and inorganic, metallic, and ceramic materials, are typical reinforcements for polymers. These materials are heavy, expensive, and harmful to the environment. Due to their relatively low strength, natural fibers cannot compete with the impressive properties of synthetic fibers (Biswas et al., 2011). Nevertheless, there is a growing trend towards utilizing natural fibers as reinforcements in polymer matrix composites, gradually replacing traditional synthetic fibers.

Because of their mechanical properties, natural fiber-reinforced polymer composites are used in various products and applications. Many reviews have discussed the potential uses of natural fiber-reinforced polymer composites in construction and building applications. These natural fibers, including coir, have exceptional mechanical properties (Ilyas & Sapuan, 2020). Coir is a strong, durable, and versatile material that can improve the mechanical properties of a material. It is also inexpensive, lightweight, and biodegradable, making it a greener alternative to synthetic fibers. Adding coir to polymer matrices can improve the material's thermal properties and resistance to water absorption, making it ideal for outdoor applications.

Natural fibers are of primary interest owing to their advantages, notably in weight and sustainability. The typical approach is to blend existing polymers with other components to reduce costs and tailor products to specific applications. The growing emphasis on environmental rules and ethical issues has prompted a search for cost-effective and environmentally benign materials. In this setting, using natural fibers becomes critical, providing a viable path for materials that adhere to ecological and ethical standards.

An ecological evaluation, or eco-balance, of the natural-fiber mat compared to the glass-fiber mat offers another perspective. The energy required to produce a flax-fiber mat (9.55 MJ/kg), encompassing cultivation, harvesting, and fiber separation, totals around 17% of the energy needed to produce a glass-fiber mat (54.7 MJ/kg) (Patel et al., 2002 and Wang, 2010). Though natural-fiber-reinforced polymer parts offer many benefits compared to fiberglass, several primary technical considerations must be addressed before the engineering, scientific, and commercial communities gain the confidence to enable wide-scale acceptance (Ghassemieh, 2011).

Natural fibers, such as coir, jute, sisal, and opuntia, are attractive alternatives to synthetic fibers, such as glass and carbon, for reinforcing PMCs because they are abundant, renewable, biodegradable, low-cost, and have comparable mechanical properties (Hasan et al., 2021). However, natural fibers also have some drawbacks, such as high moisture absorption, poor compatibility with polymer matrices, and variability in quality (Neto et al., 2022). Therefore, natural fibers must be treated or modified to enhance their surface properties and adhesion with the matrix (Martinelli et al., 2023).

Table 1. Physical and mechanical properties of natural fibers (Sapuan, 2021).

Fibers	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Elongation at Break (%)**	**Tensile Modulus (GPa)**
Bamboo	1.25	140-230	-	11-17

Jute	1.3	393-773	1.5-1.8	26.5
Sisal	1.5	511-535	2.0-2.5	9.4-22
Coir	1.2	138.7	30	4-6
Pineapple	0.8-1.6	400-627	14.5	1.44

Coconut Fiber, also known as coir, is a lignocellulosic fiber sourced from coconut palms in tropical areas. Due to its sturdiness, endurance, and valuable attributes, it is widely utilized in flooring materials, yarn, and rope (Satyanarayana et al., 1986). However, traditional coir products utilize only a fraction of the total coconut husk production, prompting research efforts to explore new pathways for coir utilization, particularly as a reinforcing component in polymer composite materials (Geethamma et al., 1998). The amount of waste generated from coconut shells has increased due to the rising consumption of coconut fruit pulp (Ayrilmis et al., 2011). The build-up of coconut shells presents problems in some areas, with adverse social, economic, and environmental effects (Biggs et al., 2015).

These shells break down slowly, and their careless disposal ruins the urban environment. They serve as a mosquito breeding ground, eventually spreading disease (Banerjee et al., 2013). It is unclear how many coconut shells are thrown away at consumption locations, which makes handling the leftovers difficult (Santos et al., 2019). Coconut dumping frequently occurs in inappropriate places, such as uncompleted building sites and beaches, and is, therefore, difficult to measure. Addressing this issue is vital for promoting sustainability and unlocking the substantial potential of coconut waste.

Coconut shells, in powder or fiber form, have been shown to have extensive unrealized potential for a variety of applications, including thermal insulation (Araújo et al., 2015), panel production (Ayrilmis et al., 2011), reinforcement in polymer matrices (Das & Biswas, 2016), and cement composite enhancement (Asasutjarit et al., 2007). Coir fibers exhibit excellent elongation at break, indicating their ability to stretch well beyond the elastic limit without breaking (Karthikeyan & Balamurugan, 2012).

Using natural fibers for composite fabrication has many drawbacks, like poor compatibility with polymers, low thermal degradation, and high-water absorption capacities (Senthilkumar et al., 2018). Thus, fiber surface modification is necessary. The surface modification of natural fibers aims to remove hemicellulose, which can improve interfacial adhesion between fibers and polymer matrices. Removing hemicellulose can also reduce fibers' hydrophilicity (Saba et al., 2015).

Removing fiber surface impurities produces cleaner and rougher fiber surfaces (Li et al., 2007). Various approaches can be used to improve natural fibers' adhesion to polymer matrices. These approaches can be physical or chemical and are not strict formulas that, once implemented, will result in substantial improvements. Several natural fiber research techniques for physical treatment methods have been identified, including fibrillation and electric discharge (cold plasma, corona). This treatment modifies the fibers' surface and structure properties without using chemicals. It strengthens the bond between the polymer matrix and the reinforcement fiber, resulting in stronger composites (Ilyas & Sapuan, 2020). Physical treatments, such as hydrothermal treatment, have been used to modify fiber surfaces, improve compatibility between fibers and polymer matrices, and remove hemicellulose components (Norrrahim et al., 2018).

Xue Li et al. discuss how chemical treatments can also improve interface adhesion between the fiber and the matrix and reduce water absorption by fibers (Li et al., 2007). Chemical treatments should also be considered when altering the properties of natural fibers. For example, treating natural fibers with sodium hydroxide (NaOH) is commonly used to change the chemical composition of the cellulosic polymer (Mwaikambo & Ansell, 1999).

Ariffin et al. (2018) cut the coir into short pieces and washed it with double-distilled water to remove dust particle impurities. Then, the coir was soaked in 2% NaOH solution at ambient temperature for 24 hours to remove lignin from the coconut coir and avoid bacterial infection. This process allows for greater accessibility to substances that penetrate the fiber skin (Parkash, 2015).

Table 2. Physical treatment for modifying natural fibers (Nurazzi et al., 2021).

Method	**Description**
Corona Treatment	I. Apply low-temperature corona discharge plasma to convey changes in the properties of the fiber's surface. II. Use of oxygen-containing species. III. Increase fiber surface roughness. IV. Improves wettability and polarity of the fibers and adhesion of plastic surface.
Plasma Treatment	I. Modify the fiber surface. II. Reduce weakly attached layers in fiber. III. Improve fiber surface roughness. IV. Increases the surface adhesion between fiber and matrix.
Superheated steam	I. Hydrothermal treatment of fiber. II. This results in the removal of thermally unstable and hydrophilic components of fiber. III. Improves the fiber-matrix compatibility interaction.

The fiber-to-matrix ratio in composite fabrication is a critical determinant of the mechanical properties of the final product (Shesan et al., 2019). The fibers, which are the reinforcing phase, provide strength and stiffness to the composite. At the same time, the matrix binds the fibers together, transferring stresses between the fibers and protecting them from environmental damage (Shesan et al., 2019). The ratio between these two components determines the balance between the strength and flexibility of the composite material (Rajak et al., 2019).

A high fiber-to-matrix ratio often results in a composite with excellent strength and stiffness, as the load-bearing capacity of the composite is primarily due to the fibers (Shesan et al., 2019). However, if the ratio is too high, there may be insufficient matrix material to effectively bind the fibers together, leading to a brittle composite that can fail under stress (Hull, 1981). Conversely, a low fiber-to-matrix ratio can result in a composite with good toughness and ductility but at reduced strength and stiffness. Therefore, achieving the optimal fiber-to-matrix ratio is crucial for tailoring the properties of the composite to meet specific application requirements (Rajak et al., 2019).

After investigating agricultural residue-based composites' physical and mechanical properties, Ariffin et al. (2018) and Singh et al. (2021) concluded that natural fibers can replace synthetic fibers. They show the capability of hybrid natural fiber composites as a useful material in lightweight applications. Meanwhile, Edge et al. (1996) and Ailenei et al. (2021) provided insights into the degradation and stability of polymer-based composites.

2.4. Natural Fiber-Reinforced Composites for Roofing Applications

Composite materials have been increasingly used in roofing due to their unique properties and benefits. To maintain loading, live load, wind load, and, in some situations, snow load, the roof material should be light, resistant to water, and resistant to harsh weather (Al-Azad et al., 2021). Sectors where moderate strength is required, and high demand is demonstrated provide considerable opportunities for the easy adoption of natural fiber composites. The use of natural fiber composites such as sisal fiber/cashew nutshell liquid (CNSL) and recycled paper-reinforced acrylated epoxidized soybean oil (AESO) with a foam core as roof materials (Dweib et al., 2006) is an example of roofing materials manufactured using natural fiber composites forming sandwich panels. A sandwich-structured composite is a special class of composite material fabricated by attaching two thin but stiff skins to a lighter core (Gay et al., 2003, p53).

Whether flat-surfaced or corrugated, composite panels demonstrate versatility in both dimensions and applications. They find utility in various settings, including wall partitions, floors, and roofs, particularly when crafted from plant-based polymers (Van Erp & Rogers, 2008). This adaptability underscores the potential of composite materials, especially those derived from natural sources, in sustainable construction practices.

Darsana et al. developed coir fiber cement boards for wall panels, roofing, and flooring using a 70:30 combination of cement and coir fiber. They discovered that adding fibers increased attributes such as breaking load and ductility. Tiles with coir fiber had fewer acute cracks than those without (Darsana et al., 2016). Another study discovered that immersing coir fibers in hot water boosted their effectiveness as a strengthening compound by improving adhesion between the coir and the matrix (Asasutjarit et al., 2007).

Cook et al. investigated randomly oriented coir fiber-reinforced composites for roofing sheets, focusing on fiber length and volume. They determined that the best composite had a fiber length of 3.75 cm and a fiber volume content of 7.5%. This composite proved a cost-effective solution, significantly cheaper than locally available roofing materials (Cook et al., 1978).

In a study on the durability of natural fibers and the effect of corroded fibers on mortar strength, coir fibers retained a higher proportion of their initial strength than other fibers after exposure to various mediums (Ramakrishna & Sundararajan, 2005). These studies lay the groundwork for comprehending the structural characteristics critical to this research. While composite materials offer several benefits for roofing applications, it is essential to consider their potential drawbacks. The choice of roofing material should be based on various factors, including the local climate, aesthetic preferences, and budget. Composite fabrication often comes with a steeper price tag due to the cost of materials and the fabrication and design process.

2.5. Natural Fiber Composite Fabrication

Most composites reinforced with natural fibers, processed through various methods, exhibit a favored orientation of fibers (Serrano,2013). Factors such as part geometry, material flow, viscosity, wettability, and mold surface roughness collectively impact the orientation of fibers. The arrangement of fibers during the preparation of composites plays a pivotal role in determining the material properties (Alam et al., 2010). Optimal strength and modulus are achieved when using continuous fibers. In contrast, discontinuous fibers tend to have a random orientation, leading to decreased strength and modulus, but they prove cost-effective. As a result, discontinuous fibers find application in scenarios where cost outweighs the significance of strength.

