የኢፌዲሪ የቴክኒክና ሙያ ስልጠና ኢንስቲትዩት
FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

FEDERAL TECHNICAL AND VOCATIONAL TRAINING INSTITUTE (FTVTI)

SCHOOL OF GRADUATE STUDIES

FACULTY OF TEXTILE AND APPARAL FASHION TECHNOLOGY

(DEPARTMENT OF TEXTILE TECHNOLOGY)

DEVELOPMENT AND CHARACTERIZATION OF ECO-FRIENDLY SANDWICH BIO-COMPOSITE FROM FLAX FIBER FOR SUSTAINABLE FURNITURE APPLICATIONS

BY: ASEGEDECH TEREFE

ADVISOR: DR. GURUMURTHY B R

JUNE, 2026

ADDIS ABABA, ETHIOPA

የኢፌዲሪ የቴክኒክና ሙያ ስልጠና ኢንስቲትዩት
FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

DEVELOPMENT AND CHARACTERIZATION OF ECO-FRIENDLY SANDWICH BIO-COMPOSITE FROM FLAX FIBER FOR SUSTAINABLE FURNITURE APPLICATIONS

A THESIS PROPOSAL SUBMITTED TO FEDERAL TECHNICAL AND VOCATIONAL TRAINING INSTITUTE

FACULTY OF TEXTILE AND APPAREL FASHION TECHNOLOGY (DEPARTMENT OF TEXTILE TECHNOLOGY)

IN PARTIAL FULFILLMENT FOR THE DEGREE MASTER OF SCIENCE IN TEXTILE TECHNOLOGY

BY: ASEGEDECH TEREFE

ADVISOR: DR. GURUMURTHY B R

JUNE, 2026

ADDIS ABABA, ETHIOPA

FEDERAL TECHNICAL AND VOCATIONAL TRAINING INSTITUTE (FTVTI)

FACULTY OF TEXTILE AND APPARAL FASHION TECHNOLOGY

(DEPARTMENT OF TEXTILE TECHNOLOGY)

APPROVAL SHEET

APPROVED BY EXAMINING BOARD

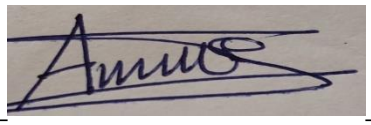
BY: ASEGEDECH TEREFE

Name of Advisor	Signature	Date
Dr. Gurumurthy B R		
Name of Co-advisor	Signature	Date
Name of Examiner, Internal	Signature	Date
Name of Examiner, External	Signature	Date
Dr.Abera Kechi		10/8/2026
Name of chairperson	Signature	Date

Declaration

I hereby declare that the work which is being presented in this thesis entitled "Development and Characterization of Eco-Friendly sandwich Bio-Composite from Flax Fiber for Sustainable furniture applications" is the original work of my own, has not been presented for a Degree in this or other universities and all sources of materials used for this thesis work have been fully acknowledged.

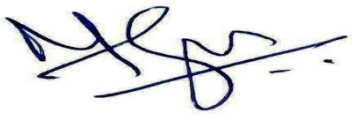
Name: **Asegedech Terefe (ID TTMR/249/16)**

Signature: _____  _____

Place: Addis Ababa

Date of Submission: _____

This thesis proposal has been submitted for examination with my approval as a TVTI advisor.



Dr. Gurumurthy B R _____ _____ _____

Advisor Name Signature Date

Acknowledgements

This thesis expresses deep gratitude to Almighty God for the strength, wisdom, and health that facilitated its successful completion.

I would also like to express my heartfelt appreciation to my advisor, Dr. Gurumurthy B R, for his constructive comments, consistent support, and insightful direction throughout the development of this work. His professional advice, critical feedback, and scholarly insights significantly contributed to the successful completion of this thesis.

My sincere thanks also go to the Federal Technical and Vocational Training Institute (FTVTI) for providing a supportive academic environment. Particularly, School of Graduate Studies, Faculty of Textile and Apparel Fashion Technology, Department of Textile Technology, for providing the academic environment, technical support, and institutional resources necessary for conducting this study

I would also like to express my gratitude to all laboratory technicians, instructors, and staff members in ETIDI, ASTU, and FTVTI who provided technical assistance during material testing, prototype development, and experimental evaluation processes. Their cooperation and professional support were highly valuable to the successful execution of the experimental work.

I am deeply indebted to my beloved family for their unconditional love, encouragement, patience, prayers, and emotional support throughout my academic journey. Their understanding and motivation gave me the strength to overcome challenges and successfully accomplish this study.

Finally, I would like to acknowledge all scholars, researchers, and authors whose published books, journals, articles, and academic materials served as important references and sources of knowledge for this research entitled “Development and Characterization of Eco-Friendly Bio-Composite from Flax Fiber and Bio-Resins for Sustainable Textiles” May all those who contributed to the success of this work receive my sincere appreciation and gratitude.

Acronyms

ASTM: American Society for Testing and Materials

DSC: Differential Scanning Calorimetry

FRB: Fiber Reinforced Polymer

ISO: International Organization for Standardization

LCA: Lifecycle Assessment

NFBCs: Natural fiber bio-composites

NFCs: Natural fiber composites

NFRCs: Natural fiber reinforced composites

PHA: Polyhydroxy Alkanoates

PLA: Polylactic Acid

PMCs: Polymer Matrix Composites

RTM: Resin Transfer Molding

SDGs: United Nations Sustainable Development Goals

SEM: Scanning Electron Microscope

Tg: Glass Transition Temperature

TGA: Thermogravimetric Analysis

UTM: Universal Testing Machine

UV: Ultra Violate

Table of Contents

Declaration i
Acronyms iii
List of Tables vii
List of Figures viii
Abstract x
CHPTER ONE 1
INTRODUCTION 1
1.1 Background of the study 1
1.2 Statement of Problem 2
1.3.1 General Objective 4
1.3.2 Specific objectives 4
1.4 Basic Research Question 4
1.5 Significance of the research 4
1.6 Scope of the Research 5
1.8 Operational Definition of Terms 5
CHAPTER TWO 7
LITERATURE REVIEW 7
2.1 Introduction 7
2.2 Composite Materials 7
2.2.1 Types of Composite Materials 7
2.2.2 Properties of Composite Materials 9
2.3 Natural Fibers 10
2.3.1 Classification of Natural Fibers 10
2.3.2 Natural Fibers in Composite Development 11
2.4 Flax Fiber 13
2.4.1 Properties of Flax Fiber 13
2.4.2 Surface Treatment of Flax Fiber 13
2.5 Bio-Resins 14
2.5.1 Bio-Resins for Sustainable Composites 15
2.5.2 Mechanical and Thermal Properties of Bio-Resins 16
2.5.3 Environmental and Biodegradation Aspects of Bio-Resins 16
2.5.4 PLA Features 17
2.6 Bio-Composites 17

2.6.1 Types of Bio-Composites 17
2.6.2 PLA based composites 18
2.6.3 Composition of Bio-Composite Materials 18
2.6.4 Manufacturing Techniques 18
2.6.5 Key Properties of Bio-Composites 19
2.7 Applications of Natural Fiber Bio-Composites in Textiles 19
2.7.1 Natural fiber reinforced composites 20
2.7.2 Technical Textiles and Functional Uses 20
2.7.3 Comparative Analysis with Traditional Textile Materials 21
2.8 Challenges and Limitations 21
2.9 Research Gaps and Future Trends 22
CHAPTER THREE 25
RESEARCH METHODOLOGY 25
3.1 Introduction 25
3.2 Research Design 25
3.3 Materials and Equipment 26
3.3.1 Raw Materials 26
3.3.2 Equipment and Instruments 27
3.4 Research Variable 28
3.4.1 Dependent Variables 28
3.4.2 Independent Variables 29
3.5 Sample Preparation 29
3.5.1 Fiber preparation and Treatment 29
3.5.2 Flax fiber characterization 32
3.5.3 Making Nonwoven Mats 33
3.5.4 Non-woven development 33
3.5.5 3D Printing Development Procedure 34
3.5.6 Composite Development 36
3.6 Experimental Design 37
3.7 Characterization and Testing procedures 40
3.7.1. Specimens Preparations and Test Machines 40
3.7.2 Mechanical Testing 42
3.7.3 Thermal Properties 46
3.7.4 Physical Properties 48

3.7.5 Fourier-Transform Infrared Spectroscopy Analysis (FTIR) 49

3.8 Data Analysis 50
3.9 Ethical Considerations 51
CHAPTER FOUR 52
RESULT AND DISCUSSION 52
4.1 Introduction 52
4.2 Flax fiber characterization 52
4.2.1 Tensile Properties of Flax Fibers 52
4.2.2 Fourier Transform Infrared Spectroscopy (FTIR) 54
4.2.3 Physical and thermal characterization of flax fiber 55
4.3 Experimental Test Results of the Composites 57
4.3.1 Mechanical Properties 57
4.3.2 Physical Properties 64
4.3.3 Thermal Properties 69
4.3.4 Fourier-Transform Infrared Spectroscopy Analysis of Composite 71

4.4 Comparative Analysis with Literature 82
Reference 34
APPENDIXS 45
Appendix 1 Tensile strength result of Flax fiber 45
Appendix 2: FTIR Result of Flax Fiber 47
Appendix 3: Researcher Laboratory Activities 47
Appendix 4: Summary of experimental test results 34

List of Tables

Table 2.1: Classification of composite materials relevant to the study 9
Table 3.1: Required raw materials 27
Table 3.2: Require equipment and instruments 28
Table 3.3: Printing Parameters Used for 3-D Printing Development 34
Table 3.4: Printing Parameters Used for 3-D Printing Development 36
Table 3.5: Experimental factors and levels 38
Table 3.6: Experimental Run Order Using Taguchi L8 Orthogonal Array 38
Table 3.7: ASTM Standards specifications of specimen for preparations 42
Table 4.1: Testing Conditions 52
Table 4.2: Tensile Strength Test Result of Flax Fiber 53
Table 4.3: Flax Fiber Characterization Test Results 56
Table 4.4: Tensile Strength Test Result of Developed Flax Fiber/PLA Bio-Composite 58
Table 4.5: Flexural strength and modulus test result of the bio-composite 60
Table 4.6: Compressive strength test result of the developed bio-composite 63
Table 4.7: Density test result of the developed flax fiber-reinforced bio-composite 64
Table 4.8: Water absorption test result of the developed bio-composite 66
Table 4.9: Thickness swelling test result of the developed bio-composite 67

List of Figures

Figure 2.1: Classification of natural fibers (Raj et al., 2023) 11
Figure 2.2: Life cycle of biodegradable, NFRCs (Clark, 2019) 12
Figure 3.1: Research Flow Diagram 26
Figure 3.2: Chemicals for Bio-composite development 27
Figure 3.3: Flax crop harvesting in farming 29
Figure 3.4: Water retting of raw flax 30
Figure 3.5: Separation of fiber from flax stem 30
Figure 3.6: Combed and oriented fiber 31
Figure 3.7: Alkaline treatment of fiber 31
Figure 3.8: Drying of fiber and web formation.....33
Figure 3.9: Making nonwoven Mats 33
Figure 3.10: Non-woven development 34
Figure 3.11: 3D printing machine and printed PLA layer 35
Figure 3.12: Under Bio-resin composite product developing.....36
Figure 3.13: Bio-resin composite product developed in different variable factors 37
Figure 3.14: Preparing of standard samples to conduct different laboratory test 41
Figure 3.15: Typical samples for tensile strength 43
Figure 3.16: Typical specimen under tensile strength test.....43
Figure 3.17: Typical representation of bio-composite sample for flexural strength test ...44
Figure 3.18: Typical specimen under flexural strength test (ASTM D790) 44
Figure: 3.19: Typical notched specimen for impact test.....45
Figure 3.20: Impact Teste machine.....45
Figure 3.21: Typical reresentation of bio-composite smples for compressive test.....46
Figure 3.22: Typical specimen on compression machine test 46
Figure 3.23: DSC testing machine 48
Figure 3.24 FTIR testing machine 50
Figure 4.1: Tensile properties of flax fiber 54
Figure 4.2: FTIR graph of flax fiber 55
Figure 4.3: Bio-composite samples after rapture.....58
Figure 4.4: Tensile strength test result of developed bio-composite 59
Figure 4.5: Flexural test specimens after ruptures 60
Figure 4.6: Impact strength test result of the developed bio-composite 61

Figure 4.7: Sample of impact specimen after testing (rupture) 62
Figure 4.8: Sample of compressive test specimen after testing 63
Figure 4.9: Density test result of bio-composite 65
Figure 4.10: Water absorption test result of the developed bio-composite 67
Figure 4.11: Thickness swelling test result of bio-composite.....68
Figure 4.12: Thermogravimetric analysis (TGA) test result of the product 69
Figure 4.13: DSC graph of endothermic and exothermic heating cycle of bio-composite 70
Figure 4.14: FTIR Characterization of PLA/flax bio-composite.....71

Abstract

The global textile and structural material industries are under scrutiny for their reliance on non-renewable, petroleum-based synthetic fibers, which contribute to environmental pollution. This research addresses a critical gap by developing a fully biodegradable, bio-composite using flax fiber and poly lactic acid (PLA). An experimental design employed a Taguchi L8 orthogonal array to examine the effects of flax fiber volume fraction, processing pressure, and fiber PLA content in gm. The flax was processed through water retting and chemical modification to enhance its properties and formed into composite plates using mechanical carding and compression molding. Characterization tests, including tensile, flexural, impact, and thermal profiling, confirmed the composite's high intrinsic properties, such as tensile strength (36.62 MPa) and flexural strength (averaging 57.14 MPa). The optimal configuration yielded a dense structure with minimal internal voids. Thermal analysis revealed notably, affirming the composite's environmental sustainability. The findings highlight the potential for flax fiber/PLA composites as high-performance alternatives to petroleum-based materials, benefiting tech fabrics and eco-friendly furniture production. This research supports circular economy initiatives and aligns with Sustainable Development Goals, promoting the use of local renewable resources in manufacturing.

Keywords: Bio-composites, Flax Fiber, Poly lactic Acid (PLA), Scouring Compression Molding, Sustainable Textiles, Biodegradability.

CHPTER ONE

INTRODUCTION

1.1 Background of the study

In recent decades, growing environmental concerns and the depletion of non-renewable resources have accelerated the demand for sustainable materials across various industries, including textiles (Farhana et al., 2022). The global textile sector, traditionally reliant on petroleum-based synthetic fibers and polymers, contributes significantly to environmental degradation through resource-intensive production, non-biodegradable waste, and greenhouse gas emissions (Biranje et al., 2024). To address these challenges, the development of bio-composites materials composed of natural fibers and bio-based resins that have emerged as a promising solution.

From many natural fibers flax, jute, hemp, kenaf, and sisal are renewable, biodegradable, lightweight, and have good mechanical properties, making them suitable alternatives to synthetic reinforcements like glass and carbon fibers (Shaker et al., 2020). For this study flax fiber, in particular, is one of the most widely used natural fibers due to its high tensile strength, low density, environmental reachability, good thermal insulation, and acoustic damping properties. Its high cellulose content and favorable aspect ratio make it an ideal candidate for reinforcing polymers in structural and semi-structural applications, including textiles (Prabhakaran et al., 2014).

Parallel to the advancement in natural fibers, bio-resins derived from renewable resources such as vegetable oils, starch, and polylactic acid (PLA) have gained significant attention. These resins offer partial or complete biodegradability, reduced carbon footprint, and compatibility with natural fibers (Raj et al., 2023). Polylactic acid, for instance, is thermoplastic aliphatic polyester derived from corn starch or sugarcane and is widely used in sustainable textile applications due to its mechanical performance and biodegradability (Fattahi et al., 2020). Similarly, soy-based and epoxidized vegetable oil resins provide flexibility and environmental benefits, although their mechanical and thermal properties need enhancement for demanding applications (Fakhri et al., 2024).

Bio-composites composed of natural fibers and bio-resins offer a unique blend of mechanical performance and environmental friendliness, making them attractive in automotive, packaging, construction, and textile industries (Carvalho et al., 2024). Within the textile domain, bio-composites are being explored for semi-rigid and functional components such as protective clothing, sportswear inserts, and biodegradable fashion products. However, despite their potential, these materials face challenges including fiber–matrix incompatibility, moisture sensitivity, and thermal limitations (Skosana et al., 2025).

This study seeks to address these gaps by focusing on the development and characterization of an eco-friendly bio-composite using flax fiber and selected bio-resins for construction and furniture applications. The rationale behind choosing flax fiber lies in its superior mechanical properties, availability, and established role in composite development. The research aims to investigate the interaction between treated flax fibers and different types of bio-resins, and to assess the resulting bio-composite in terms of its tensile strength, flexural properties, thermal stability, and biodegradability optimization that are the key parameters for sustainable textile performance.

By integrating material science, textile engineering, and environmental sustainability, this study contributes to the broader objective of reducing the ecological footprint of the textile industry while providing high-performance alternatives to synthetic composites. The outcomes of this research are expected to support the design of innovative textile solutions aligned with circular economy principles and green material standards.

1.2 Statement of Problem

The global textile and composite industries are increasingly facing scrutiny due to their significant environmental impacts, largely stemming from the widespread use of synthetic fibers and petroleum-based resins. These conventional materials, while offering desirable mechanical and thermal properties, are non-renewable, non-biodegradable, and energy-intensive to produce. Their disposal also contributes heavily to environmental pollution and carbon emissions (Farhana et al., 2022; Fattahi et al., 2020). In light of the escalating global demand for environmentally responsible materials, the development of bio-composites that incorporate renewable and biodegradable components has emerged as a critical area of research.

Natural fibers such as flax are particularly attractive in this context due to their biodegradability, renewability, lightweight nature, and reasonably good mechanical strength (Raj et al., 2023). Similarly, bio-resins derived from renewable resources such as polylactic acid (PLA), deoxidized plant oils, and other bio-based polymers offer a sustainable alternative to synthetic resins. However, despite the promise of these materials, their broader adoption in textile applications remains limited due to technical and performance-related challenges. These include poor fiber–matrix interfacial bonding, high moisture sensitivity, inconsistencies in mechanical performance, and insufficient compatibility with textile performance requirements such as flexibility, durability, drapeability, and breathability (Carvalho et al., 2024; Gupta & Thanki, 2024).

Moreover, while bio-composites have gained attention in industries like automotive, construction, furniture, and packaging, significantly less research has been devoted to exploring their potential in textile-related domains. Existing studies often fail to address the specific functional requirements of furniture and construction applications or to assess the environmental performance of these materials throughout their lifecycle. Consequently, there remains a significant research gap in the development and comprehensive characterization of natural fiber-based bio-composites tailored for sustainable textile uses (Guridi et al., 2024).

This study seeks to address this critical gap by focusing on the development, characterization, and evaluation of eco-friendly bio-composite materials using flax fiber and selected bio-resins (PLA). The core problem this research addresses is the absence of scientifically validated, biodegradable, and high-performance bio-composites that simultaneously meet mechanical, thermal, and environmental standards for furniture applications. Furthermore, the study was investigated the effect of fiber surface treatments and different bio-resin systems on composite behavior, aiming to improve interfacial bonding and enhance overall material performance. By doing so, this research contributed to the advancement of sustainable materials in the manufacturing sector and supports global sustainability objectives, including waste reduction, circular economy implementation, and the transition toward climate-neutral manufacturing.

1.3 Objective

1.3.1 General Objective

To develop and characterize an eco-friendly sandwich bio-composite material using flax fiber for sustainable furniture products

1.3.2 Specific objectives

- To identify and prepare appropriate combinations of flax fibers and bio-based resins for the fabrication of sustainable composite materials.
- To evaluate the mechanical, thermal, and physical properties of the fabricated flax fiber-reinforced bio-composites.
- To assess the functional performance and application potential of the bio-composites in textile-related fields.
- To optimize material formulation and processing parameters for enhanced performance and sustainability of flax fiber bio-composites.

1.4 Basic Research Question

- ✓ What are the most suitable combinations of flax fibers and bio-based resins for fabricating environmentally sustainable composite materials for textile applications?
- ✓ How do the mechanical, thermal, and physical properties of the developed flax fiber-reinforced bio-composites compare across different material formulations?
- ✓ To what extent are the developed bio-composite optimization of biodegradability, and what is their overall environmental impact throughout the lifecycle?
- ✓ What is the functional performance of the fabricated bio-composites in terms of textile-related applications such as flexibility, durability, and suitability for wearable or interior use?
- ✓ What are the optimal formulation ratios and processing conditions that maximize the performance, durability, and sustainability of flax fiber bio-composites?

1.5 Significance of the research

This research is crucial for promoting sustainability in the textile sector, aiming to reduce pollution by replacing synthetic fibers and petroleum-based polymers with natural,

biodegradable materials. It expands knowledge on natural fiber-reinforced composites, focusing on flax fiber and bio-resins for furniture applications. The study offers valuable insights for future material development and innovation in fiber science and polymer engineering. It encourages value addition in local fiber supply chains, supports rural economies, and aligns with the goals of developing nations. The research supports the United Nations Sustainable Development Goals by promoting resource-efficient and environmentally sound industrial practices.

1.6 Scope of the Research

The study aims to develop eco-friendly bio-composite materials using flax fiber and bio-resins, with a specific focus on sustainable textiles. The research involves material selection, preparation, composite fabrication, and characterization of mechanical, thermal, and physical properties. The study aims to evaluate the suitability of the composites for various applications in the textile industry, including protective wear, structured textile components, and semi-rigid elements for garments or accessories. The research is conducted at the laboratory scale, with no field testing or external industrial collaborations. Large-scale industrial testing and economic feasibility analysis are recommended for future research. The research is conducted within a defined timeframe and primarily at an academic institution or laboratory setting.

1.8 Operational Definition of Terms

1. **Composite material:** Composite materials combine components with different properties to achieve desired physical, chemical, and mechanical properties. Main constituents include matrices, fibers, and additives, which enhance strength, lightness, electrical resistance, stiffness, and strength (Bhong et al., 2023).
2. **Characterization:** A series of analytical and testing procedures used to evaluate the physical, chemical, mechanical, and thermal properties of the developed bio-composites (AL-Oqla et al., 2023).
3. **Bio-Composite**: A composite material formed by combining natural fibers (e.g., flax) with bio-based resins derived from renewable sources. In this study, bio-composites refer specifically to the materials developed using flax fiber and selected bio-resins for textile-related applications.

4. **Flax Fiber**: A natural cellulose-based fiber extracted from the stem of the flax plant (*Lignum usitatissimum*), used as a reinforcement material in composite development due to its biodegradability, strength, and eco-friendliness (Sathish et al., 2024).
5. **Bio-Resin**: A polymeric matrix derived from biological or renewable resources such as poly lactic acid (PLA), plant oils, or starch. Bio-resins in this research serve as the matrix component that binds with flax fiber to form bio-composites (Akter et al., 2022).
6. **Sustainable Textiles**: Textile materials and products developed with environmental, social, and economic sustainability in mind. In this context, it refers to textiles that incorporate biodegradable and renewable composite materials with minimal environmental impact (Biranje et al., 2024).
7. **Biodegradability**: The ability of the developed bio-composite materials to break down naturally by biological processes over time. This is evaluated through standard testing methods to determine the material's environmental impact (Kaliyannan et al., 2023).
8. **Eco-Friendly**: A term used to describe processes or products that are not harmful to the environment. In this study, it refers to the use of biodegradable, renewable, and low-emission materials in composite development (Skosana et al., 2025).

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review of existing literature relevant to the development and characterization of eco-friendly bio-composites, particularly focusing on flax fiber and bio-resins. The aim is to explore the current understanding, advancements, and gaps in research concerning the use of natural fibers and bio-resins in sustainable textile applications. The chapter is organized into thematic sections covering natural fibers (with an emphasis on flax), bio-resins, bio-composite technologies, and their potential applications in the textile industry. It concludes by identifying knowledge gaps and justifying the need for the present study.

2.2 Composite Materials

Composite materials, also known as composites, are a combination of two or more materials that are combined to create a new material with improved properties (Yao et al., 2019). Engineered materials composed of two or more constituent elements with distinct chemical or physical characteristics are called composite materials. When combined, they produce a material with characteristics that are superior to the individual components. These materials are typically made up of a strong, stiff material called reinforcement and a weaker, flexible material called a matrix. The reinforcement is dispersed throughout the matrix, creating a material that is stronger, lighter, and more durable than either of the individual materials (Gay, 2022).

The key advantage of composite materials is their ability to provide high performance in terms of strength, durability, and weight reduction while enabling material customization for specific applications (Simões, 2024). This flexibility allows engineers and designers to tailor the material properties to meet the exact needs of a project, optimizing performance while minimizing costs. As a result, composite materials are increasingly utilized across various industries, including aerospace, automotive, and construction (Bhong et al., 2023).

2.2.1 Types of Composite Materials

There are several types of composite materials, and from those some of the followings are listed below:

Metal Matrix Composites: These composites consist of a metal reinforcement such as aluminum or titanium embedded in a metal matrix (Ramasamy & Daniel, 2021).

Ceramic Matrix Composites: These composites consist of a ceramic reinforcement such as silicon carbide or alumina embedded in a ceramic matrix (Chawla & Chawla, 2019).

Sandwich Composites: These composites consist of two thin, high-strength facings separated by a low-density core material (Ramnath et al., 2019).

Fiber Reinforced Polymer (FRP) Composites: These composites consist of fiber reinforcement such as carbon, glass, or aramid embedded in a polymer matrix grouped under this class (Rajak et al., 2021). The main types of composite materials relevant to this research are:

a. Polymer Matrix Composites (PMCs)

Polymer matrix composites are made by embedding reinforcing fibers in a polymer-based matrix. They are widely used due to their light weight, corrosion resistance, and good mechanical properties (Oladele et al., 2020). In this study the matrix is a bio-resin (such as polylactic acid (PLA), epoxy derived from plant oils, or other biodegradable polymers), which serves as the continuous phase that binds the fibers and transfers stress (Rajak et al., 2019).

b. Natural Fiber Composites (NFCs)

These are composites in which natural fibers (e.g., flax, hemp, jute, sisal) are used as the reinforcement material instead of synthetic fibers like glass or carbon. For this paper flax fiber is used as the reinforcing agent due to its renewable nature, biodegradability, high specific strength, and availability. It is embedded in a bio-resin matrix to form a fully biodegradable and eco-friendly composite (Maiti et al., 2022).

c. Bio-Composites

Bio-composites are a subclass of natural fiber composites where both the matrix and the reinforcement are derived from renewable biological resources**.** The developed material qualifies as a bio-composite because it uses flax fiber (natural reinforcement) and bio-resins (biodegradable polymer matrix) (Zwawi, 2021). This makes the composite eco-friendly**,** biodegradable, and suitable for sustainable textile applications, such as protective wear, semi-structural clothing parts, and eco-footwear components (Seydibeyoğlu et al., 2023).

d. Green Composites

A green composite is a type of bio-composite in which both the fiber and matrix components are fully biodegradable**.** When both flax fibers and 100% biodegradable resins (like PLA) are used, the resulting material is categorized as a green composite, aligning with circular economy and zero-waste goals (Mitra, 2024).