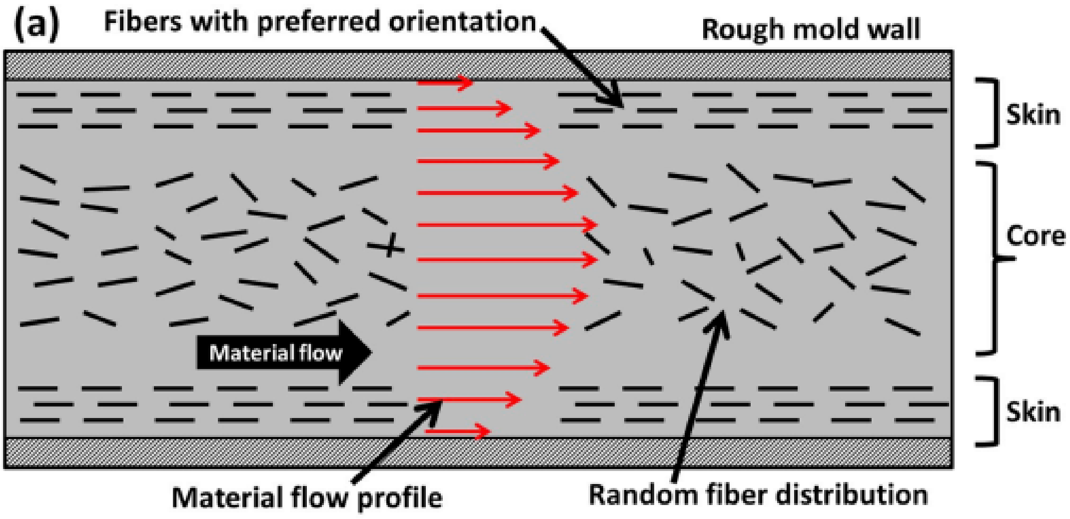


Figure 2.6. (a) Schematic fiber orientation and distribution variations due to material flow during NFRC processing (Gallos et al., 2017).

Traditional manufacturing techniques for fiber-reinforced polymer composites are usually used to fabricate natural fiber polymer composites. Due to their repelling properties, natural fibers have high moisture absorption. They also have low thermal resistance, inconsistent quality, and wettability (Ramasamy, 2021). In addition, specific fabricating methods can affect the quality of composite materials (Potter et al., 2008).

2.5.1. Compression Molding

Compression molding is a commonly used composite material creation method. After the matrix and fiber are placed on the mold, the counter mold closes it. The assembly is placed in a press with a 0.1 to 0.2 MPa pressure. After that, the mold is sealed and exposed to ambient temperature or higher (Gay et al., 2003, p17), which causes the material to take on the mold's shape. The substance forms the intended product when it solidifies.

This process is preferred because it can create intricate geometries with high fiber volume fractions, resulting in composite products that are reliable and sturdy. Compared to an injection molding cycle, a molding cycle lasts between one and six minutes (Kopeliovich, 2023). The process works well for producing flat or slightly curved pieces in bulk. It works especially well with thermoplastic polymers like PET, HDPE, polypropylene, and thermoset resins like Sheet Molding Compounds (SMC). In the compression molding process, fibers such as fiberglass, aramid, carbon fiber, and natural fibers may be utilized.

When using this approach for PMC fabrication, numerous critical parameters come into play, including compression pressure, pressure-holding time, compression temperature, mold-opening temperature, and cooling rate. Changes to these factors affect the product's tensile strength, bending strength, and overall mechanical performance. The reinforcement fibers are equally distributed throughout the composite, resulting in minimal variations in physical qualities during production (Kangishwar et al., 2023).

2.5.2. Injection molding

One popular method of producing polymer matrix composites is injection molding (Wang, 1992). It entails injecting molten polymer—typically thermoplastic—under high pressure into a mold cavity while combining it with 10–40% short reinforcing fibers (Kopeliovich, 2023). A hopper feeds the polymer-fiber mixture usually pellets—into an injection molding machine (Kopeliovich, 2023).

The injection molding procedure involves multiple stages, including filling the cylinder, shutting the mold, plasticizing the polymer, injecting pressure, chilling the material, and finally, ejecting the material (Islam, 2021). The polymer granules are first heated, mixed, and then melted into a viscous fluid in a heated barrel (Lau, 2019). Once injected into a mold cavity, the liquid polymer cools and solidifies to take on the shape of the cavity (Lau, 2019). The mold is precisely machined and designed to form the features of the desired product (Lau, 2019).

Because injection molding guarantees precision and consistency, it is especially well-suited for large-scale manufacturing (Lau, 2019). It can create intricately shaped, high-precision parts at a very low cost (Wang, 1992). However, the fiber's chemical treatment, the matrix mix, and the fabrication method affect the final composite material's qualities. Thus, to achieve the necessary qualities in the final composite part, precise management of the injection molding process parameters is essential (Islam, 2021).

2.5.3. Resin Transfer Molding (RTM)

Injection and compression molding characteristics are combined in a production technique called resin transfer molding (RTM) (Xometry, 2023). This closed mold method involves clamping matching male and female molds replaced with fiber preform to create composite parts (Fong & Advani, 1998).

A predetermined amount of raw material is used in the process; it is heated and put into a chamber called the pot at the top of the mold (Xometry, 2023). One cycle is used for the material in the pot, which is usually a heated reservoir that can fill many mold holes at once (Xometry, 2023). The polymer is then forced through a channel known as a sprue using a piston into a heated mold. The mold stays closed until the material within has completely hardened (Xometry, 2023). The main use of RTM is for the rubber or plastic encasement of electrical components. RTM allows for producing parts with sharper corners and edges (Xometry, 2023).

Three steps make up the RTM process: pre-processing, injection, and post-processing (Delgado, 2019). The preform, or reinforcements in the shape of the component, is first made and placed in the mold during pre-processing (Delgado, 2019). The preform is then squeezed, and the mold is sealed (Delgado, 2019). The resin mixture is injected into the cavity at a comparatively low pressure via injection ports. Fong and Advani (1998) say the typical injection pressure is less than 690 kPa or 100 psi. Comparing this process to other methods, such as compression molding, reveals several advantages. Xometry (2023) lists these benefits as increased design flexibility, lower production cycle times, and a higher cavity count. It is appropriate for medium-volume production of high-performance composite components (Carruthers, 2018).

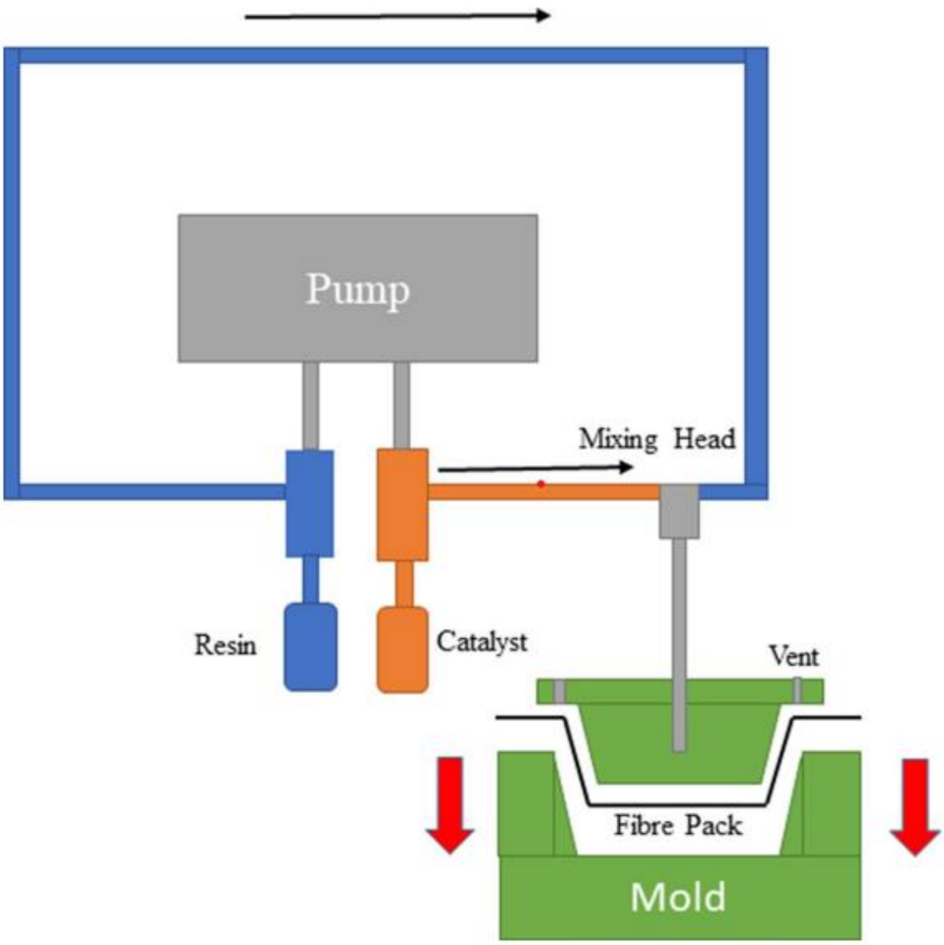


Figure 2.7. Resin Transfer Molding (RTM) (Kangishwar et al., 2023).

2.5.4. 3D Printing

3D printing, or additive manufacturing, is a layer-by-layer process for creating 3D items from various materials. It has been utilized more frequently to create composite materials, which have special benefits regarding adaptability and personalization (Ye, 2021). Most 3D printers that can process composite materials rely on Fused Filament Fabrication (FFF) (Autonomous Manufacturing, 2020), a polymer-extrusion method. In FFF, an object is created layer by layer by extruding a molten plastic thread known as a filament through a nozzle that moves above the build platform (Autonomous Manufacturing, 2020). Compared to previous molding techniques, this one can manufacture more complicated pieces in larger quantities, allowing for elaborate designs and quick prototyping (Martin, 2019).

3D printing is especially popular in materials engineering to optimize mechanical qualities since it strengthens materials in specified directions (Carlota, 2023). By eliminating the requirement for conventional tooling and enabling the creation of composite parts without it, 3D printing drastically reduces production time and mold-making expenses (Zelinski, 2021). Furthermore, 3D printing expands the tooling options available to the composites industry by facilitating the creation of intricate shapes and geometries that would be difficult or impossible to do using traditional techniques. Therefore, 3D printing offers a viable path forward for improving the fabrication of composite materials and raising the bar for composite applications across various industries.

2.5.5. Extrusion

Extrusion is a manufacturing process that involves transforming a material, typically in a molten or semi-solid state, into a product with a specific cross-sectional profile. This transformation is achieved by applying heat and pressure to force the material through a specially designed opening known as a die shape (Jegla, 2023). Once it passes through the die, the material takes on the shape of the die's opening. This shaped material emerges on the other side, ready for its final application (Jegla, 2023). This process is highly versatile and can be used with various materials, including metals, plastics, and composites.

In the context of composite materials, extrusion takes on an additional layer of complexity. The composite extrusion process allows for the continuous embedding of reinforcing into a matrix material. As the material is extruded, additional materials (reinforcing elements) are incorporated into the matrix, creating a composite material with properties that can be tailored to specific applications (Dahnke, 2014).

The process in question, which combines the economic advantages of conventional direct extrusion, such as low cost and high production speed, with the benefits of a multi-material profile design, allows for creating a final product with the benefits of multiple materials. These benefits include increased strength or improved thermal properties, and the product can still be produced cost-effectively. (Dahnke, 2014).

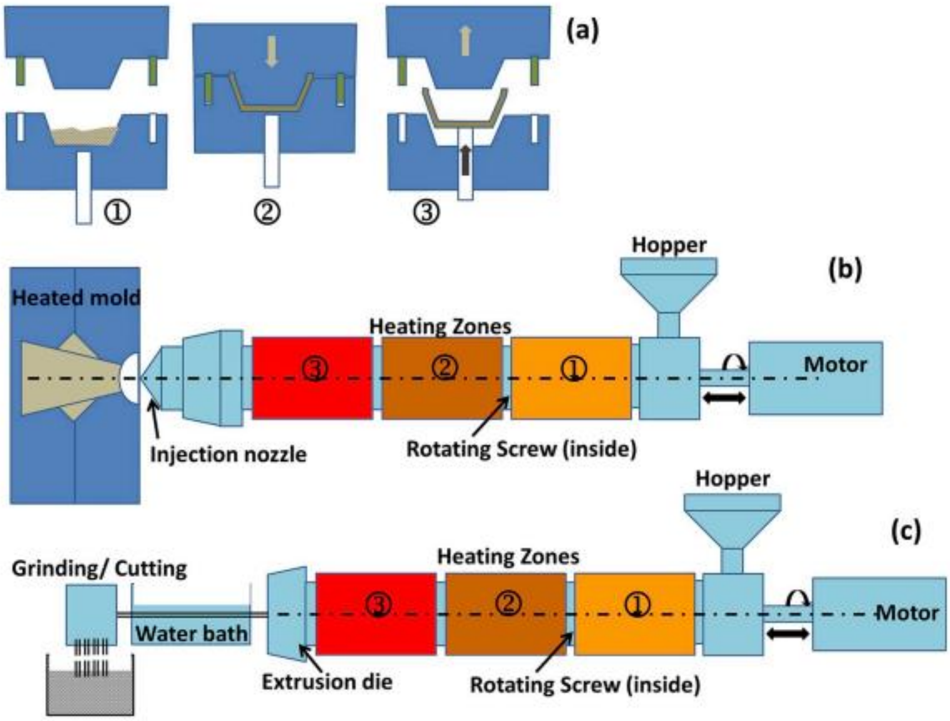


Fig 2.8. Schematic diagram showing (a) compression molding, (b) injection molding, and (c) extrusion of NFRCs (Balla et al., 2019).

2.6. Research Gaps and Opportunities

While research has extensively explored composite materials for various applications, a gap exists in synthesizing a composite material that combines recycled polymers and coconut fiber. Studies have investigated using renewable resources in recycled PET composites (Shaikh et al., 2020) and the potential of natural fibers like jute (Wang et al., 2019), sisal (Li et al., 2000), and coir (Adeniyi et al., 2019) as reinforcement materials. However, the combined recycled PET and coconut fiber in a composite material remains largely unexplored.

This research aims to bridge this gap by pioneering the fabrication of a composite material that marries the structural strength of recycled PET with the sustainable and renewable qualities of coconut fiber. A comprehensive study in this niche area is essential to understand better the unique properties, challenges, and opportunities associated with these materials in sustainable construction. Such opportunities pave the way for additional research into efficiently utilizing these materials and their potential applications in the construction industry.

This chapter establishes the critical need for sustainable composite materials and identifies the current research gaps, laying the foundation for the subsequent chapter. The next chapter will outline the methodology employed to fabricate, characterize, and evaluate the performance of this novel material in sustainable roofing applications. These steps are crucial to achieving the desired outcomes and significantly advancing sustainable materials.

3. Methodology

This chapter provides a robust framework for creating and analyzing sustainable composite materials for roofing applications, leveraging recycled PET and coconut fibers. The methodology includes a detailed description of the materials, the fabrication technique, comprehensive laboratory testing protocols, and rigorous data analysis. The research aims to thoroughly understand the properties of the composite, informing the development of more sustainable and durable roofing materials. This systematic approach underscores the importance of rigorous research in achieving the study's objectives and contributing to the field of sustainable materials.

3.1. Materials

The choice of materials for this study is crucial to ensuring the quality and performance of the composite material under consideration. Coconut fibers and Polyethylene Terephthalate (PET) were selected for their unique properties and suitability for the intended application of the composite material. Coconut fibers were used as a renewable and environmentally sustainable material. On the other hand, PET was chosen for its excellent mechanical properties and corrosion resistance, making it an ideal matrix material for the composite.

Coir, a natural cellulose fiber sourced from coconut husks, is preferred for fiber reinforcement in composites due to its unique properties and benefits. One of the primary reasons for its popularity is its sustainability. As a natural, renewable, and biodegradable material, coir aligns with the growing demand for eco-friendly and recyclable materials. Additionally, coir is widely available, particularly in tropical regions where coconuts are extensively cultivated. This ensures a readily accessible raw material source for composite fabrication (Hasan et al., 2021).

Moreover, coir fibers are known for their impressive strength and stiffness, which are essential for reinforced composite materials. They offer superior mechanical, thermal, and physical properties to synthetic fiber-reinforced composites. Coir also exhibits exceptional resistance to degradation, particularly in saltwater environments, making it well-suited for applications in harsh or marine conditions (Bongarde & Khot, 2019). Its versatility is evident in its compatibility with various thermoplastic, thermosetting, and cement-based materials, allowing us to produce diverse biocomposites. Furthermore, the mechanical performance of coir fiber-reinforced composites can be enhanced through surface pretreatment of the coir fibers (Hasan et al., 2021). This potential for enhancement adds to the appeal of using coir in composite materials.

Figure 3.1. Coconut fibers.

The matrix PET is key for load transfer and mechanical strength in tandem with coconut fibers. PET's wide availability and superior properties, including stiffness, strength, design flexibility, and resistance to fatigue and corrosion, make it a popular choice in commercial and aerospace applications. Its advanced mechanical properties and ease of fabrication further enhance its appeal across various industries (Kangishwar et al., 2023).

Waste polyethylene Terephthalate (PET) obtained from post-consumer waste sources, such as discarded plastic bottles, goes through a shredding and cleaning process to turn it into clean flakes. This shredding stage is necessary for the later inclusion of recycled PET into the composite matrix, where it plays the role of the polymer matrix component. The recycled PET acts as the matrix in the composite material, providing cohesion and overall stability to the finished product.

The selection of recycled PET as the polymer matrix in composites is primarily driven by its widespread availability from the packaging industry and the substantial volume of post-consumer PET produced worldwide. This ensures an easily accessible supply of raw materials for composite production, promoting the creation of environmentally friendly materials. The recyclability of PET and its inherent properties enable its use in an open-loop waste material utilization (Torres et al., 2000) process for composite manufacturing. By incorporating recycled PET into the composite matrix, the study supports the circular economy model, which emphasizes continuous recycling and repurposing of resources to minimize resource exhaustion and waste production.

Figure 3.2. Post-consumer PET.

The composite material's fabrication hinges on carefully selecting and processing coconut fibers and Polyethylene Terephthalate (PET). These materials were sourced and processed to ensure their quality and consistency. The coconut fibers were purified, while the PET is shredded and cleaned, preserving the integrity of the recycled PET. This thorough preparation paves the way for the next steps in the methodology, which will explore the detailed procedures for composite preparation, the tools used, and the safety measures taken.

3.2 Materials Processing and Composite Fabrication

During the preparation phase, we implement extra steps to ensure the composite's components are uniformly dispersed and optimized. We meticulously control the fiber length and moisture content to boost the composite's mechanical strength and structure. Processing, storage, and handling conditions were strictly regulated to maintain consistent material properties.

The mechanical recycling of PET begins with collecting, sorting, cleaning, and drying waste PET. Post-consumer waste was manually sorted to ensure that only PET was recycled, and contaminants were removed (Valerio, 2020).

The sorted PET waste was then thoroughly cleaned to remove impurities like dirt, debris, and residual substances. This step is vital for preserving the quality of the recycled PET and preventing contamination during future processing stages. The PET products were dried to eliminate excess moisture, which could degrade the recycled material's quality and performance in downstream applications.

After drying, the PET flakes were shredded into small, uniform pieces using a shredder. This facilitated the subsequent melting and processing steps. The PET flakes were then cleaned to remove any debris or contaminants from the shredding process. Once cleaned, the PET flakes were melted, transforming into a molten state suitable for fabricating sheets through compression molding.

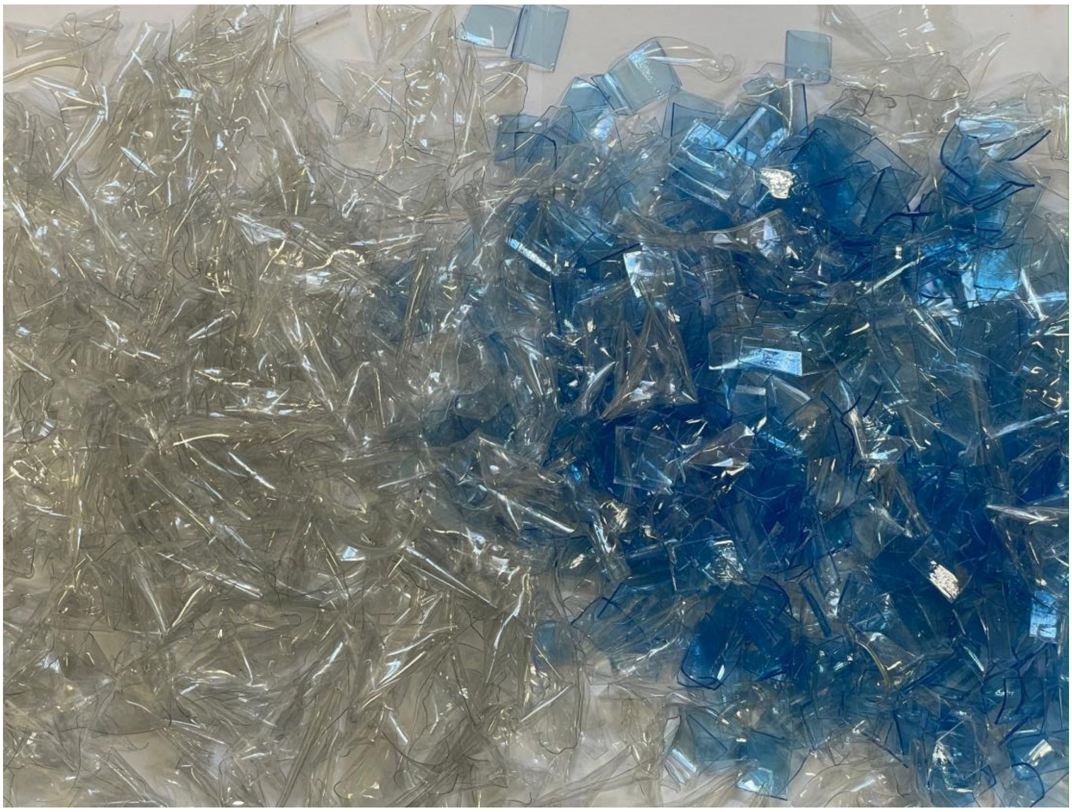


Figure 3.3. Shredded and cleaned waste PET.

Following the mechanical recycling of PET, the next key step was treating the coconut fibers to improve their compatibility with the recycled PET matrix. This treatment, known as hydrothermal treatment, enhances the adhesion between the fibers and the matrix, thereby improving the composite material's mechanical properties (Nurazzi et al., 2021).

The coconut fibers were soaked in distilled water at elevated temperatures of 110°C for two hours, allowing deeper penetration into the fiber structure and modifying the fibers. After soaking and heating, the fibers were dried at 110°C for two hours to remove residual moisture and ensure material uniformity (Norrrahim et al., 2018). This thorough treatment process prepared the coconut fibers for integration into the recycled PET matrix, optimizing the composite material's performance.

Hydrothermal processing induced a transformative change in the coconut fibers. Due to steam permeation, the fibers expanded and became more porous, enhancing the composite material's performance by promoting superior adhesion with the recycled PET matrix (Norrrahim et al., 2018). The fibers' hydrophilicity and surface energy increase due to the controlled steam exposure, aiding in hydrolyzing the hemicellulose components (Xiao et al., 2017). These significant changes in fiber chemistry increased composite strength and durability by improving wetting and interfacial adhesion with the rPET matrix. These changes in the hemicellulose structure enhanced wetting and interfacial adhesion with the matrix.