Table 2.1: Classification of composite materials relevant to the study

Composite Type	Fiber Type	Matrix Type	Relevance to Study
Polymer Matrix Composite	Flax Fiber	Bio-resin	Base structure of the developed material
Natural Fiber Composite	Flax Fiber	Bio or synthetic	Eco-friendly alternative to synthetic fibers
Bio-Composite	Flax Fiber	Bio-resin	Fully bio-based and biodegradable
Green Composite	Flax Fiber	100% Biodegradable	Highest environmental sustainability standard

Source: (Sharma et al., 2019)

2.2.2 Properties of Composite Materials

Composite materials are engineered by combining two or more constituents, typically a reinforcement phase (such as fibers) and a matrix phase (such as a polymer) to achieve superior properties that cannot be obtained by any of the components alone (Rajak et al., 2019). The properties of composite materials largely depend on the nature of the reinforcement and matrix, their volume fractions, orientation, and the quality of the interfacial bonding. These properties can be tailored to specific applications by manipulating these variables, making composites highly versatile and suitable for various industrial sectors, including aerospace, construction, automotive, and textiles (Gan, 2019).

The key properties that define the performance of composite materials include mechanical properties such as tensile strength, flexural strength, impact resistance, and stiffness (Saba et al., 2019). Natural fiber-reinforced composites, such as those developed using flax fiber and bio-resins, have shown promising mechanical characteristics, particularly in terms of specific strength and lightweight structure (Patel et al., 2023). Additionally, thermal stability and moisture absorption are critical considerations, especially for textile applications where composites may be exposed to fluctuating environmental conditions. Enhancements in these properties can be achieved through fiber surface treatments and matrix modification techniques (Skosana et al., 2025).

Another essential property of composite materials, particularly bio-composites, is their environmental compatibility. This includes aspects like biodegradability, recyclability, and life-cycle performance (Akter et al., 2022) . Bio-composites made from renewable resources like flax fibers and biodegradable resins such as PLA or bio-based epoxy offer an eco-friendly alternative to synthetic composites. These materials exhibit not only adequate strength and durability for semi-structural textile applications but also lower environmental impact in terms of carbon footprint and end-of-life disposal (Alsuwait et al., 2022). Understanding these properties is crucial for optimizing bio-composite materials for sustainable textile innovations.

2.3 Natural Fibers

Natural fibers, derived from renewable sources like plants, animals, or minerals, have been used in various applications like textiles, construction, packaging, and composite material development (Akter et al., 2022). These fibers, like flax, jute, hemp, sisal, coir, and kenaf, are considered environmentally sustainable due to their biodegradability, low density, low cost, and reduced energy consumption. Flax fiber is particularly well-suited for reinforcement in bio-composites due to its high tensile strength and modulus. Its natural abundance, ease of cultivation, and compatibility with biodegradable matrices make it a preferred choice for eco-friendly composites (Nair et al., 2023). However, natural fibers have limitations like variability in quality, high moisture absorption, and poor interfacial bonding with hydrophobic polymer matrices (Ali et al., 2018). These challenges can be addressed through fiber treatment methods like alkali treatment, salinization, or acetylation.

2.3.1 Classification of Natural Fibers

Plant, animal, and mineral fibers are the three types of natural fibres that are separated according to their origin. Mineral fibers are naturally occurring minerals, plant fibers are cellulose-based, and animal fibers are primarily proteins (Thapliyal et al., 2023). While plant fibers are abundant and affordable, animal fibers are used in biopolymer composites. Plant fibers are widely used in green composites since they are abundant, don't need animals, and pose no health dangers in comparison to asbestos fibers. Most fibers are modified before being utilized in bio-composites; chemical treatment is the most common technique (Sonali et al., 2023).

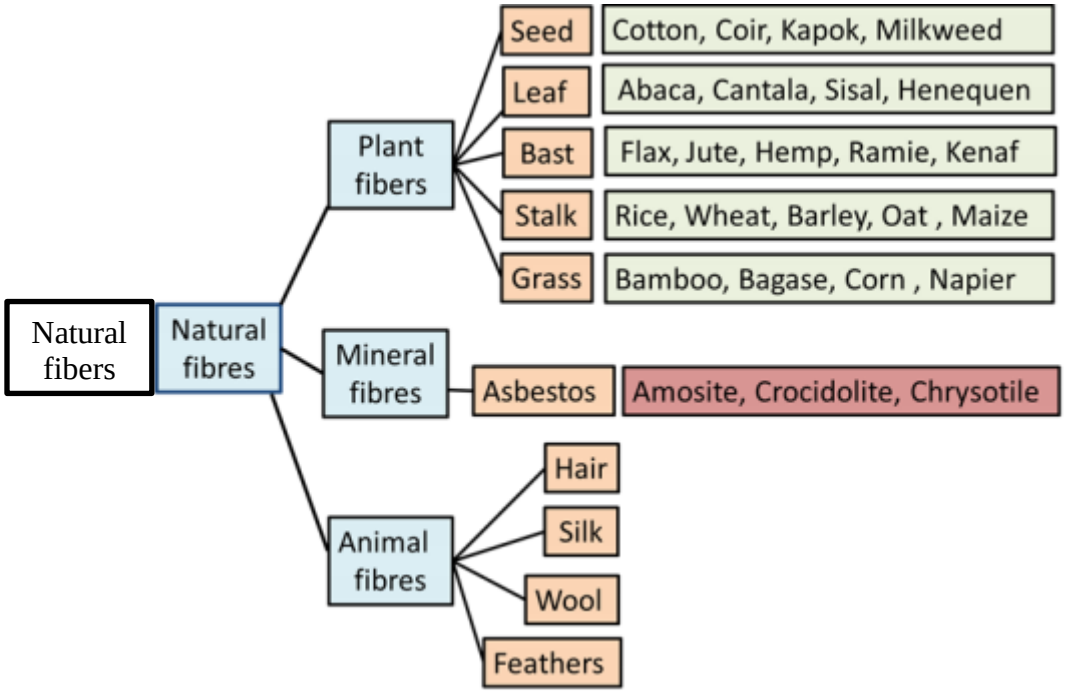


Figure 2.1: Classification of natural fibers (Raj et al., 2023)

2.3.2 Natural Fibers in Composite Development

Natural fibers play a vital role in the development of eco-friendly composite materials, serving as sustainable alternatives to synthetic reinforcements. Natural fibers are increasingly recognized as sustainable and renewable alternatives to synthetic fibers in composite applications (Maiti et al., 2022). Derived from renewable sources and characterized by biodegradability, low density, and cost-effectiveness, natural fibers have attracted significant attention in the fields of automotive, construction, and textiles. Among them, flax fiber stands out due to its high mechanical performance and wide availability (Skosana et al., 2025). In the context of this study, natural fibers particularly flax are investigated due to their renewable nature, biodegradability, and suitable mechanical properties for textile-based composite applications.

Flax, jute, hemp, sisal, and kenaf are examples of natural fibers that have been thoroughly studied and used in composite creation. These fibers are primarily composed of cellulose, hemicellulose, lignin, pectin, and waxes, each contributing to the structural and performance characteristics of the fibers (Ramesh, 2018). Their mechanical performance depends on several factors, including botanical source, growth conditions, extraction method, and processing parameters (Naik & Kumar, 2021).

Flax fiber, in particular, has gained popularity in composite manufacturing due to its relatively high tensile strength, stiffness, and aspect ratio compared to other natural fibers. The specific modulus of flax fiber is comparable to that of glass fiber, making it a strong candidate for use in high-performance bio-composites intended for textile applications (Sanivada et al., 2020).

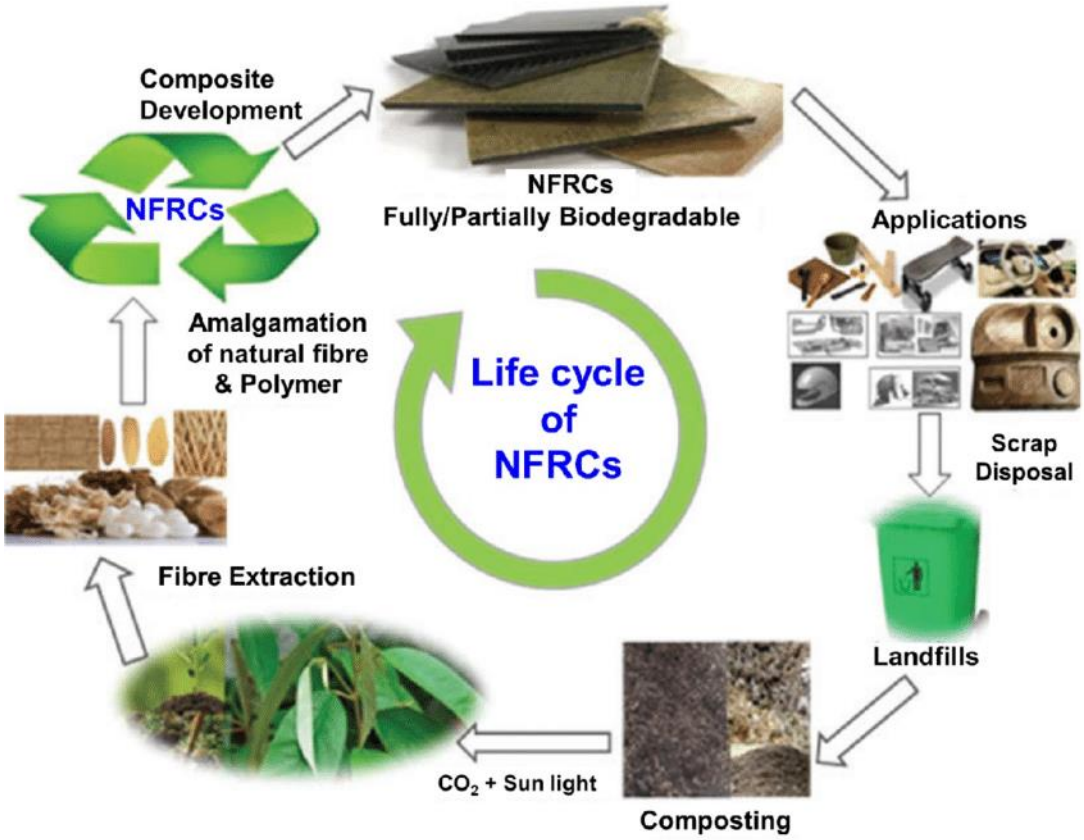


Figure 2.2: Life cycle of biodegradable, NFRCs (Clark, 2019)

Natural fibers offer benefits in composite development, including lightweight, high strength-to-weight ratio, low environmental impact, and compatibility with composting and biodegradation systems (Skosana et al., 2025). However, challenges like poor moisture resistance, variability, and weak interfacial bonding hinder widespread use (Maiti et al., 2022). For this study, the researcher was selected flax fiber not only for its mechanical and ecological benefits but also for its availability and proven performance in previous textile composite studies. It is anticipated that its integration with bio-resins was lead to the development of a high-performance, sustainable composite material suitable for various textile applications.

2.4 Flax Fiber

Flax fiber is one of the most extensively used natural fibers in bio-composites due to its excellent tensile properties, low elongation at break, and favorable specific stiffness and strength. Flax fibers exhibit a tensile strength of up to 1500 MPa and Young's modulus in the range of 50–70 GPa (Sahu & Gupta, 2020). Their crystalline cellulose content enhances their stiffness, while their hollow structure contributes to thermal and acoustic insulation properties. Despite these advantages, the hydrophilic nature of flax fiber can reduce moisture resistance and interfacial bonding with hydrophobic matrices. Alkaline treatment and coupling agents are commonly used to enhance fiber–matrix interactions (Mohammed et al., 2022).

2.4.1 Properties of Flax Fiber

Flax fiber, derived from the Lignum usitatissimum plant, is a versatile material with a unique blend of physical and chemical components, making it ideal for bio-composite applications. Its primary components include cellulose, hemicellulose, and lignin, with minor amounts of pectin, waxes, and moisture (Azzouz, 2021). The fiber's mechanical performance is influenced by its chemical components, which influence its interaction with composite structures. Flax fibers have high tensile strength, a Young's modulus, and moderate elongation at break, making them ideal for reinforcement in bio-composites. They also have a high aspect ratio and specific strength, making them suitable for lightweight, durable composite materials (Moudood et al., 2019). Despite its advantages, flax fiber has limitations, such as its hydrophilic nature, which can lead to dimensional instability and degradation in humid environments. Surface treatments like alkali or silane modification can help address these issues. Despite these challenges, flax fiber's overall property makes it a promising material for sustainable composite development in textiles and beyond (Santhosh et al., 2024).