Figure 3.4. Coir treatment in distilled water.

During material preparation, rigorous quality control measures were enforced to ensure the produced composite materials were uniform and consistent. A key aspect of quality control was managing fiber length during preparation. Since coconut husk-derived fibers vary in length, they can significantly affect the final composite's mechanical properties. Precise cutting processes were used to standardize fiber lengths and reduce variability. The coir fibers were trimmed to create uniform lengths, ensuring consistency throughout the composite material.

Integrating coconut fibers and recycled polyethylene terephthalate (rPET) into a composite material was a critical fabrication step that demanded meticulous attention to detail and optimal control over processing conditions. The dried fibers were chopped (Ariffin et al., 2018) to

20mm and 30mm lengths, ready for inclusion in the composite material. These fibers were randomly oriented and compressed to enhance manageability and uniform distribution, facilitating easier bonding with the molten rPET matrix and improving overall composite properties.

Figure 3.5. Cleaned and trimmed coir.

Additional stringent procedures were implemented to minimize potential variability sources that could affect the composite material's qualities. For example, a material's mechanical performance and dimensional stability can be heavily influenced by its moisture content. Therefore, it was necessary to dry the coir (Norrrahim et al., 2018) and rPET separately to maintain the composite material's ideal moisture content. Strict cleaning techniques were also employed to remove contaminants or impurities that could affect the material's performance or quality.

Figure 3.6. Compressed randomly oriented coir.

In addition, the fiber orientation inside the composite matrix was random. The configuration and orientation of fibers were critical factors that could impact the properties of the composite material. The fibers were maintained in situ and randomly orientated, utilizing specific procedures during the composite fabrication. Consequently, this guaranteed that the material's stiffness, strength, and resistance to deformation were evenly distributed throughout, thus giving it anisotropic properties (Cook et al., 1978).

The fabrication process used compression molding due to its ability to uniformly distribute fibers within the rPET matrix (Kangishwar et al., 2023). Compression molding also provides material and energy efficiency. Compared to an injection molding cycle, a molding cycle lasts between one and six minutes. The process works well for producing flat or slightly curved pieces in bulk (Kopeliovich, 2023). It contributed to production efficiency and product quality and allowed for incorporating recycled PET into a composite, enhancing sustainability. The process aimed to maximize PET's strength and sustainability benefits, reinforced with coconut fiber.

During compression molding, treated and randomly oriented fibers were placed between rPET layers in a mold to form a sandwich composite. This facilitated strong interfacial adhesion between the fibers and the rPET matrix, which was crucial for improving the composite material's mechanical properties.

A key aspect of the fabrication process was adjusting the coconut fiber to rPET ratio. The study methodically varied this ratio to optimize the composite material's composition. It involved creating composite samples with various fiber-matrix mixes and evaluating their mechanical characteristics, chemical properties, and interfacial adhesion. The goal was to determine the ideal blend that balances durability and resilience.

In this study, we systematically varied the fiber content of the Coir-Reinforced rPET Composite, using fiber ratios of 10%, 20%, and 30% by weight. These ratios were chosen to examine how changes in fiber content affect the composite's mechanical and interfacial properties (Shesan et al., 2019). We compared these samples to pure recycled PET specimens to establish a reference point.

Our choice of fiber ratios was informed by preliminary experiments that showed a significant impact of fiber content on the composite's mechanical properties, such as tensile strength and elongation at break. By exploring different compositions, we aimed to find the optimal blend that maximizes the composite's desired qualities while minimizing waste. This approach comprehensively understood the composite's behavior (Rajak et al., 2019).

The rPET was heated to its melting point of 260 °C during molding. A layer of molten rPET was poured into the mold, followed by the placement of randomly oriented fiber. Then, another layer of molten rPET was added, and a compressive force of 0.1 Mpa was applied for 3 minutes. This combination of heat and pressure allowed the rPET to flow into and adhere to the fibers, resulting in a dense and homogeneous composite material.

We carefully monitored and controlled the distribution of the rPET matrix within the composite to prevent discrepancies in mechanical properties and structural integrity. Process parameters like temperature and pressure were controlled to ensure uniform matrix dispersion (Kangishwar et al., 2023).

Figure 3.7. Mold inside box furnace for compression molding.

This study focused on a composite sample weighing 18 grams. The sample is formed using a mold that is 50 mm in diameter and 10 mm thick. The chosen mass and dimensions ensured consistent experimental conditions and allowed for precise comparisons across different samples. Following fabrication, samples of the composite material were tested and analyzed to determine their mechanical and physical properties and interfacial adhesion.

Figure 3.8. Coir Reinforced rPET composite.

3.3. Laboratory Testing

The fabricated composite materials were comprehensively evaluated using various analytical techniques. These techniques include Tensile testing, Fourier-transform infrared (FTIR) spectroscopy, and Scanning Electron Microscopy (SEM). Each sub-section assesses different aspects of the composite materials, such as mechanical properties, molecular structure, and morphology, providing valuable insights into their performance and characteristics.

3.3.1. Tensile Testing

The mechanical properties of the Coir-Reinforced rPET Composite (CRPC) are crucial for assessing its structural integrity and potential uses. The Instron 5500, a universal testing machine, was used to determine these properties through tensile tests. CRPC samples were subjected to controlled axial loading during the test until failure. This process allowed for measuring the applied force and resulting deformation, which helped identify key mechanical properties like tensile strength, modulus of elasticity, and elongation at break (Khan et al., 2023). The analysis of these properties provided essential insights into the CRPC's load-bearing capacity and deformation behavior, which were critical for assessing its suitability for various structural applications.

Figure 3.9. Instron 5500 for tensile testing.

The procedure began with preparing CRPC specimens using standardized dimensions and configurations, typically measuring 50 mm by 10 mm. These specimens were carefully mounted onto the grips of the universal testing machine, ensuring proper alignment to prevent any potential stress concentrations or premature failures. Once secured, the machine applied a gradually increasing tensile force to the specimens at a controlled rate, typically 10 mm/min.

Figure 3.10. CRPC dog bone-shaped samples.

When tensile force was applied, the CRPC samples deformed along the loading axis until they reached failure, marked by a sudden decrease in the applied force, signaling the material's rupture. The force-displacement curve generated during testing extracted key mechanical properties.

Tensile testing was used to evaluate the CRPC's performance under tension quantitatively, supplying crucial design and material selection data. By comparing the test results of CRPCs with different fiber-to-matrix ratios, we could understand their relative performance and potential benefits in various applications.

3.3.2. Fourier-transform infrared (FTIR) spectroscopy

Fourier-transform infrared (FTIR) spectroscopy provided detailed insights into the chemical composition of the composite by identifying functional groups and bond structures through the analysis of their Infrared (IR) absorption bands (Kathiresan & Meenakshisundaram, 2022). FTIR is particularly effective in detecting chemical interactions between fibers and the matrix, helping us understand component compatibility and bonding mechanisms. (da Silva et al., 2012). This understanding is crucial for studying the complex dynamics between coir-reinforcing fibers and the rPET matrix.

Thin solid CRPC samples were placed in IRSpirit FTIR Spectrophotometer with QATR-S (Shimadzu Corporation, Japan) FTIR was invaluable in determining the chemical compositions of both unaltered and modified natural fibers and provides essential data on their super-molecular structure (Fan et al., 2012).

Figure 3.11. IRSpirit FTIR Spectrophotometer.

In addition to composite analysis, FTIR was used to conduct individual analyses on the composite samples and compared them to established baseline spectra of PET and coir. This comparative approach helped distinguish the unique spectral features of each material from the composite spectra. Comparing the FTIR spectra of the composite samples to PET, and coir elucidated any shifts or modifications in chemical composition induced by the composite fabrication process.

3.3.3. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a comprehensive analytical tool used to examine the Coir-Reinforced rPET Composite (CRPC) microstructure at high magnification and resolution. It played a crucial role in evaluating the interfacial adhesion between coconut fibers and the rPET matrix, a key factor influencing the CRPC's mechanical strength and long-term durability.

SEM revealed the microscopic interactions between the fibers and the matrix, essential for understanding how these interactions influenced the composite's overall properties (Khan et al., 2023). It also provided high-resolution images of the composite's surface topography to identify any surface irregularities that could impact its performance (Zhao et al., 2023).

The SEM analysis process involved careful sample preparation to ensure optimal imaging results. The fractured surface of the samples from tensile testing were viewed under the SEM. Given the non-conductive nature of the materials, the samples were coated to ensure proper electron conduction and prevent the charging of the composite. Imaging parameters such as accelerating voltage, beam current, and working distance were meticulously calibrated to maximize image clarity and resolution.

Figure 3.12. Scanning Electron Microscope, JSM-7000F.

Detailed micrographs obtained from SEM provided valuable insights into the material's microstructure, which significantly affected the composite's macroscopic characteristics. These comprehensive micrographs also offered a view of the interface region's morphology, roughness, and integrity (Zhao et al., 2023). By visually examining the interface, the quality of bonding between the fibers and matrix, the presence of any voids or defects, and the overall interfacial adhesion were assessed, providing a comprehensive understanding of the interfacial adhesion in CRPC.

3.4. Data Analysis

The mechanical, chemical, and morphological data derived from testing Coir-Reinforced rPET Composite (CRPC) samples underwent a thorough examination to discern any notable discrepancies among the assessed composite formulations. The primary objective of this analysis was to unveil the chemical interaction of the two materials and the influence of varying ratios of coconut fiber to PET on the mechanical attributes and the composite material's morphology.

3.4.1. Mechanical Testing Data Analysis

The data from the tensile tests were analyzed using Microsoft Office Excel. This software facilitated the calculation of key mechanical properties such as tensile strength, modulus of elasticity, and elongation at break. It also allowed for a comparative analysis of CRPCs with different fiber-to-matrix ratios, providing insights into their relative performance and potential benefits in various applications.

3.4.2. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

The FTIR spectra were analyzed using Microsoft Office Excel. This software helped identify the fibers' functional groups and bond structures through the raw data of Infrared (IR) absorption band peaks. It also revealed the most typical absorption bands of specific molecular components of natural fibers, aiding in understanding the interaction between the natural fiber and the polymer matrix.

3.4.3. Scanning Electron Microscopy (SEM) Data Analysis

In addition to analyzing tensile and FTIR data, an assessment through Scanning Electron Microscopy (SEM) imaging was undertaken to delve into the interfacial bonding dynamics between coconut fibers and the PET matrix. The SEM images were analyzed visually. This detailed the CRPC's microstructure, including the interfacial adhesion between coconut fibers and the rPET matrix and the morphology of the fibers and the matrix. It also helped identify surface irregularities that could impact the composite's performance.

The SEM images were thoroughly examined, focusing on capturing and interpreting subtle nuances in the interface between the coconut fibers and the PET matrix. SEM imaging helped pinpoint regions of inadequate bonding or structural irregularities in fiber orientation (including alignment and dispersion) and voids or discontinuities. By scrutinizing these aspects, valuable insights are gained into the effectiveness of different composite formulations in achieving optimal interfacial bonding.

3.5. Methodological Limitations

We faced several challenges while developing recycled PET and coconut fiber composites. Compression issues during fabrication were a common problem, likely due to factors like temperature (Delgado et al., 2019), pressure (Lokesh et al., 2023), and material properties(Baran et al., 2017). We addressed this by adjusting the compression force. Residual stresses and distortions within the composites were another concern. These can cause deformations and cracks, especially during assembly. Predicting these distortions was crucial to maintaining the composite's integrity.