2.4.2 Surface Treatment of Flax Fiber

Surface treatment of natural fibers like flax is crucial for improving their compatibility with polymer matrices, especially in bio-composite applications. Alkaline treatment, also known as mercerization, removes impurities from the fiber surface, enhancing mechanical interlocking and adhesion with the matrix (McKay et al., 2024). Chemical modifications like

sodium hydroxide acetylation, and maleic anhydride grafting also improve the fiber-matrix interface. These techniques directly influence interfacial bonding and overall performance of flax fiber composites. Effective treatment improves stress transfer between the fiber and matrix, leading to higher tensile strength, flexural strength, and impact resistance (Zwawi, 2021). Poorly treated flax fibers can result in poor dispersion and weak interfacial adhesion, reducing composite integrity and durability (Sanivada et al., 2020). Therefore, optimizing surface treatment is essential for tailoring flax-based bio-composites for high-performance and sustainable textile applications.

2.5 Bio-Resins

Polymeric materials called bio-resins are made from renewable biological sources like cellulose, lignin, plant oils, starches, and other agricultural waste products. Bio-resins are sustainable, biodegradable, and frequently have less of an adverse effect on the environment during the production and disposal stages than traditional petroleum-based resins (Kumar et al., 2021). These resins are increasingly utilized in bio-composite development, especially in applications where environmental considerations and material sustainability are critical, such as in packaging, automotive parts, building materials, and textiles (Carvalho et al., 2024).

Various types of bio-resins have been developed to meet mechanical and processing needs. These consist of soy-based epoxy resins, polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based resins, and thermoplastics and thermosets based on lignin or cellulose (A. Latif et al., 2020). PLA is one of the most studied and widely accessible bio-resins, has good mechanical qualities and biodegradability. However, it is brittle and hydrolysis-sensitive (Sathish et al., 2024). Soy-based resins, particularly soy epoxy resins, have gained attention for their compatibility with natural fibers and improved adhesion performance, making them ideal matrices for fiber-reinforced composites. Bio-resins can be tailored to possess desirable thermal, mechanical, and biodegradation characteristics by modifying their chemical structure or through blending with other biopolymers (Capretti et al., 2023).

The selection of bio-resins plays a significant role in determining the interfacial bonding, thermal stability, mechanical integrity, and biodegradability of the resulting composite. In flax fiber composites, the synergy between the natural fiber and bio-resin enhances the sustainability profile of the material while maintaining adequate performance for targeted applications (Pattnaik et al., 2025). However, some bio-resins may suffer from limitations

such as low thermal resistance or high moisture absorption, which can be addressed through resin modification or hybridization (Bahrami et al., 2020).

2.5.1 Bio-Resins for Sustainable Composites

Bio-resins have emerged as a cornerstone of sustainable composite development due to their renewable origins, biodegradability, and reduced environmental footprint compared to conventional petroleum-based resins (Carvalho et al., 2024). Derived from biological sources such as starch, vegetable oils, lignin, cellulose, and proteins, bio-resins serve as the matrix component in bio-composites, encapsulating natural fibers like flax to form high-performance, eco-friendly materials (Mohanty et al., 2002). The development of bio-resins aligns with global efforts to reduce carbon emissions, dependence on fossil fuels, and waste accumulation, making them especially suitable for sustainable textiles and related applications.

As mentioned above different types of bio-resins have been explored for use in composites, including polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based polymers, soy-based epoxy resins, and lignin-derived thermoplastics (Phiri et al., 2023). Among these, PLA is one of the most widely utilized bio-resins due to its high strength, biodegradability, and compatibility with natural fibers. Soy-based resins, particularly modified epoxies, have shown promise in textile and automotive applications, offering improved adhesion and flexibility (Raj et al., 2023). Starch- and cellulose-based resins, while biodegradable and low-cost, often require chemical or physical modifications to improve water resistance and thermal stability. Because of these developments, bio-resins may be used in a wide range of functional applications, such as wearable fabrics, construction materials, and packaging.

From a sustainability perspective, the use of bio-resins in composite materials addresses multiple challenges such as, reduce environmental impact, support circular economy models, and offer end-of-life degradability (Carvalho et al., 2024). Moreover, when combined with natural fibers such as flax, bio-resins can produce fully bio-based composites that meet mechanical and performance standards while maintaining ecological integrity (Skosana et al., 2025). However, limitations such as lower thermal resistance and mechanical strength compared to synthetic resins remain (McKay et al., 2024). To address these issues, ongoing research focuses on hybrid resins, resin modification, and nanomaterial incorporation to optimize bio-resin properties for advanced applications.

2.5.2 Mechanical and Thermal Properties of Bio-Resins

The mechanical and thermal properties of bio-resins are critical factors influencing their performance as matrix materials in bio-composites. These properties determine the overall strength, stiffness, durability, and heat resistance of the final composite, directly impacting its application potential in structural, packaging, and textile fields (Santulli et al., 2023). While bio-resins are environmentally sustainable, their mechanical and thermal properties must be engineered or enhanced to compete with conventional petroleum-based polymers such as polypropylene and epoxy resins (Sanivada et al., 2020).

In terms of mechanical properties, bio-resins like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) exhibit moderate to high tensile strength (40–70 MPa for PLA) and elastic modulus (2–4 GPa), comparable to some synthetic plastics (Patel et al., 2023). However, they tend to be more brittle and less impact-resistant, which can be mitigated through plasticization or blending with more flexible biopolymers. Soy-based epoxy resins, which are commonly used in bio-composites, offer improved toughness and adhesion when crosslinked properly, making them suitable for natural fiber reinforcement (Rajak et al., 2019). The mechanical bonding between fiber and resin depends significantly on the interfacial adhesion, which is influenced by the chemical compatibility and processing conditions (Prabhakaran et al., 2014).

Bio-resins have lower thermal stability than synthetic materials, making them less suitable for high-temperature environments. However, they can be improved through copolymerization, chemical modification, or inorganic fillers (Gan, 2019). Soy-based and lignin-based bio-resins can be chemically tailored to enhance thermal resistance. Research shows that tailoring molecular structure and blending strategies can enhance performance without compromising biodegradability, particularly in textile composites (Akter et al., 2022).

2.5.3 Environmental and Biodegradation Aspects of Bio-Resins

Bio-resins, derived from renewable biomass like starch, vegetable oils, lignin, and cellulose, offer a significant environmental advantage over petroleum-based resins due to their sustainable sourcing and improved end-of-life options (Raza et al., 2024). They contribute to a lower carbon footprint throughout their lifecycle, reducing dependency on finite fossil fuels and contributing to rural economic development. The lifecycle of bio-resins includes raw material extraction, processing into polymer resins, application in composites, and eventual

degradation or recycling (Fitzgerald et al., 2021). A lot of bio-resins are designed to decompose in composting environments, which lessens pollution in the environment. End-of-life considerations are central to the environmental performance of bio-resins, with some being home-compostable and others requiring industrial composting facilities. Biodegradable bio-resins do not release toxic residues upon degradation, enhancing soil quality and minimizing ecological harm. However, proper waste management infrastructure is necessary to ensure the environmental benefits (Liyakat, 2024).

2.5.4 PLA Features

Poly lactic acid is an essential polymeric material for biomedical applications due to its mechanical strength, biocompatibility, biodegradability, and process ability. By mixing PLA with other polymers, it is feasible to improve associated characteristics or produce special PLA polymers or blends for use in certain applications (Ebrahimi & Ramezani Dana, 2022).

2.6 Bio-Composites

Natural fibers are reinforced within a biodegradable or bio-based resin matrix to create bio-composites. They offer mechanical performance, lightweight qualities, and environmental advantages by combining the best features of both parts (Madhu et al., 2022). Applications include consumer goods, construction, automotive interiors, packaging, and increasingly textiles. For the production of semi-rigid components like protective panels, biodegradable fashion items, and functional apparel, bio-composites are particularly appealing in the textile industry (Azzouz, 2021). Their application is in line with life-cycle assessment (LCA) principles and the objectives of the circular economy, which are to lessen environmental burdens. Utilizing bio-resins and natural fibers helps reduce end-of-life pollution, emissions, and the use of fossil fuels (Sahu & Gupta, 2020).

2.6.1 Types of Bio-Composites

Bio-composites are composite materials made from natural fibers and a biodegradable or bio-based matrix, designed to provide mechanical performance while preserving environmental sustainability (Zwawi, 2021). These materials are used in various sectors like textiles, automotive, packaging, and construction. Natural fiber-reinforced bio-composites, made from plant-based fibers and bio-resins, are renewable and biodegradable, making them suitable for green product development (Zwawi, 2021). Hybrid composites, which combine natural and

synthetic fibers or mix bio-based and synthetic matrices, balance performance and sustainability by introducing synthetic components to improve mechanical strength, impact resistance, or thermal performance. These composites are particularly useful in applications where a balance between eco-friendliness and industrial performance is critical (Santhosh et al., 2024).

2.6.2 PLA based composites

PLA-based composites were a useful substitute for synthetic materials that are neither biodegradable nor renewable. Cellulose and natural fibers can be used to reinforce them. The most current studies on the synthesis, viability, processing, characterization, applications, and potential of PLA composites were covered in this review paper (Ahmad et al., 2024; Ramezani Dana & Ebrahimi, 2023).

2.6.3 Composition of Bio-Composite Materials

Environmentally friendly composites derived from biological or renewable resources are known as bio-composite materials. They consist of a reinforcement phase, typically a natural fiber, and a bio-based matrix or binder (Maiti et al., 2022). The interaction between these components determines the structural, thermal, and ecological characteristics of the final composite product. Bio-composites are used in industries like textiles due to their sustainability and biodegradability. Flax fibre is selected because of its exceptional tensile strength and stiffness. It is mostly made up of cellulose, hemicellulose, lignin, and pectin (Bhat et al., 2021). Bio-composites are also made from bio-resins like poly lactic acid, polyhydroxyalkanoates, starch-based polymers, and plant-oil-derived epoxies. The interaction between flax fibers and a biodegradable matrix is crucial for achieving structurally sound and environmentally friendly composites. The ratio of fiber to matrix significantly influences the mechanical and physical performance of bio-composites (Stanescu & Ciuca, 2025).

2.6.4 Manufacturing Techniques

Bio-composite fabrication involves various manufacturing techniques, including hand lay-up, compression molding, and resin transfer molding (RTM). Hand lay-up is the simplest and most economical method, involving manual arrangement of flax fibers and application of bio-resin (Phiri et al., 2024). However, it can be labor-intensive and may result in inconsistent quality. Compression molding is more industrially scalable and suitable for thermosetting and

thermoplastic bio-resins (Alsuwait et al., 2022). RTM is a closed-mold method that produces high-quality composites with a low void content and a superior surface finish by impregnating dried flax fiber preforms with liquid bio-resin. Factors influencing the processing and quality of bio-composites include fiber treatment, moisture content, resin viscosity, temperature, curing time, and pressure. Improper control can lead to defects, compromising the composite's mechanical performance and durability. Therefore, process optimization is crucial for achieving high-quality, eco-friendly textile composites (Chen, 2021).

2.6.5 Key Properties of Bio-Composites

Bio-composites' performance is influenced by their mechanical, thermal, and moisture-related properties, which are crucial for their suitability in textiles. These properties include reinforcement (e.g., flax fiber) and matrix (e.g., bio-resin), processing methods, fiber orientation, and interfacial bonding (Sahu & Gupta, 2020). Mechanical properties like tensile strength, flexural strength, and impact resistance are essential indicators of load-bearing capacity and structural integrity. Chemical treatments like alkali can enhance these properties (Yang et al., 2024). Thermal properties, such as Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC), assess the composite's stability and behavior under temperature variations (Natali et al., 2022). TGA provides insights into degradation temperatures and thermal stability, while DSC analysis helps identify glass transition temperature (Tg) and melting points. Moisture absorption and dimensional stability are critical challenges in bio-composites, especially in humid or moisture-rich environments like textiles. Surface treatments, matrix selection, and hybridization strategies are employed to mitigate these issues. Studies show that using moisture-resistant bio-resins or surface modifications can significantly reduce water uptake and enhance long-term performance (Capretti et al., 2024).

2.7 Applications of Natural Fiber Bio-Composites in Textiles

Natural fiber bio-composites (NFBCs) are increasingly applied in technical textiles, industrial clothing, sportswear, insulation materials, and smart garments. Their benefits include biodegradability, lower carbon footprint, and adaptability for various textile functions such as UV protection, moisture control, and mechanical support (Anamika et al., 2021). Flax fiber composites have been explored for use in helmet linings, orthopedic supports, and eco-

friendly luggage. In fashion, NFBCs offer opportunities for innovation in sustainable apparel design (Kumari et al., 2024). Despite these potentials, challenges in large-scale manufacturing, durability, and consumer acceptance hinder their widespread textile integration. Innovative solutions like hybrid composites, improved fiber treatments, and smart textile integration are being researched to enhance the performance and appeal of NFBCs (Thapliyal et al., 2023).

2.7.1 Natural fiber reinforced composites

The term Natural Fiber Reinforced Composites (NFRCs) refers to the class of composite material formed through the combination of natural fibers with polymeric matrix to develop light-weighted and sustainable composite materials. In this material system, the natural fiber serves as the reinforcing material, whereas polymeric matrix acts as the matrix material that holds the fibers in place and transmits applied stresses among fibers. The source of natural fibers is biological in nature and includes plant, animal, and mineral sources, with plant-based natural fibers being more common in engineering/textile applications (Arunprasath et al., 2025).

Due to rising environmental consciousness, scarcity of fossil fuels, and sustainability requirements in various industrial sectors such as textiles, automotive, construction, packaging, aerospace, and biomedical engineering, NFRCs have attracted widespread attention (Kamarudin et al., 2022).

2.7.2 Technical Textiles and Functional Uses

One of the most promising areas for natural fiber bio-composites is in technical textiles, where performance and function are prioritized over fashion. Applications include protective clothing, automotive interiors, footwear components, and interior design textiles (Thapliyal et al., 2023). In protective clothing, bio-composites can offer structural reinforcement, puncture resistance, and thermal insulation, especially when designed with layered or sandwich structures. Flax fiber composites have shown potential in producing lightweight and breathable armor panels, gloves, and knee protection elements due to their tensile strength and flexibility (Carvalho et al., 2024).

In the automotive sector, flax bio-composites are already used for door panels, dashboard trims, and seat backs, especially in European car brands, due to their low density, renewable origin, and acoustic insulation properties (Jabu et al., 2024). The footwear industry also

leverages bio-composites in midsoles and structural inserts, where rigidity and biodegradability are desired. In interior design, these materials are suitable for acoustic panels, wall coverings, and furniture fabrics where both aesthetics and environmental impact matter (Ghosh et al., 2024).

These functional textiles benefit from the mechanical reinforcement, aesthetic natural fiber textures, and biodegradability of the composites, making them appealing for both industry and environmentally conscious consumers (El Messiry, 2021).

2.7.3 Comparative Analysis with Traditional Textile Materials

When compared to traditional textile materials such as synthetic fibers (e.g., polyester, nylon) and non-reinforced fabrics, natural fiber bio-composites show a unique balance of performance, cost-effectiveness, environmental impact, and durability (Aisyah et al., 2021). While traditional synthetic textiles may outperform bio-composites in some extreme mechanical or chemical resistance scenarios, they come at the cost of non-renewable sourcing, high carbon footprint, and end-of-life disposal problems (Talabi et al., 2024).

Bio-composites made from flax and bio-resins typically provide comparable tensile and flexural strength, with added benefits of light weight, biodegradability, and reduced environmental footprint (Carvalho et al., 2024). Their cost is often competitive due to the abundant availability of flax in regions such as Europe, Africa, and Asia, and the increasing scalability of bio-resin production. Moreover, the lower energy requirements in the production process and absence of toxic by-products further strengthen their ecological credentials (Fragassa et al., 2024).

However, bio-composites face challenges such as moisture sensitivity, inconsistent fiber quality, and limited chemical resistance, which are currently under extensive research and technological improvement (Pawłosik et al., 2025). When viewed holistically, natural fiber bio-composites represent a strong candidate for replacing conventional textile materials in applications where moderate-to-high performance and sustainability are both required (Bhat et al., 2021).

2.8 Challenges and Limitations

Natural fiber bio-composites, particularly those using flax fiber and bio-resins, face numerous technical and economic challenges. Moisture absorption due to their hydrophilic nature can cause dimensional instability, reduced mechanical properties, and fungal growth (Kaliyannan

et al., 2023). Stress transmission and composite performance are limited by poor interfacial adhesion between the fiber and matrix. Natural fibers degrade thermally at lower temperatures than synthetic alternatives, restricting processing options (Akter et al., 2022). Standardization in testing methods, quality control, and lack of mass production infrastructure also hinder industrial scaling. The high cost of bio-resins and variability in fiber supply contribute to inconsistent material performance and higher product prices (Patel et al., 2023).

Inconsistencies in natural fibers, such as flax, can result in non-uniform mechanical properties and compromise interfacial bonding with hydrophobic bio-resins. Poor interfacial adhesion between untreated flax fibers and polymer matrices adds complexity, cost, and environmental considerations to the production process (Cihan, 2020). Processing techniques like hand lay-up or compression molding require careful control of temperature, pressure, and fiber alignment (Clark, 2019). Bio-resins, while renewable and locally available, are relatively expensive and have less mature supply chains than conventional petrochemical-based resins. Standardization and testing protocols also have limitations, as natural fiber bio-composites lack universally accepted benchmarks and lifecycle analysis methods (A. Latif et al., 2020).

In this study, while flax fiber and bio-resin composites hold substantial promise for sustainable textile innovation, overcoming this material, processing, and systemic limitations is essential for broader adoption and commercialization.

2.9 Research Gaps and Future Trends

The scholar written by Pawłosik et al. (2025) stated that Even though the growing interest in sustainable materials, significant research gaps remain in the effective development and application of flax fiber-reinforced bio-resins specifically tailored for textile use. Current research has largely concentrated on structural and automotive applications, leaving textile-specific requirements, such as flexibility, drapability, breathability, and comfort underexplore (Fitzgerald et al., 2021). According to Baley et al. (2020) flax fiber is widely valued for its high mechanical strength, renewability, and biodegradability, inconsistencies in fiber quality due to agricultural and processing variables introduce variation in composite performance, that didn’t studied in agricultural stage. A persistent challenge lies in the incompatibility between the hydrophilic nature of flax fibers and the hydrophobicity of most bio-resins.

While chemical treatments like acetylation, and alkaline (NaOH) have been suggested to enhance fiber-matrix adhesion, thorough, standardized studies assessing their efficacy in the context of textile-relevant composites are lacking(Olonisakin et al., 2022). Furthermore, while a wide variety of bio-resins that including PLA, soy-based epoxy, and starch blends have been individually studied, comparative studies that explore their interaction with treated flax fibers under textile-specific mechanical and environmental conditions are scarce (Capretti et al., 2023).

Environmental performance assessments also tend to focus narrowly on biodegradability, overlooking more holistic life cycle perspectives such as carbon footprint, resource use, and recyclability in real-world textile scenarios (Tassinari, 2023). Existing biodegradability tests are primarily lab-based and do not accounts for stressors such as moisture fluctuations, temperature changes, or mechanical wear that occur during actual textile use. This results in an incomplete understanding of the long-term durability and environmental behavior of flax-based composites (Highmoore et al., 2024).

In terms of composite architecture, most studies have examined short fiber-reinforced composites, while the potential of woven or nonwoven flax structures for enhanced performance in flexible textile forms remains underexplored (Hasan et al., 2021). Moreover, standardized testing methods for textile-specific properties like tear strength, wear resistance, and hand feel are lacking. Without aligning testing protocols to textile industry norms, the scalability and industrial adoption of such eco-composites remain limited (Saha et al., 2025).

According to Carvalho et al. (2024) the economic and environmental sustainability of bio-resins is a concern, as first-generation bio-resins often come from food-based feedstocks and require high energy input during processing. Third-generation bio-resins sourced from non-food biomass, algae, or industrial waste are needed to reduce costs and environmental impact (Capretti et al., 2023). Smart functionalities like thermal regulation, antimicrobial behavior, and conductivity are still being explored in synthetic textiles. The transition from lab-scale innovation to industry-scale textile product development is a critical gap, with a lack of research linking composite development with existing textile manufacturing techniques and product performance testing (Norkhairunnisa et al., 2024). Challenges include poor interfacial bonding between hydrophilic natural fibers and hydrophobic bio-resins, inconsistent fiber quality, insufficient textile-specific performance evaluations, and limited environmental lifecycle assessments. Future research should focus on enhancing fiber-matrix

interfacial adhesion through advanced, cost-effective, and environmentally safe surface treatments (Sankar Lal et al., 2023).

Addressed these research gap was significantly advance the development and practical application of eco-friendly textile composites, supporting a sustainable transition in the global textile industry.

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Introduction

By outlining the methodical processes used in the selection of the research design, material preparation, composite sample production, and property assessment, this chapter explains the research methodology used to accomplish the study's goals. The methodology also includes the experimental design, material treatments, composite manufacturing techniques, and testing protocols for mechanical, thermal, physical, and environmental properties. The chapter aims to provide a clear and replicable framework for the development and analysis of bio-composites intended for sustainable textile applications, ensuring the reliability and validity of the research findings.

3.2 Research Design

This study was adopted an experimental research design to develop and evaluate bio-composite materials using flax fibers and bio-resins (PLA). The research was involved material selection, preparation, processing of composites, and laboratory testing to characterize physical, mechanical, thermal, and biodegradation properties. This approach enables a systematic investigation of the effect of varying compositions and treatments on the performance of the developed eco-friendly composites.

The researcher follow research flow diagram as shown in figure 3.1 below to presents a step-by-step overview of the experimental process followed in the study. It begins with the collection of raw flax and the identification of its stem parts**,** followed by alkaline treatment using NaOH to modify the fiber surface. The treated flax undergoes fiber extraction and non-woven preparation**.** Next, the mold is prepared**,** and Polylactic Acid (PLA) is selected as the bio-resin for composite fabrication. This leads to the production of the bio-composite**,** from which test specimens are prepared. Finally, various tests were conducted mechanical (tensile strength, flexural rigidity, impact resistance)**,** thermal (stability, transitions)**,** and physical (density, moisture absorption) to evaluate the material properties. The processes were concluded with results analysis and check the pre-requirements settled in objective achieved.

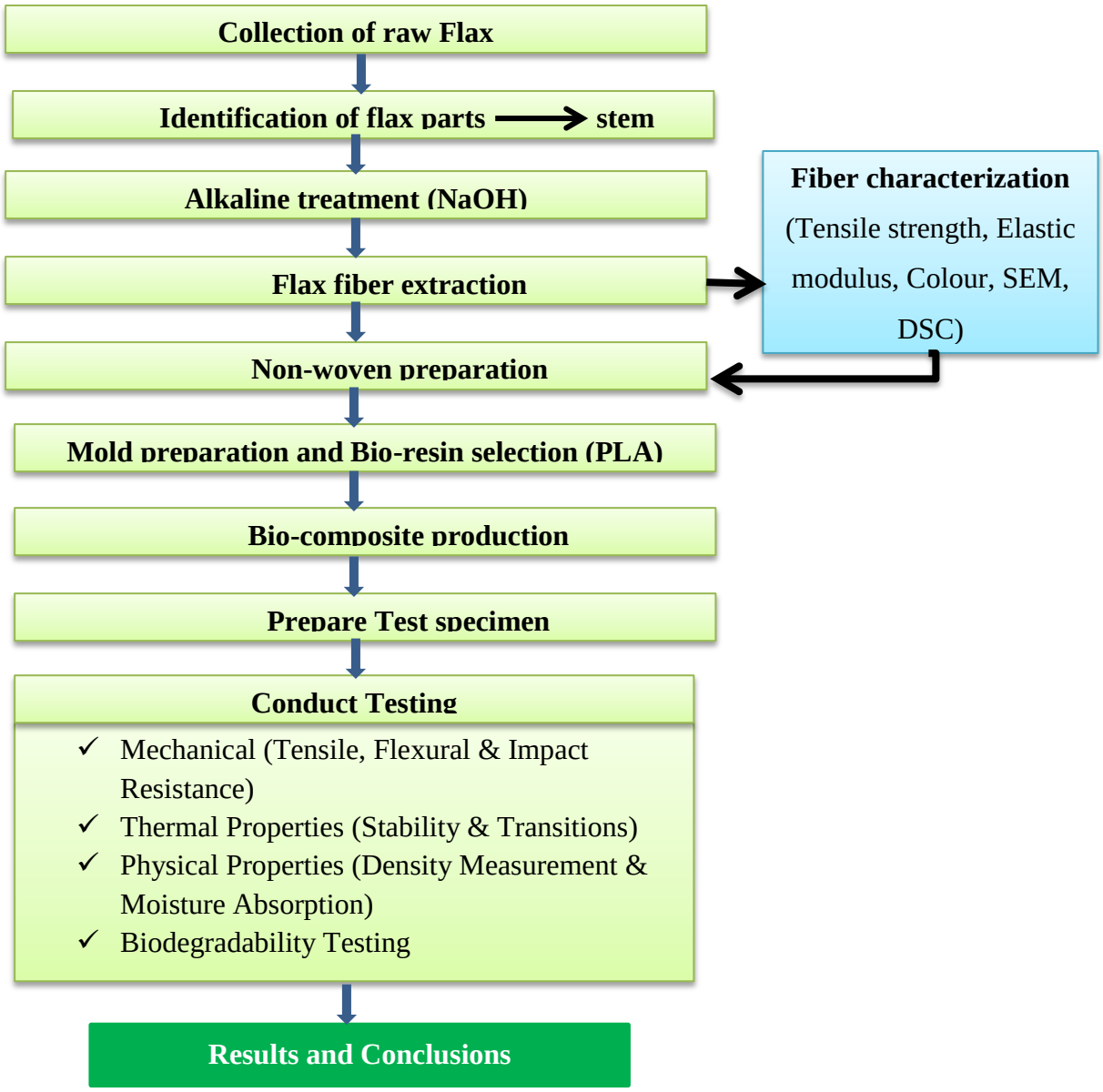


Figure 3.1: Research Flow Diagram

3.3 Materials and Equipment

3.3.1 Raw Materials

Materials are needed to create a PLA/flax eco-friendly bio-composite with improved bio-degradability, mechanical and thermal characteristics. Flax fibers, poly lactic acid (PLA) pellet sheet, sodium hydroxide, epoxy, and hardener were used to develop this product. The raw materials used and detailed description for this study was listed in the following table 3.1 bellow.