Temperature and pressure management were key to the quality of the components. As per Darcy's law, resin flow, which affects the impregnation of fibrous preforms in Liquid Composite Molding (LCM), depends on pressure gradient, reinforcement geometry, and resin viscosity (Rubino et al., 2022). Careful control of these parameters was necessary for high-quality, void-free laminates. These challenges highlighted the complexities of composite fabrication and the need for precise process control and optimization to develop natural fiber reinforced polymer composites.

The methods used in this study gave a thorough approach to the study of Coir-Reinforced rPET Composite. Each step, from material selection and preparation to composite characterization and testing, was planned to ensure the results' dependability and validity. Employing advanced analytical techniques and software in data analysis increased the accuracy of the results. This allowed for a full understanding of the composite's mechanical characteristics, microstructure, and chemical composition.

4. Results

This chapter outlines the results from the characterization described in the methodology. The goal was to determine the composite's mechanical properties, detect the functional groups present within the composite and study the morphology of the fabricated composite samples.

Following fabrication, a tensile test was conducted to evaluate its strength and ductility. Scanning Electron Microscopy (SEM) was employed to study the composite's morphology and composition, and Fourier Transform Infrared (FTIR) Spectroscopy was used to analyze the chemical composition.

Finally, a thorough analysis of the collected data. The subsequent sections will provide detailed findings from characterizing the CRPC, offering insights into the composite's properties.

4.1. Tensile Properties of Coir-Reinforced rPET Composite

The main goal of tensile testing was to determine the material's mechanical properties, especially strength and ductility. In this research, the tensile test was conducted following standard procedures. The data collected from the tensile tests provided valuable insights into the mechanical properties of the composite materials. The stress-strain curves in Figure 4.1 show the material's behavior under tension.

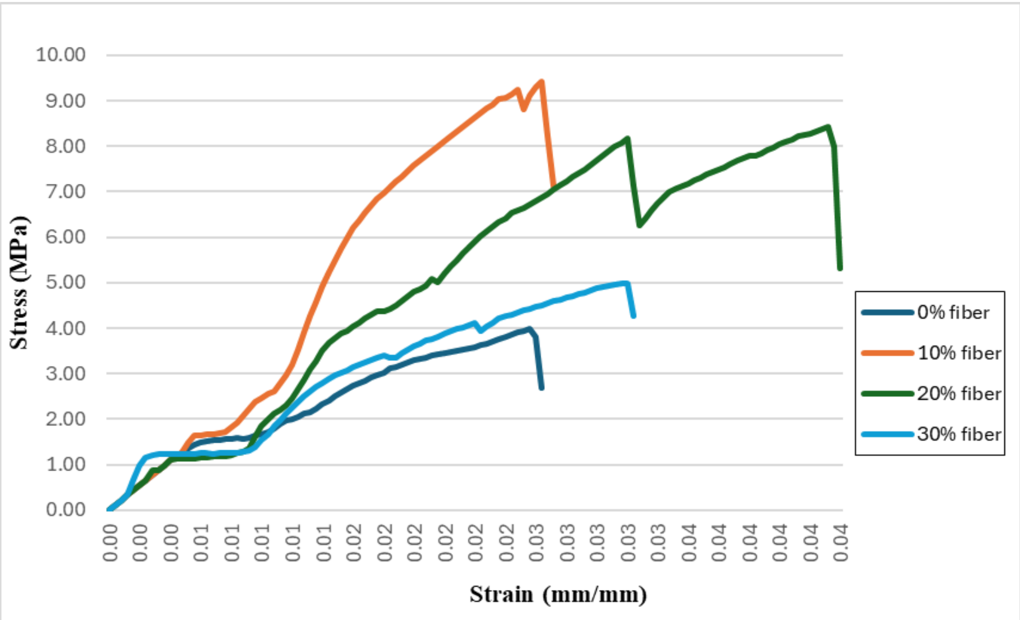


Figure 4.1. Stress-strain curves of Coir-Reinforced rPET Composites at various fiber ratios.

The graph depicts the stress-strain curves for composites with 0%, 10%, 20%, and 30% fiber weight content. Each curve illustrates a distinct behavior under applied force, indicating variations in strength and elasticity. The maximum stress observed in the stress-strain curve corresponds to the material's ultimate tensile strength, and the strain at this maximum stress point indicates the material's ductility. One common observation among all the samples is the sudden failure of the material.

Composite materials with varying weight percentages of coconut fibers demonstrated different mechanical properties. The composite with 0-weight % fiber, essentially pure PET, showed the least resistance to tensile stress at 3.98 MPa. The lower resistance of the pure PET composite is evident from its lower peak stress value on the stress-strain curve. Compared to other composites, the pure PET composite exhibits the lowest ductility.

The composite showed improved strength by adding 10-weight % coir, as shown by a higher peak stress value of 9.43 MPa. on the curve. The composite with 20-weight % coir fibers demonstrated improved strength, with a high peak stress value of 8.42 MPa, slightly lower than the peak observed at 10-weight % fiber content. As the coconut fiber content increased to 30-weight .% fiber, we observe a decline in the ultimate tensile strength of 5.00 MPa.

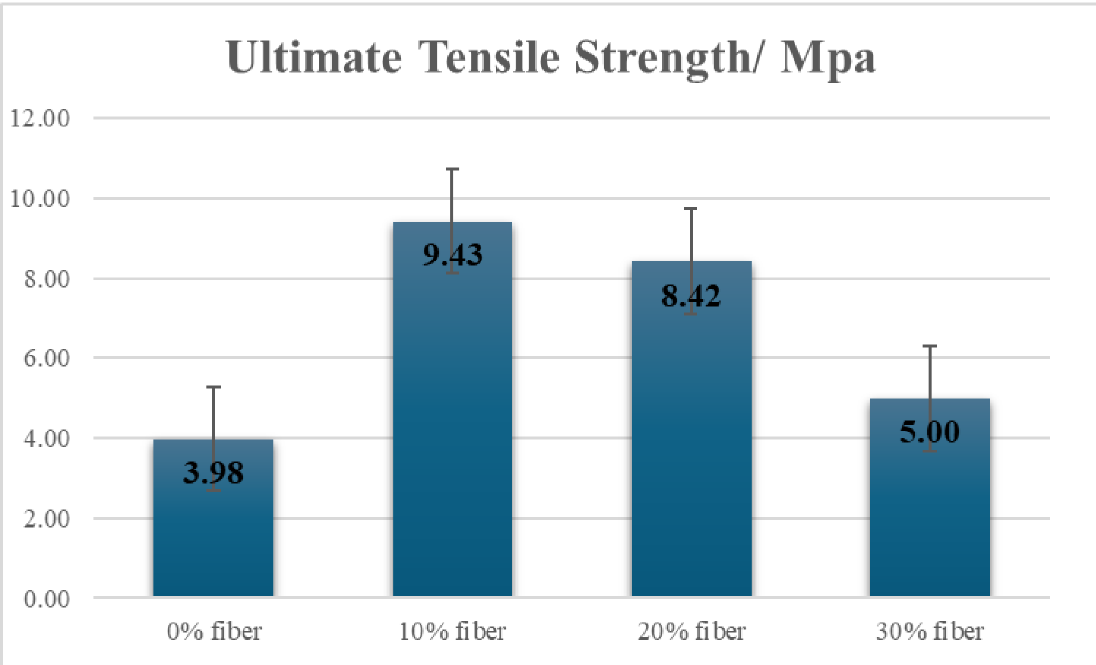


Figure4.2. Ultimate Tensile Strength.

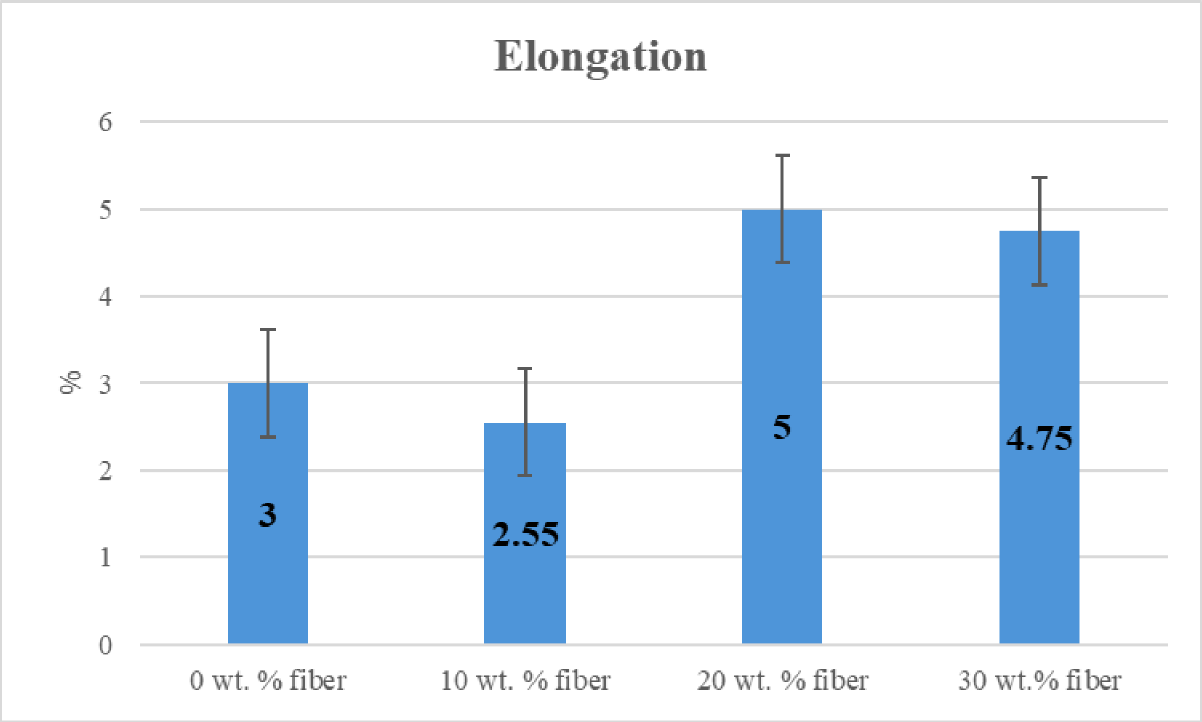


Figure 4.3. Elongation at the break.

For the elongation at break, the extracted data reveals a progression of changes across different levels. At 0-weight % fiber, the elongation percentage begins at approximately 3%. A slight decrease to 2.55 % is observed as we move to the 10-weight %. There is a significant increase with the 20-weight %, where the elongation break surges to about 5%. Finally, in the 30-weight % fiber level, there is a minor reduction in the elongation to approximately 4.75%.

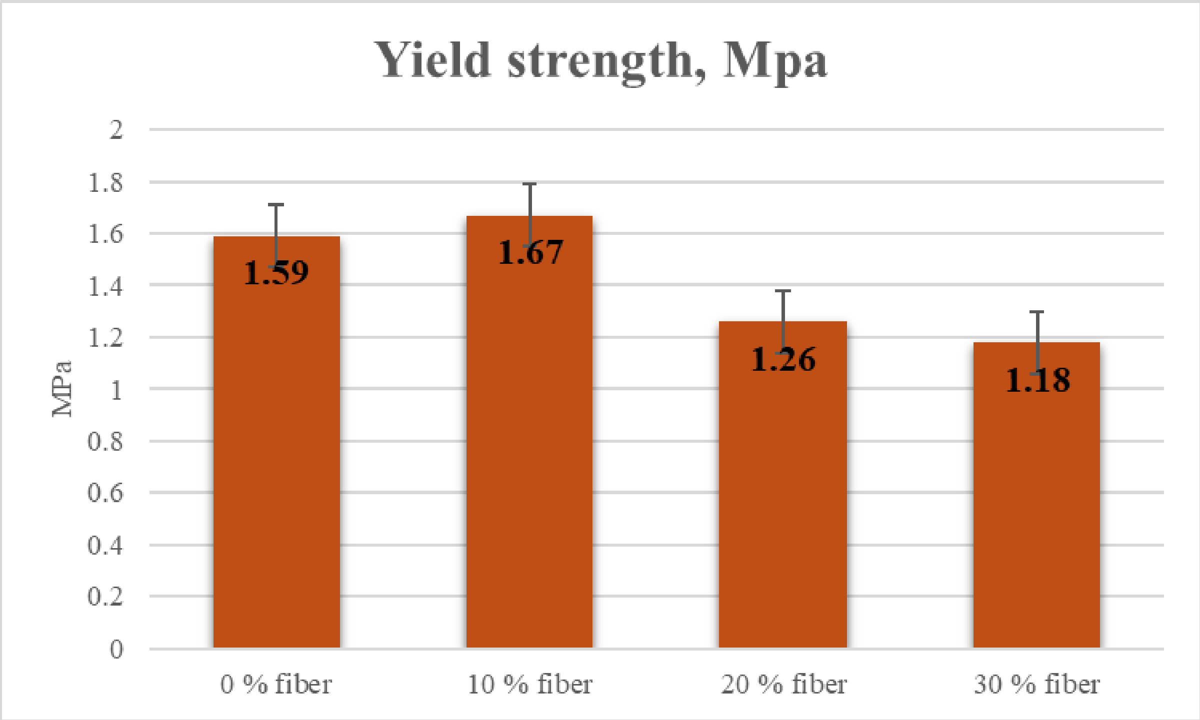


Figure 4.4. Yield strength.

Upon analyzing the data, it was observed that progressing from 0 to 10-weight % fiber content, there was a slight enhancement in yield strength, from 1.59 Mpa to 1.67 Mpa. However, this declines in the 20% and 30%-weight % fiber samples. The values decrease to 1.26 Mpa and 1.18 Mpa, respectively.

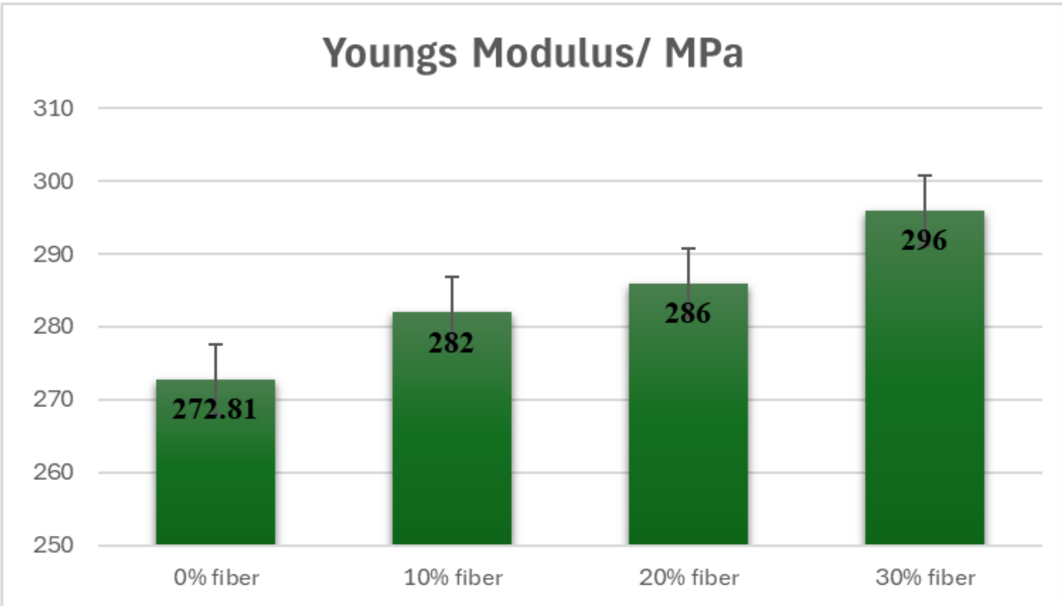
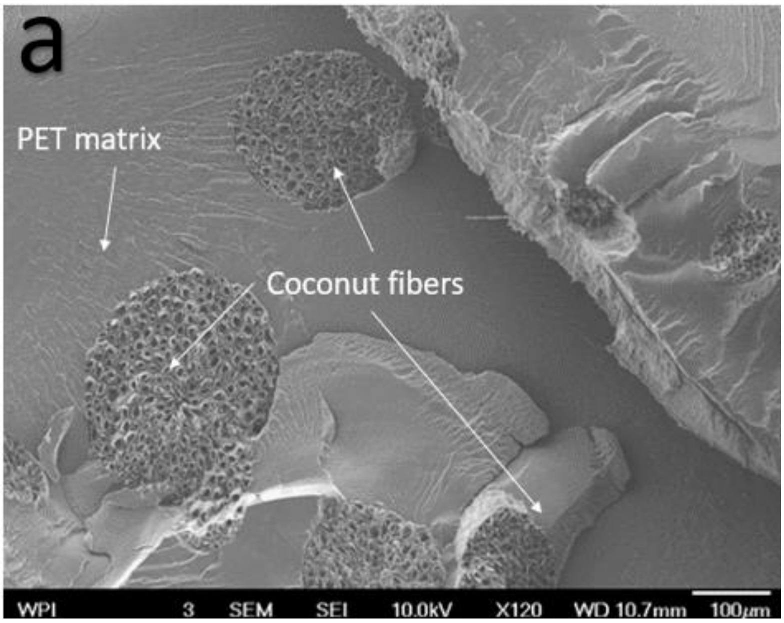


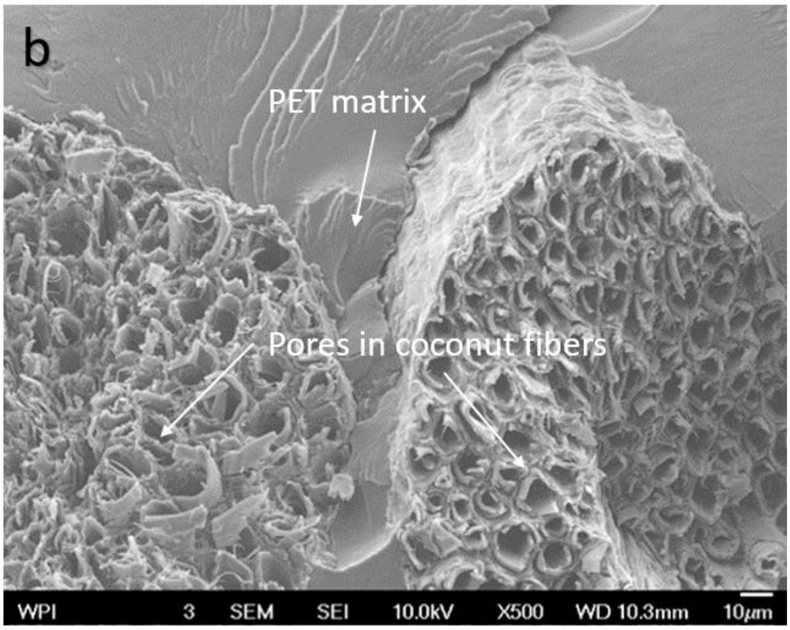
Figure 4.5 Young's Modulus.

The bar graph illustrates Young’s Modulus in MPa for different fiber percentages. At 0-weight % fiber, the modulus is 272.81 MPa. As the fiber percentage increases to 10-weight %, there is a slight rise in the modulus 282 MPa. The trend continues at 20-weight % fiber, with the modulus reaching 286 MPa. The peak is observed at 30-weight % fiber, where the modulus is approximately 296 MPa.

4.2. Morphology of Coir-Reinforced rPET Composite

Specimens of the CRPC material prepared using the conventional fabrication method outlined in Section 3.3 were subjected to SEM analysis. The morphology of the composite material was examined in detail using scanning electron microscopy (SEM). As depicted in Figure 3.8, the coconut fibers were observed to be randomly oriented within the recycled PET matrix. The SEM images revealed that the fibers exhibited varying diameters.





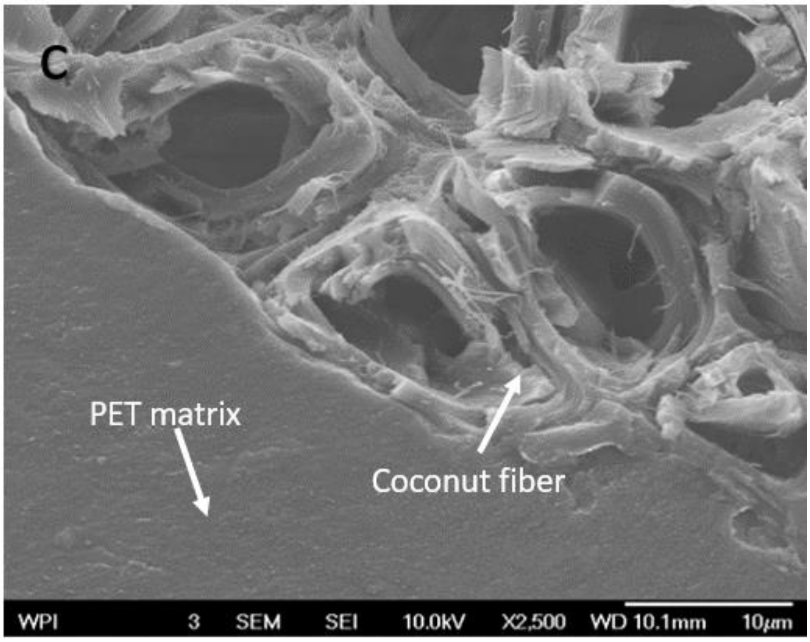
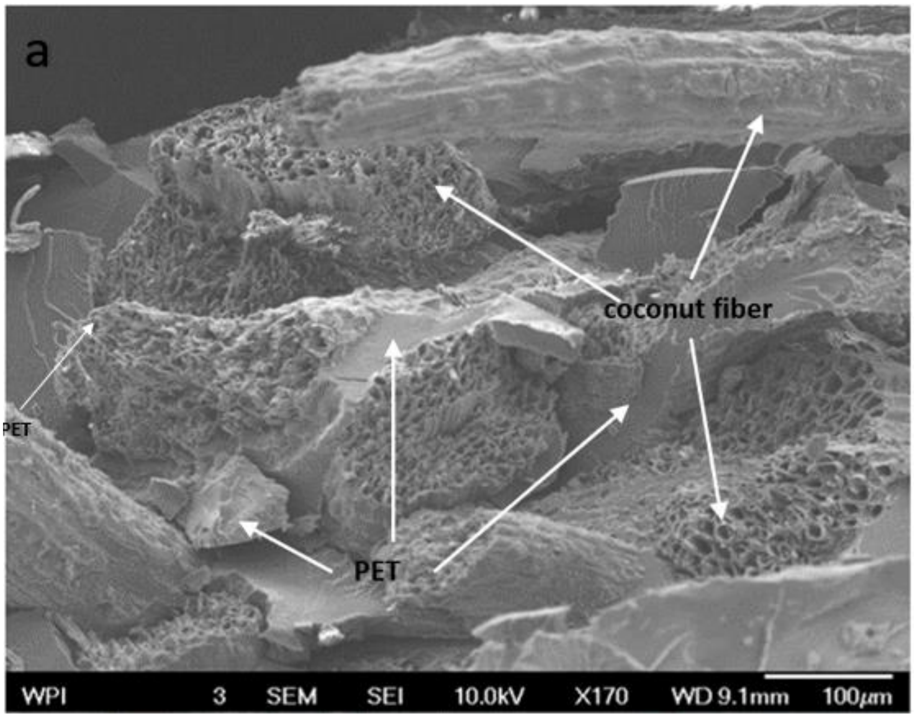
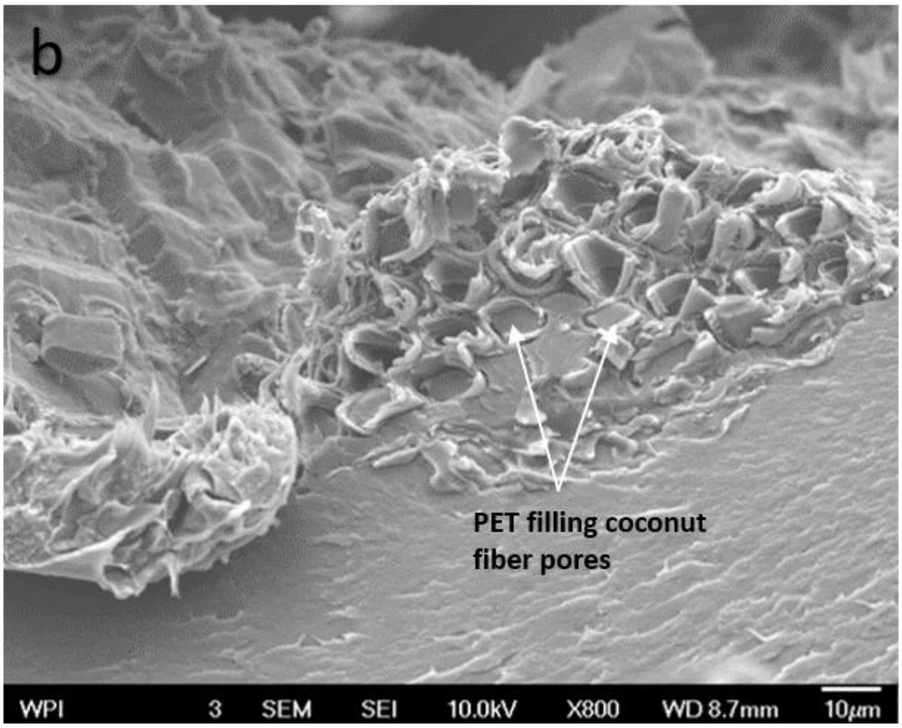