The table 3.1 below interprets the required materials used in the stud which is flax fiber as a reinforcement material and various bio-resins (PLA) for the composite matrix. Surface

treatment with reagents like NaOH, acetic anhydride, and improved bonding between the fibers and bio-resin matrix, enhancing the mechanical and thermal properties of the eco-friendly composite material.



Figure 3.2: Chemicals for Bio-composite development

Table 3.1: Required raw materials

Raw Material	Description
Flax Fiber	Long or short fibers (scutched or hackled); Source: Locally harvested or commercially available
Polylactic Acid (PLA)	Bio-resin for composite matrix and 3D printing
Hardener/Curing Agent	To initiate and complete resin curing process
Epoxy resin	Binding Matrix
Sodium Hydroxide (NaOH)	For alkaline treatment of flax fibers
Acetic Anhydride	Used in acetylation of fibers
Ethanol or Distilled Water	Used for washing and dilution
Acetic Acid or Diluted HCl	Neutralizing agent post-treatment

3.3.2 Equipment and Instruments

The equipment and instruments essential for the study include flax fiber extraction, treatment, composite manufacturing tools such as mold, 3D printing tool, hot press/compression molding machine for forming composite plates, and others that details stated in the table 3.2 below.

Table 3.2: Require equipment and instruments

Equipment/Instruments	Purposes/Uses
Hot Press/Compression Molding Machine	Fabricating composite plates
Stirring rods and mixing containers	For combining chemicals and resin
Mold Frames or Plates	Shaping the composite layers
Vacuum Pump/Degassing Unit	Removing air bubbles from resin
Beakers	For chemical preparation
Digital Weighing Scale	For accurate measurement of materials
Mechanical or Magnetic Stirrer	To maintain uniform chemical solutions
Oven (Hot Air)	Drying treated fibers
Desiccator	Cooling and storing dried fibers
Universal Testing Machine (UTM)	Tensile, flexural, and impact tests
Thermogravimetric Analyzer (TGA)	Thermal degradation analysis
Differential Scanning Calorimeter (DSC)	Thermal transitions
Fourier Transform Infrared Spectroscopy	Chemical structure analysis
Scanning Electron Microscope (SEM)	Examining the fracture morphology and fiber surface
Moisture Absorption Testing Chamber	Evaluating water uptake behavior
Digital Vernier Caliper or Micrometer	Dimensional measurements
Laboratory Safety Gear	Gloves, goggles, lab coat
Fume Hood	Safe handling of volatile chemicals
Fire Extinguisher & First Aid Kit	Basic lab safety

3.4 Research Variable

In this study, the research variables are categorized into dependent and independent variables to systematically investigate the development and performance of eco-friendly bio-composites. The selection and control of these variables are essential to ensure a consistent and valid experimental process and to accurately assess how changes in raw materials and processing conditions affect the final properties of the composites.

3.4.1 Dependent Variables

The dependent variables in this research are the mechanical, thermal, and physical properties of the fabricated bio-composites. These include tensile strength, flexural strength, impact

resistance, thermal stability (from TGA analysis), thermal transition temperatures (from DSC analysis), density, and moisture absorption. These variables are directly influenced by the type of bio-resin used, the fiber surface treatment, and the overall composite fabrication process. The primary goal is to measure how these properties change in response to the variations in the independent variables.

3.4.2 Independent Variables

The independent variables include the content or type of bio-resin (PLA, soy-based epoxy, and starch-based resin), fiber treatment method (untreated), and fiber-to-resin ratio. These factors are manipulated during the fabrication process to observe their influence on the composite's performance. The variations in resin chemistry and fiber treatment are expected to impact the fiber–matrix adhesion, composite homogeneity, and overall material behavior under mechanical and environmental conditions.

3.5 Sample Preparation

In this paper the researcher prepared four main products, i.e., fiber extraction, web formation, nonwoven preparation, and finally composite development as explain in the following detail subheadings. The raw flax was collected from farming area and identifies the steam part.



Figure 3.3: Flax crop harvesting in farming

3.5.1 Fiber preparation and Treatment

The process of incorporating flax fibers into a bio-resin matrix involved several surface treatment steps. These included manual cleaning, immersing into container water for 10 -15 days with changing of water every three day, alkaline treatment, acetylation treatment, combing, web formation, and non-woven production.

In this study the researcher was undergo alkaline treatment using of flax fibers using 5% NaOH solution to remove lignin and hemicellulose and enhance fiber-matrix adhesion. Other fibers may be modified using acetylation for comparison.



Figure 3.4: Water retting of raw flax

As shown in the figure 3.3 the raw flax was immersed in cold water for 12 consecutive days with changing of water every three day to extract flax fiber.



Figure 3.5: Separation of fiber from flax stem

After flax fiber was ready for extraction the researcher undergoes separation of fibers from flax stem and treated with sodium hydroxide (NaOH) to increase fiber strength, whiteness and to remove lignin celluloses and pectin.



Figure 3.6: Combed and oriented fiber

Fibers for better aligned combing were conducted as shown in figure 3.5, where their alignment is done in one direction. Through combing, any entanglements and contaminants present in the fiber are removed. The alignment of fibers is important since previous studies have shown that combing contributes to proper fiber alignment and distribution, which is essential in the performance of fiber reinforced composites (Ruan et al., 2025).



Figure 3.7: Alkaline treatment of fiber

Figure 3.6 shows the process of alkali treatment of flax fibers, wherein soaking the fibers in an aqueous solution of sodium hydroxide (NaOH) at high temperatures makes the removal of contaminants, such as waxes and lignin, easier. This not only improves fiber roughness but also allows for the exposure of more cellulose content for better interaction between the fibers and matrix. It also makes available hydroxyl groups that can be used to chemically modify the fibers further for reinforcement purposes. The formation of foam is an indication that the process is going well.

3.5.2 Flax fiber characterization

Flax fibers obtained through extraction processes were characterized in order to analyze their properties as potential reinforcement materials for the manufacture of green and sustainable bio-composites. Different physical, chemical, mechanical, morphological, and thermal characterization techniques were adopted in order to conduct a thorough analysis of the properties of the fibers. The researcher conducted physical characterization involved the determination of fiber length, diameter, density, and moisture content of the fibers. This analysis is very important since the length and diameter of the fibers have a great impact on the performance of fibers in the composite structure (Capretti et al., 2023).

The mechanical characterization of the flax fibers was performed by utilizing the Universal Testing Machine (UTM) to determine their tensile strength, Young's modulus, and elongation behavior. These tests are necessary to determine the fiber's capability in carrying load and stress within the bio-composites. Moreover, the effect of chemical treatment was determined to see the cleanliness of the fibers as well as the bonding characteristics with other compounds.

Moreover, TGA (Thermogravimetric Analysis) and DSC (Differential Scanning Calorimeter) techniques were used in analyzing the thermal characteristics of the flax fibers including their thermal stability, degradation pattern, and transition temperature. The process is very important in analyzing these fibers so that their best application in the production of bio-composites can be determined.

FTIR (Fourier Transform Infrared Spectroscopy) spectra of the analyzed flax fiber sample (upper spectrum) compared with a standard microcrystalline cellulose reference (lower spectrum) from the spectral library was conducted. The FTIR matching software compares both spectra and shows a high matching score (884), to indicate similarity between the tested flax fiber and cellulose-rich material.



Figure 3.8: Drying of fiber and web formation

3.5.3 Making Nonwoven Mats

Using a mechanical carding machine the web and non-woven preparation method separated fibers into individual strands. Three kinds of webs are produced: hybrid, cross, and parallel. Randomly placed webs have reduced tensile and tear strengths, but parallel-lay webs have superior mechanical qualities. For fabric integrity, cross-laid webs are combined to create multi-layered webs. Figure 3.8 below illustrates the flowing micro carding procedure.



Figure 3.9: Making nonwoven Mats

3.5.4 Non-woven development

After web formation non-woven development was conducted. This mat made up of natural fibers from flax for composite manufacturing involved the process of mechanical web

formation and bonding of the fibers. These flax fibers were extracted, processed, washed, dried, and mechanically laid in random order to create the web by carding process. Bio-based binding agents help in increasing fiber integrity and cohesion. Further, PLA bio-resin was added along with the mat by compressive molding method, giving flexibility and sustainability to the textile.



Figure 3.10: Non-woven development

3.5.5 3D Printing Development Procedure

This bio-composite sample was created utilizing FDM technology. It is ideal for processing thermoplastic polymers, including PLA, which is well-known for being easily biodegradable and having minimal shrinkage during processing. In this case, the bio-composite specimen was modeled on CAD and sized to precise dimensions (100 mm x 250 mm x 0.8 mm). It was then exported as an STL file and sliced in Ultimaker Cura or similar slicer programs to produce G-code to be printed on a 3D printer.

Table 3.3: Printing Parameters Used for 3-D Printing Development

Parameter	Specification
Printing Technology	Fused Deposition Modeling (FDM)
Filament Type	White PLA
Material Thickness	0.8 mm
Material Dimensions	100 mm × 250 mm
Nozzle Temperature	220°C
Bed Temperature	50°C
Layer Height	0.2 mm
Number of Layers	Approximately 4
File Format	STL / G-code
Slicing Software	Cura / PrusaSlicer
Cooling Method	Room temperature

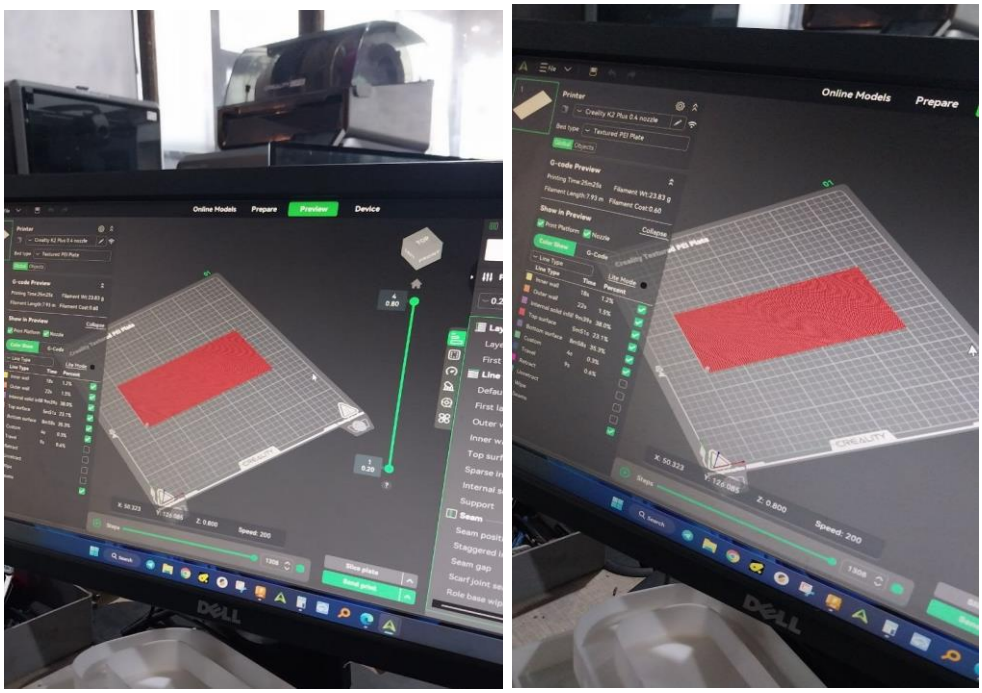


Figure 1.11: 3D printing machine and printed PLA layer

Preparation of the printer for use included cleaning and leveling the print bed for maximum adhesion. Standard diameter white PLA filament was placed into the printer, where the nozzle temperature was set at 220°C while the bed was heated to 50°C to reduce warping effects. The sample was printed with a layer height of 0.2 mm to produce approximately four layers.

PLA was extruded layer by layer based on the programmed path until the desired dimension was obtained. The printed sample was allowed to cool to room temperature to prevent any form of deformation. Finally, quality assurance was carried out through visual inspections and measuring of the sample's dimensions and layer adhesion.

Table 3.4: Printing Parameters Used for 3-D Printing Development

Parameter	Specification
Printing Technology	Fused Deposition Modeling (FDM)
Filament Type	White PLA
Material Thickness	0.8 mm
Material Dimensions	100 mm × 250 mm
Nozzle Temperature	220°C
Bed Temperature	50°C
Layer Height	0.2 mm
Number of Layers	Approximately 4
File Format	STL / G-code
Slicing Software	Cura / Prusa Slicer
Cooling Method	Room temperature

3.5.6 Composite Development

The researcher developed composite different samples using compression molding using the pre-determined factors as mentioned in the table 3.5 below. Moreover composite panels were fabricated using compression molding and bio-resins (Polylactic acid). Nonwovens layered with PLA and hardener, coupling agent uniformly in mold frames, impregnated and pressed with 3-D printing layers in different load as mentioned in the variable factors. The assembly was heated and molded in a hot press machine, ensuring complete curing and bonding. The composites were post-cured in an oven for 2 hours. Different formulations were created by varying fiber content (10%, 20%, 30%, 40%, 60% by weight), resin type and proportion, treated vs. untreated flax fibers, number of layers and thickens of 3-D printing. Composite plates were cut into standard sizes according to ASTM/ISO test specifications.