Figure 4.6 (a, b and c). SEM images of 10-weight % fiber.

In Figure 4.6. (c), the coconut fibers are visible and appear well integrated within the PET matrix. In Figure 4.6. (b), we observe a rough and irregular surface texture of the recycled PET matrix. The porous nature of the fiber is particularly notable in Figure 4.6. Figure 4.6. (a) shows good integration between the coir reinforcements and the PET matrix.


a
coconut fiber
PET
PET
WPI 3 SEM SEI 10.0kV X170 WD 9.1mm 100μm


b
PET filling coconut
fiber pores
WPI 3 SEM SEI 10.0kV X800 WD 8.7mm 10μm

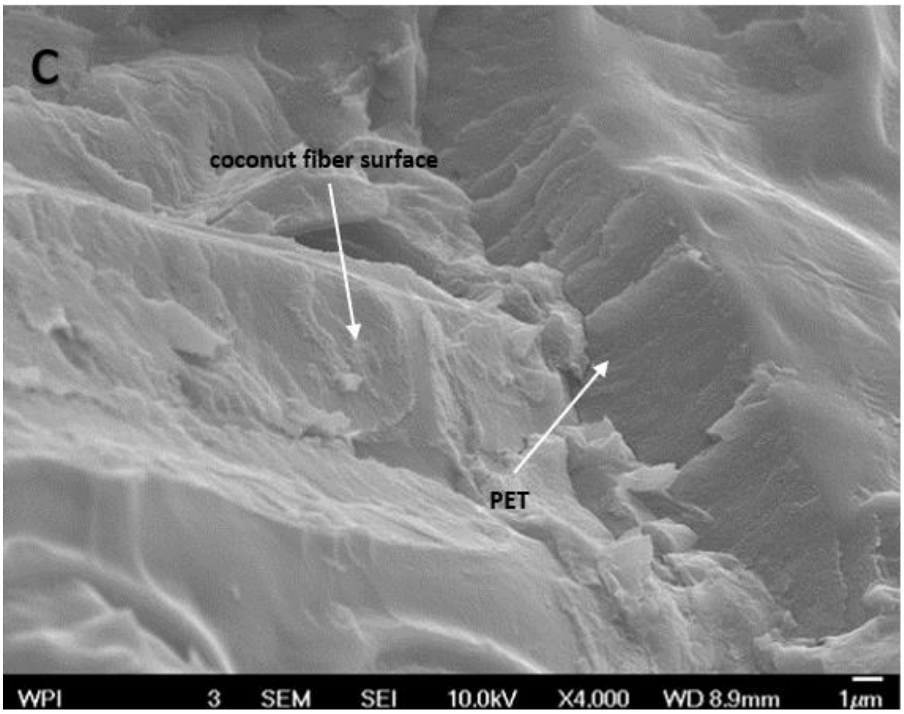
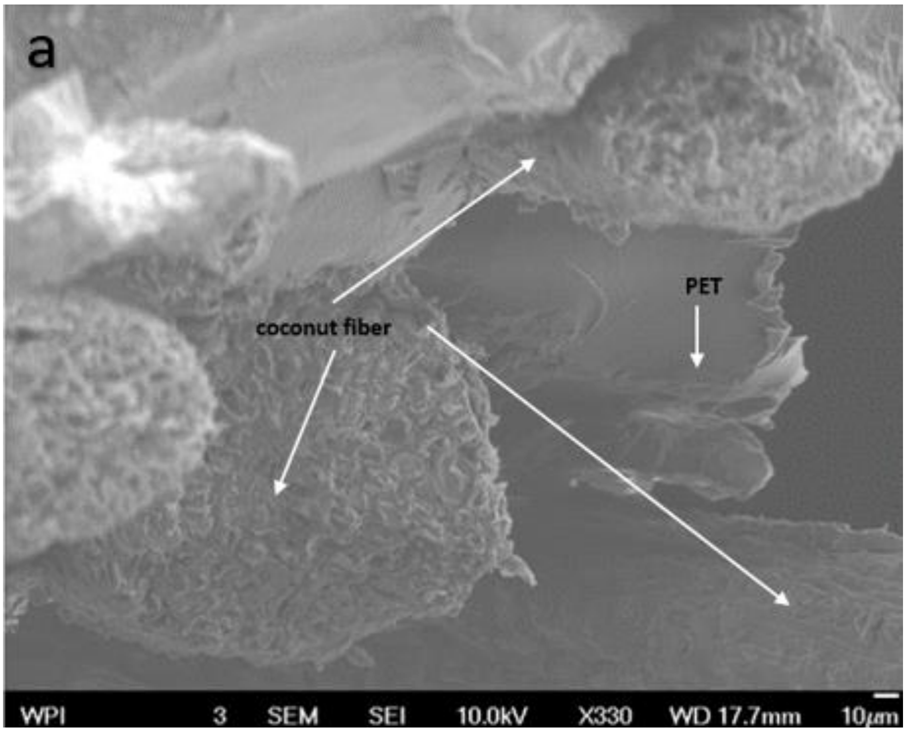
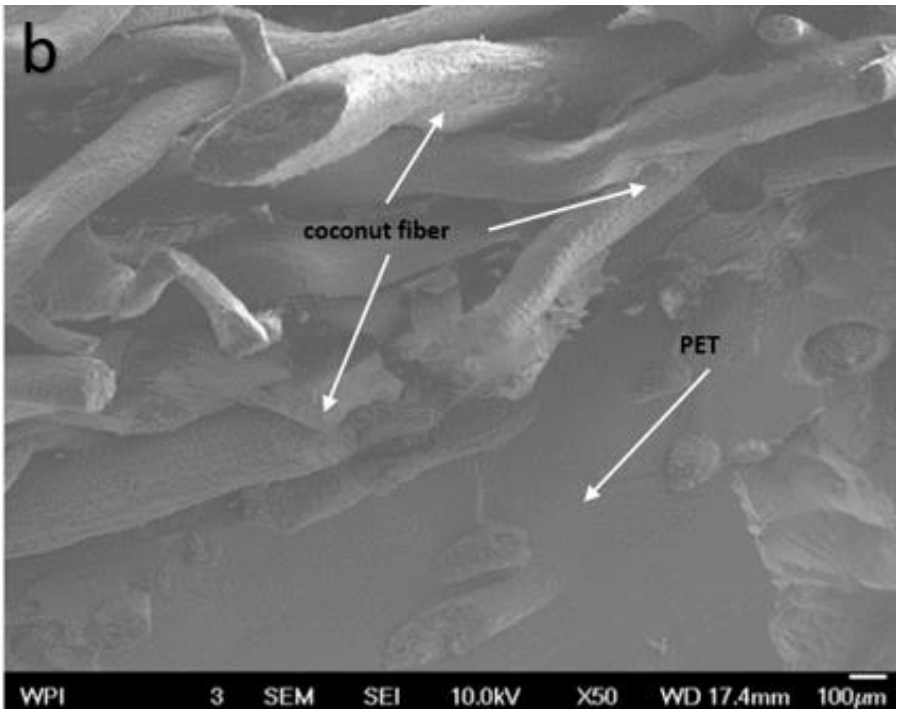


Figure 4.7 (a, b and c). SEM images of 20-weight % fiber.

As the ratio of coconut fiber to rPET increases, a notable augmentation in the coverage of coconut fiber in the composite material matrix is observed. In Figure 4.7, the images reveal a significant observation about the interaction between the coir fibers and the PET matrix in the composite with 20% fiber content. It is evident from 4.7. (b) the PET matrix flows to fill the pores of the coir fibers, indicating good compatibility between the two materials. 4.7. (c) clearly shows the surfaces of the coir fibers and the PET matrix and how they bond together.

Figure 4.7. (a) shows a random orientation of the coconut fibers within the PET matrix.





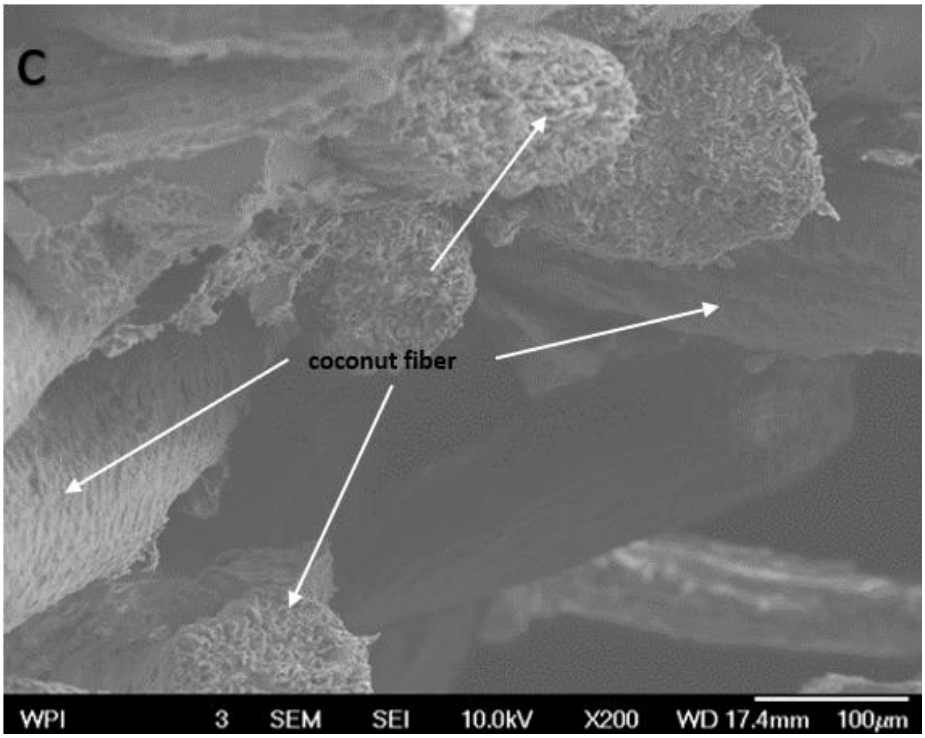


Figure 4.8 (a, b, c). SEM images of 30-weight % fiber.

Figure 4.8. (a) shows a high weight percent of coconut fibers, exhibiting a random orientation. However, a notable observation across all three images is the inconsistent bonding between the PET matrix and the coir fibers. While some regions show the PET matrix adhering to the fibers, indicating a degree of compatibility, there are also areas where the matrix does not bond with the fibers. Figure 4.8. (c) shows that the PET matrix does not fill or encapsulate the fibers, leaving noticeable voids or gaps between the fiber and matrix interfaces.

SEM images of sections derived from coconut fibers and rPET composites reveal significant variations in morphology depending on the coconut fiber content. A uniform fiber dispersion and matrix adhesion is observed at lower loadings, while higher loadings exhibit a low degree of adhesion between the coconut fibers and the rPET matrix.

4.3 FTIR of Coir-Reinforced rPET Composite

This section explored the FTIR analysis of coconut fiber and recycled PET composite material to understand the impact of coconut fiber, rPET, on the composite's chemical composition. The detection of molecular interactions within the composite material is of significant interest, indicating the infiltration of PET chains between the layers of coconut fiber. The obtained FTIR spectra are presented in Figure 4.9.

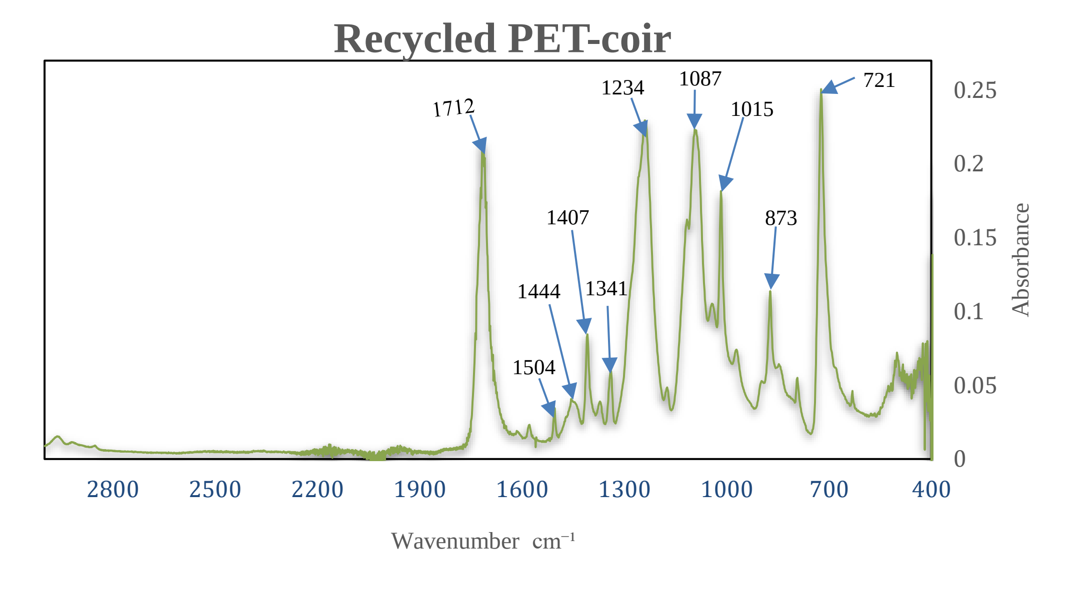


Figure 4.9. FTIR of CRPC shows the various absorbance peaks and wavenumbers.

Analysis of the FTIR spectra revealed peaks indicative of chemical bonding between the coconut fiber and rPET matrix. Specifically, characteristic absorption bands associated with functional groups in coconut fiber and PET were observed, suggesting strong intermolecular interactions between the two components. Moreover, peak intensity and frequency variations were noted, corresponding to changes in composition and processing parameters.

Table 3. Functional Groups and Corresponding Wavenumbers.

Peaks (cm^{-1})	**Possible functional Groups**
1712	C=O stretching.
1574	Vibrations aromatic skeleton with stretch C=C.
1504	Aromatic skeletal due to lignin (C=C).
1444	Stretching C-O group deformation of O-H group and bending and wagging vibrational modes of ethylene glycol segment.
1407-1368	Bending wagging vibrational modes of ethylene glycol regiment.
1341	C-H.
1234	Terephthalate groups OOC C6H4-COO.
1087	Methylene group and vibration of ester C-O bond.

1036	Ring skeletal C-O & C-C stretching.
1015	Aromatic bands.
965	Aromatic rings 1,2,3,4,5, tetra replaced.
873	C-O-C in plane symmetric.
789	Out of plane C-H and O-H bending.
721	Aromatic bands.

The FTIR spectrum presents four significant peaks. The peak around 1700 cm^{-1}, typically indicative of a carbonyl group (C=O), could suggest the presence of aldehydes, ketones, carboxylic acids, esters, or amides. This peak is observed at 1721 cm^{-1} in PET and 1716 cm^{-1} in coir, indicating the presence of ester groups. The peak around 1100 cm^{-1}, potentially corresponding to the stretching vibration of C-O single bonds and suggesting the presence of alcohols, ethers, esters, or carboxylic acids, is observed at the same wavenumber in PET and about 1207 cm^{-1} in coir. Lastly, the peak at 1234 cm^{-1} belonging to the Terephthalate groups (OOC C6H4-COO) mainly found in the functional groups of PET. Peaks below 700 cm^{-1} are often linked to bending or deformation vibrations of functional groups involving multiple atoms, such as -C-C-C- bending.

5. Discussion

This chapter discusses the findings from the experimental results presented in Chapter 4. The discussion concerns the mechanical properties, Fourier Transform Infrared Spectroscopy (FTIR) analysis, and Scanning Electron Microscopy (SEM) observations of the composites with varying weight percentages of coconut fibers.

The addition of coconut fibers influenced the mechanical properties of the composites. The composite with no fibers (pure PET) had the lowest tensile stress resistance, suggesting less ductility than other composites. With an increase in fiber content to 10 and 20-weight % fiber, there was a significant enhancement in strength, as shown by the higher peak stress values on the stress-strain curve. The ultimate tensile strength increased with the fiber content up to 20%, but a decrease was noted at 30-weight% fiber. The observation that coconut fibers can enhance the composite's mechanical properties suggests there might be an optimal fiber content beyond which the properties could deteriorate.

Th initial response from the yield strength data suggests that including the fiber contributes to the composite's ability to withstand stress. However, the decline with the 20 and 30-weight % fiber suggests an optimal range where addition of the fiber positively impacts the yield strength. The sudden drop in the stress in all the materials suggests a brittle failure. This could be because of recycling the PET which caused the material to become brittle. However, we observed from the curves how the random orientation of the fibers shows an even distribution of the material properties based on the data extracted from the tensile test.

The FTIR spectrum analysis revealed the chemical structure of the composites. A prominent peak at 1712 cm^{-1} indicates C=O stretching vibrations, which are characteristic of ester groups and are primarily derived from the composite's Polyethylene Terephthalate (PET) component. Another peak at 1234 cm^{-1} belonging to the terephthalate group (OOCC6H4-COO) confirms PET's dominance in the composite. The absorption band at 1574 cm^{-1} indicates vibrations in the aromatic skeleton with stretching of C=C bonds, underlining the aromatic nature of PET's structure. The peak at 1036 cm^{-1} corresponds to ring skeletal C-O and C-C stretching, further emphasizing the aromatic character of the composite.

A complex peak from 1341 cm^{-1} to 1444 cm^{-1} reveals stretching C-O group deformations of O-H groups and the ethylene glycol segment's bending or wagging vibrational modes. These results suggest the existence of hydroxyl-containing groups, which could be attributed to the presence of PET and some coconut fibers in the composite. However, the peak at 1087 cm^{-1} corresponds to vibrations of ester C-O bonds and methylene (CH2) groups, aligning with PET's chemical structure. Alongside, the peak supports the presence of aromatic rings with various tetra-substituted carbon atoms at 965 cm^{-1}. The broad peak at 789 cm^{-1} indicates out-of-plane bending modes of C-H and O-H groups, suggesting the potential presence of components other than PET. These could be related to the coconut fibers. This observation might suggest that the PET component predominantly affects the composite's lower wavenumber region since it has a higher content in all the studied composite ratios.

The SEM images revealed coconut fibers' random orientation and integration within the recycled PET matrix. The fibers exhibited varying diameters. The visible integration of the fibers within the matrix suggests a good dispersion, which could contribute to the composite's enhanced mechanical properties. The recycled PET matrix's rough and irregular surface texture and the fiber's porous nature were also notable. These observations could affect the composite's mechanical properties and could result from the fabrication process.

The SEM images pinpoint the regions of inadequate bonding especially within the 30-weight % fiber. This could be as result of the thick core of the composite, that is, the sandwich structure. The matrix may not fully penetrate through the core to fill the fibers and achieve uniform binding throughout the composite.

Compared to the images of the 10 and 20-weight % fiber we see the PET matrix flow to fill and bond with the fiber. We observe a proportional increase in thickness accompanies inadequate bonding. The incomplete encapsulation of the 30-weight % suggest a less ideal adhesion between the fiber and matrix. This points to the reduction in the overall mechanical properties compared to the other fiber-matrix ratios.

The study provided valuable insights into the impact of fiber content on recycled PET and coconut fiber composites' mechanical, morphological, and chemical properties. The findings suggest that adding coconut fibers can enhance the composite's mechanical properties, but an optimum fiber content may exist between 10 and 20-weight % fiber. The FTIR and SEM analyses further elucidate the composite's chemical structure and morphological characteristics, contributing to the overall material performance.

6. Conclusion

This thesis explored sustainable materials for roofing applications, focusing on the mechanical properties of a composite made from recycled Polyethylene Terephthalate (PET) and coconut fiber. This work shows that compression molding makes it possible to fabricate Coir-Reinforced rPET Composite (CRPC) with randomly oriented fiber.

The study shows that the amount of fiber content in composites profoundly affects their mechanical, morphological, and chemical properties. The pure PET composite exhibited the least resistance to tensile stress while adding coconut fibers improved the strength. However, an optimum fiber content between 90-10 weight % and 80-20 weight % matrix to fiber ratios was observed, beyond which the mechanical properties started to decrease.

The Fourier Transform Infrared (FTIR) spectroscopy analysis revealed the presence of various functional groups, providing insights into the composites' chemical structure. The Scanning Electron Microscopy (SEM) images further elucidated the composite's enhanced mechanical properties, showing the bonding between the coconut fibers and the recycled PET matrix. Treating the fiber hydrothermally opened the pores of the fiber, facilitating the adhesion with the matrix.

The findings of this study suggest that the composite of recycled PET and coconut fiber holds promise as a sustainable composite material for roofing applications. The enhanced mechanical properties and the good dispersion of fibers within the matrix could contribute to the composite's durability and performance.

This study underscores the potential of recycled PET and coconut fiber composites as a viable option for roofing applications. The findings of this study could have significant implications for the construction industry, particularly in the context of sustainability and resource conservation.

However, there is a need for further research on the long-term durability and environmental impact assessment. Future research could examine the thermal properties of these composites and refine the fabrication process. Such comprehensive research would enhance our understanding of these materials and advance sustainable eco-friendly materials.

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