Figure 3.12: Under Bio-resin composite product developing

The process used to make the bio-resin composite, which uses natural fiber reinforcement, is illustrated in Figure 3.12. The process can be divided into three main stages, including Mold Preparation where the mold is set up and fabric reinforcements are prepared; Fiber Placement and Orientation where the fiber is laid out and orientated correctly; and Matrix Wet-Out and Consolidation where bio-resin is used to wet-out the fiber.

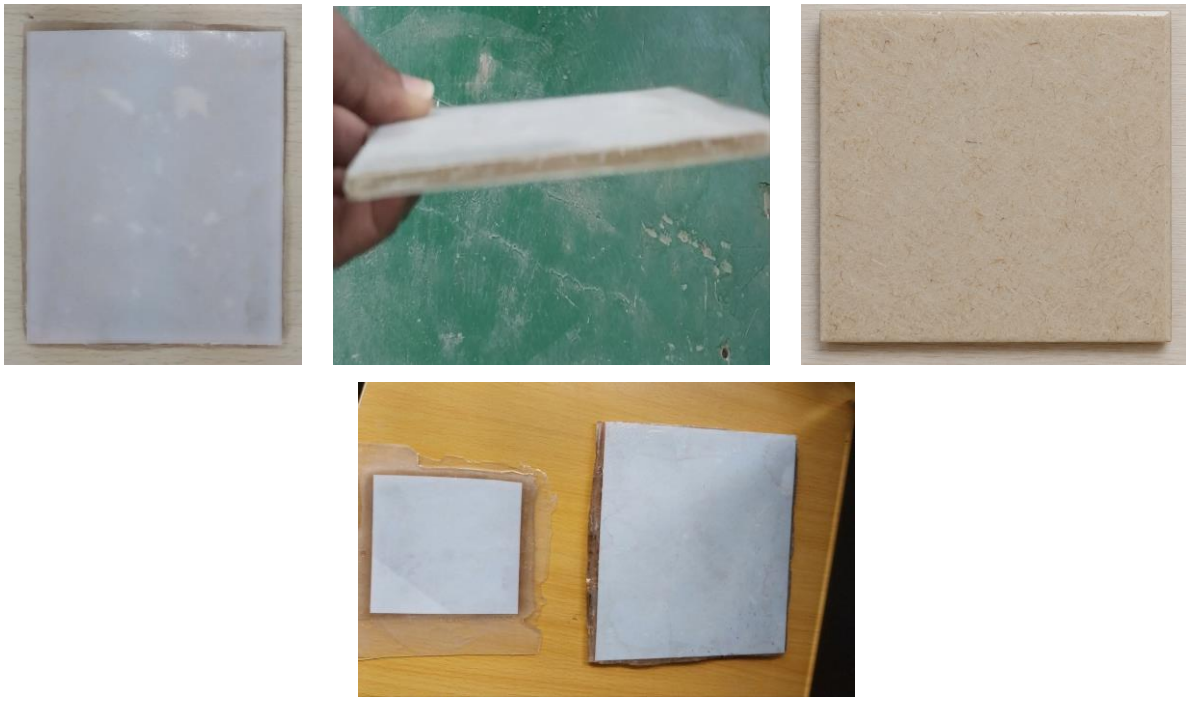


Figure 3.13: Bio-resin composite product developed in different variable factors

3.6 Experimental Design

The study aims to develop a sustainable, high-performance textile material by evaluating the performance of bio-composites based on different raw material combinations and treatment processes. A factorial design method used to assess multiple combinations of fiber treatments and bio-resin types. Composite specimens prepared using compression molding techniques, and mechanical, thermal, and physical tests were conducted according to ASTM standards. The design allows for a robust comparison of independent variables influencing the performance characteristics.

Table 3.5: Experimental factors and levels

Factor	Factors	Min	Max
A	Flax fiber content (%)	20	60
B	Processing conditions (pressure (MPa))	4	10
C	PLA Content (gm.)	60	100

Table 3.6: Experimental Run Order Using Taguchi L8 Orthogonal Array

Run	Flax Fiber Content (%)	Processing Pressure (MPa)	PLA Content (gms)	Mechanical property				Physical properties			Thermal property	
				Rt	Ri	Rf	Rc	Rd	Ra	Rts	TGA	DSC
1	20	4	60									
2	20	4	100									
3	20	10	60									
4	20	10	100									
5	60	4	60									
6	60	4	100									
7	60	10	60									
8	60	10	100									

The researcher conducts different run samples with three factors and eight experimental runs by varying each factors concentration as shown in the table 3.6 above. Mainly three responses were observed mechanical properties (tensile strength (Rt), impact strength (Ri), flexural strength (Rf), compressive strength (rc), physical properties (density (Rd), Water absorption (Ra), thickness swelling (Rts) and thermal properties (differential scanning calorimeter (DSC), and thermo gravimetric analysis (TGA).

Taguchi Experimental Design

The Taguchi experimental design adopted for this study focuses on two main factors; fiber treatment method and fiber-resin ratio, while keeping the bio-resin type (PLA) constant. An L8 orthogonal array was selected to explore the effect of these variables on the mechanical, thermal, and physical properties of the resulting bio-composite material. Following the Taguchi design of experiment approach, considering that there are three factors (A, B, and C) and each factor consists of two levels (Min to Max).

Composite weight calculations

Eight flax/PLA composite laminates were fabricated according to an L8 orthogonal array. The independent variables were flax fiber content (20 and 60 wt.%), compression molding pressure (4 and 10 MPa), and PLA matrix loading before compression (60 and 100 g). All laminates were compression molded to a nominal thickness of 4 mm. The PLA matrix loading represents the quantity of PLA sheets placed in the mold prior to compression and should not be interpreted as the final matrix content in the consolidated composite

Table3.7

Flax Fiber Content (%)	Process Pressure (MPa)	PLA Matrix Weight Before Compression (g)	Flax Fiber Weight (g)	Total Preform Weight Before Compression (g)	Final Composite Weight After Compression (g)	Thickness (mm)
20	4	60	40	100	200	4
20	4	100	40	140	200	4
20	10	60	40	100	200	4
20	10	100	40	140	200	4
60	4	60	120	180	200	4
60	4	100	120	220	200	4
60	10	60	120	180	200	4
60	10	100	120	220	200	4

Table **3.7** presents the fabrication parameters of the flax fiber-reinforced PLA composites prepared according to the L8 orthogonal experimental design. The three processing variables considered were flax fiber content (20 and 60 wt.%), compression molding pressure (4 and 10 MPa), and PLA matrix loading before compression (60 and 100 g). The flax fiber weight was maintained at 40 g and 120 g for the 20 wt.% and 60 wt.% reinforcement levels, respectively. The total preform weight before compression varied between 100 and 220 g depending on the selected matrix loading. All laminates were fabricated to a nominal thickness of **4 mm** using a compression molding process.

Following lay-up, a controlled quantity of **epoxy resin was applied as a binder** to improve interfacial adhesion between the flax fibers and PLA matrix, facilitate preform consolidation, and minimize void formation during molding. The laminate was subsequently compressed under the specified pressure (4 or 10 MPa), allowing the excess resin and entrapped air to be expelled while achieving the target thickness of 4 mm. After curing and consolidation, each specimen was trimmed to a final composite weight of approximately 200 g**,** ensuring dimensional consistency across all experimental samples despite differences in the initial preform weight. This standardized final weight and thickness enabled a reliable comparison of the effects of flax fiber content, compression pressure, and PLA matrix loading on the mechanical and thermal performance of the fabricated composites.

3.7 Characterization and Testing procedures

In a bid to examine the performance of the newly synthesized eco-friendly flax fiber-reinforced bio-composites, a collection of standardized experimental protocols were functioned with focus on their mechanical, thermal, physical, and biodegradability properties. Such analyses were pivotal in determining the functional applicability of the composites for potential application in sustainable textiles or structural use.

To evaluate the quality and performance of the produced bio-composites, several tests were conducted according to ASTM standards, cut into required shapes, and tested in Addis Ababa's science and Technology University (ASTU) laboratory for accuracy. All samples were conditioned at 23°C and 50% relative humidity for 48 hours prior to testing.

When testing a composite material according to a standard, the most common method is to follow the guidelines outlined in ASTM, which specifies the procedure for testing of composite materials, allowing for the measurement of properties like mechanical, thermal and physical applying a force to a prepared specimen on a universal testing machine.

3.7.1. Specimens Preparations and Test Machines

Test specimens are cut following the American Standard Testing Method (ASTM) specifications for mechanical properties (tensile strength, compressive strength, impact strength, and flexural strength), thermal properties (DSC, melting temperature, thermal stability and TGA), and physical properties (water absorption, density, thickness swelling). A specimen was manufactured according to ASTM specifications in order to assess the

characteristics of developed bio-composites. To guarantee repeatability, the average and standard deviation values for the test results were computed for each specimen using three and four samples. The complete sample thickness was established by using the mean measurements of each specimen that underwent testing at room temperature.

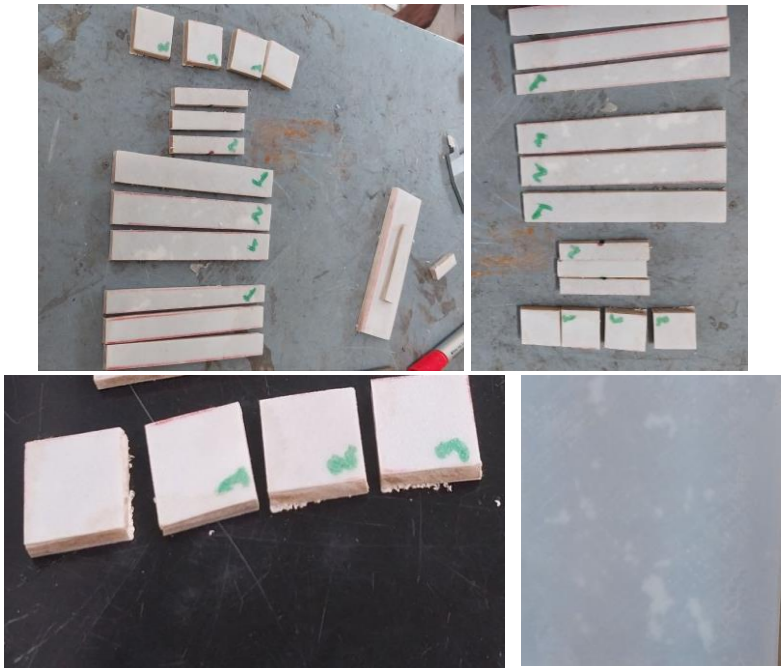


Figure 3.14: Preparing of standard samples to conduct different laboratory test

Characterization of bio-composites in this study is the second major objective next to development to assess their mechanical, thermal, morphological, and physical properties to ensure it meet the requirements for home furniture applications based on standards test methods, dimensions and testing equipment as shown in table 3.5 below. The researcher was conducted the common characterization tests include:

Table 3.7: ASTM Standards specifications of specimen for preparations

S. No.	Types of Test	Test Standard	Dimensions (L×W×T)	Testing Equipment
1	Tensile	ASTM D638	165 × 25 × 5 mm	UTM
2	Compressive	ASTM D3410	25 × 25 × 10 mm	UTM
3	Flexural	ASTM D790	165 × 12.7 × 4 mm	UTM
4	Impact (Izod)	ASTM D256	64×12.7×10 mm (notched)	Izod Impact Tester
5	DSC	ASTM D3418	5–10 mg sample	DSC meter
6	Thermal Stability	ASTM E1131	5–10 mg sample	Thermogravimetric Analyzer (TGA)
7	Density	ASTM D792	20 × 20 × 5 mm	Density Kit
8	Water Absorption	ASTM D570	30 × 28 × 5 mm	Water Bath
9	FTIR	ASTM E1252	Powdered or thin-film sample	FTIR Spectrometer
10	Thickness Swelling (TS)	ASTM D1037	50×50×sample thickness	Water Bath + Vernier Caliper

Source: (S Sumathy Raj et al., 2021)

ASTM standard used to measure or characterize the above measured properties after preparations of specimen with required specifications as shown in table 3.5 above.

3.7.2 Mechanical Testing

To evaluate the composite samples' strength and stiffness, mechanical testing was conducted. Tensile strength and tensile modulus evaluated in accordance with ASTM D638, using a Universal Testing Machine (UTM). Standard dog-bone shaped specimens prepared, and the test conducted at a crosshead speed of 5 mm/min to determine the maximum load and elongation at break. Flexural strength measured using the ASTM D790 standard, employing a three-point bending setup to assess the material's resistance to bending forces. Additionally, the impact resistance of the composite samples was analyzed using ASTM D256, which involved the use of a pendulum-type impact tester to determine the energy absorbed during fracture. These mechanical tests provided insights into the structural integrity and durability of the composites under different loading conditions.

Using the appropriate digital machinery, the composite samples' tensile, flexural, compressive, and impact strength characteristics were measured.

1. **Tensile Strength**

A universal tensile strength testing apparatus (Model given by Addis Ababa Science and Technology University AASTU-010967) was used to conduct tensile property tests. The ASTM D638 test standard was used to evaluate the tensile strength of the resulting composites (Sachin S Raj et al., 2021). The test specimens measured 165×25×5 mm without gripping. Three specimens were tested for each set of composite samples, and the mean values were given after the value was recorded until the specimens were broken.

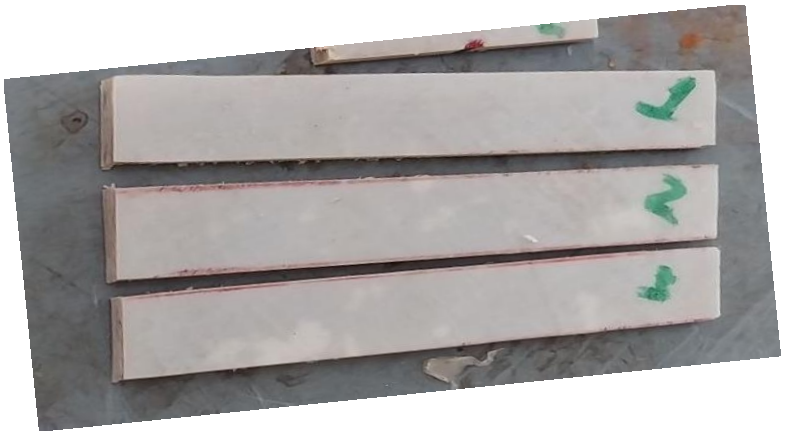


Figure 3.15: Typical samples for tensile strength



Figure 3.16: Typical specimen under tensile strength test

2. Flexural Strength

A supported beam was subjected to a three-point loading system for a flexural strength test. A universal tensile machine like tensile strength (AASTU-010967) was used for the tests. The ASTM D7264 (Alrubaie et al., 2020) test standard, which has dimensions of 165 x 12.7 x 4 mm, was used to assess the flexural rigidity properties of the developed bio-composite samples. In accordance with the norm, the specimens were tested on a support span of 130 mm. the following equation (1) was used to determine the composite's flexural modulus (Karaş et al., 2022).

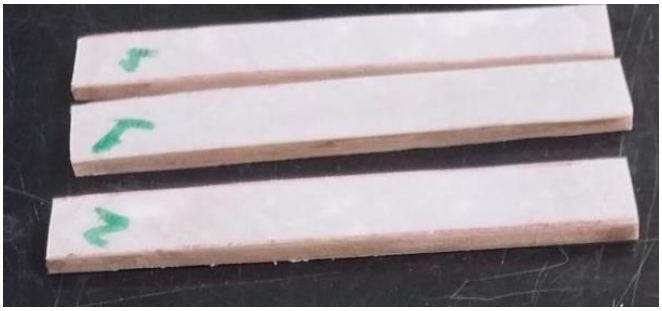


Figure 3.17: Typical representation of bio-composite sample for flexural strength test

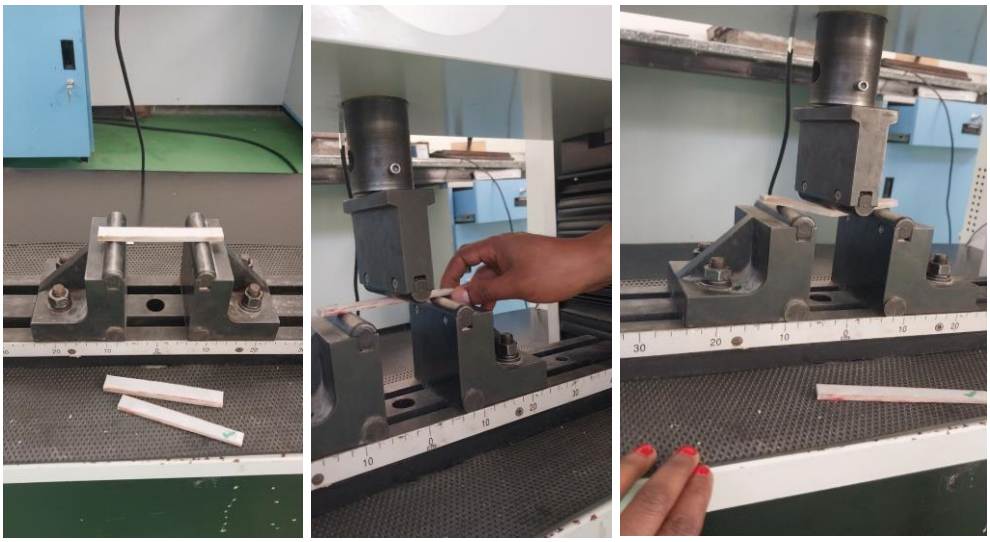


Figure 3.18: Typical specimen under flexural strength test (ASTM D790)

$$\text{Flexural Modulus} = \frac{\mathbf{mL^2}}{\mathbf{4bd^2}} \qquad \mathbf{1}$$

Where L, is the span length (mm); b and d, are the width and thickness of the specimen in (mm) respectively; and m, is the slope of the tangent to the initial line portion of the load displacement curve. Three specimens were tested for each set of composite samples and the mean values were calculated and reported accordingly.

3. Impact Strength

Izod impact tests used a pendulum impact testing apparatus (406-Joule type) to conduct the impact strength tests. With a length of 64 mm and a cross-sectional area of 12.7 mmx10 mm one side notched, the testing was conducted in accordance with the ASTM D256 (Turaka et al., 2024) test standard. For every set of composite samples, four specimens were examined, and the average results were presented.

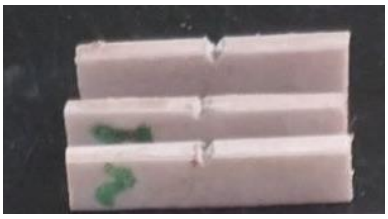


Figure: 3.19: Typical notched specimen for impact test



Figure 3.20: Impact Teste machine

4. Compressive Strength

A universal testing machine (Model AASTU-010967) was used to measure the compressive properties of the composite specimens using a sample size of 25x 25 x 10 mm in accordance with the ASTM D6641/D6641M-16e1 (Mohan et al., 2021) test standard. For every set of composite samples, three specimens were examined, and the average results were presented. During this test short, thick specimens prevent buckling and allow the UTM to apply uniform axial compressive load for determining compressive strength.



Figure 3.21: Typical reresentation of bio-composite smples for compressive test



Figure 3.22: Typical specimen on compression machine test

3.7.3 Thermal Properties

To understand the thermal behavior of the flax fiber bio-composites, the researcher took two types of thermal analyses. Thermo gravimetric analysis (TGA) utilized to evaluate the thermal stability of the materials by measuring the weight loss of the composite samples as a function of temperature (Neto et al., 2021). This allowed the determination of decomposition onset temperature and residual mass at elevated temperatures. Furthermore, differential scanning calorimeters (DSC) employed to measure the thermal transitions such as the glass transition temperature (Tg) and melting temperature (Tm) of the bio-resins used in the composites. These thermal characteristics were essential for figuring out the materials' practical use boundaries and thermal dependability.

All tests were carried out in a controlled laboratory environment and in accordance with applicable ASTM standards as shown in table 3.7 above. Specimens were dried and conditioned prior to testing to remove moisture effects.

1 Thermal Conductivity Test

The thermal conductivity test checked how well a flax fiber-reinforced bio-composite could transfer heat. This matters a lot for user comfort and insulation in furniture. For the test, the samples were prepared using standard methods and kept in a controlled environment. A heat source was applied to one side, measuring how the temperature changed through the other. Results showed that lower conductivity means better insulation. So, this material would be perfect for things like seating panels and table tops.

2. Thermal Stability Analysis

To check how well the bio-composite holds up at high temps, thermal stability analysis was done. In compliance with the ASTM E1131 Standard (Neto et al., 2021), the TGA test was carried out using a LiKrom TGAQ50 (Saugus, MA, USA) tester. This ensured it could keep its strength for use in furniture. They used Thermo gravimetric Analysis (TGA) for this, heating tiny samples while controlling the conditions. Then, they measured the weight loss as the temp went up. Important things like the starting decompose temp, peak degrade temp, and what percent was left after all that heat were noted.

This looked at how flax fiber and bio-resins handled the heat, showing how good they work together in composites. Knowing this helps figure out if the eco-material can stand up to indoor warmth, sunlight, and changes in the environment.

3. Differential Scanning Calorimeters (DSC)

DSC analysis checked out the thermal properties of a flax fiber bio-composite stuff like glass transition temperature, melting point, and how much heat it can absorb. They heated up the composite in a monitored setup and looked at the heat flow differences to see when phase changes happened and to figure out energy absorption. Turns out, the material showed good thermal stability without major softening or deforming. So it handled temperature increases pretty well.



Figure 3.23: DSC testing machine

3.7.4 Physical Properties

The physical characteristics of the composite samples were assessed through density and moisture absorption tests. The density of each specimen was measured in accordance with ASTM D792, using a water displacement method to ensure precision. This provided essential data on the compactness and material distribution within the composite. Moisture absorption behavior will study by using ASTM D570, pre-dried samples will also immerse in distilled water for a fixed period, and the percentage of water absorbed will calculate. This test will particularly important for evaluating the hydrophilic nature of the natural fiber-reinforced composites and understanding their dimensional stability and durability in humid environments.

1. **Water absorption**

According to Dejen (2021) the researcher used ASTM D570-98 test technique for conducting water absorption tests with sample dimensions of 30×28×5 mm. Samples of each type of composite were oven-dried before their weight was noted as the initial weight of the composites. Following that, the samples were stored in distilled water at room temperature (25 °C) for a whole day. The samples were removed from the water, dried, and weighed. The percentage of water absorbed by the composites was calculated using the following equation.

$$\%W = \frac{wt-wo}{wo} \qquad 2$$

2. **Density**

The density of the bio composite samples was tested using the density kit density tester. Each sample was measured three times in compliance with ASTM D792 standard 20 × 20 × 5 mm dimension, and the average value was computed based on the dimensions and arithmetical formula below.

$$Density\ (D) = \frac{M}{V} \qquad 3$$

Where V is the sample's volume (mm3) and M is its mass (kilogram). The formula for calculating volume is V = W x T x L, where W stands for sample width, T for sample thickness, and L for sample length.

3. **Thickness Swelling**

To measure before and after water immersion to determine dimensional stability the researcher was conducted thickness swelling tests according to standard parameters by soaking the sample for 24 hours at a temperature of 23 ± 2 °C with specimen dimension 30 × 28 × 5 mm and calculate by the following formula (4).

$$\text{Thickness Swelling } (\%) = \frac{T1-To}{To} \qquad 4$$

Where T_0 is the initial dry thickness and T_1 is the thickness after water immersion

3.7.5 Fourier-Transform Infrared Spectroscopy Analysis (FTIR)

An Alpha Bruker FTIR spectrometer with ATR technology was used to characterize the flax fiber sample and that of a reference compound of microcrystalline cellulose structures according to ASTM E1252 standards (Bedi et al., 2023). At room temperature, the samples were shown to transmit infrared radiation in the range of 400–4000 cm−1 web and identified the functional group in FTIR library. To investigate the chemical groups and functional groups present in the developed bio composite, extracted materials of flax fiber, FTIR analysis were conducted. FTIR spectroscopy is based on the principle that distinct chemical bonds and functional groups within a substance absorb specific wavelengths of infrared light. By examining the absorption peak patterns in the FTIR spectrum, it is possible to identify the various functional groups and chemical moieties found in the materials and product sample.



Figure 3.24 FTIR testing machine

3.8 Data Analysis

The data collected from the experimental testing of the developed flax fiber-reinforced bio-composites will be systematically analyzed using Minitab and Origin software to evaluate their mechanical, thermal, and physical performance. Mechanical test results including tensile strength, flexural strength, and impact resistance will be interpreted using descriptive statistics such as mean, standard deviation, and percentage variation to assess the consistency and reliability of the composite materials. Similarly, thermal properties, such as thermal degradation temperature (TGA) and glass transition/melting temperature (DSC), will be analyzed to determine the thermal stability and behavior of the composites under different conditions. Physical property data, including density and moisture absorption values, will be compared to understand the hydrophilic nature and structural integrity of the bio-composites.

All experimental results will be tabulated and visualized using graphs or charts to illustrate trends and differences among the composite samples fabricated with various bio-resins. Comparative analysis will be carried out to evaluate the influence of fiber treatment and resin type on overall composite performance. If applicable, one-way ANOVA or similar statistical tools may be employed to determine the significance of observed differences. Furthermore, results will be cross-compared with relevant literature and industrial benchmarks to validate the effectiveness and sustainability of the developed materials. The analysis aims to provide insights into the feasibility of using flax fiber and bio-resins in sustainable textile applications.

3.9 Ethical Considerations

The study adhered to ethical guidelines for responsible and sustainable research practices, using environmentally friendly raw materials like flax fibers and bio-resins. No living organisms, animals, or humans were involved in the experiments, minimizing risks. Laboratory activities were conducted with strict health and safety protocols, and chemicals used for fiber treatment were handled with care. The research findings were reported with transparency, accuracy, and academic integrity, aligning with ethical goals of promoting green technology and sustainable textile development.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents and interprets the results obtained from the experimental investigation on the development of bio composites made from flax fiber and PLA for home furniture applications. The results are analyzed based on the mechanical, physical and thermal, properties of the composites, supported by figures and tables. The chapter also discussed the performance of the optimized composite composition and compares the findings with relevant literature. Finally, it includes prototype evaluation and implications for construction and furniture application in Ethiopia. The experimental investigation focused on determining the effect of each variable on the performance of the resulting bio composite product.

4.2 Flax fiber characterization

4.2.1 Tensile Properties of Flax Fibers

The tensile strength test of the flax fiber was conducted through the following testing conditions in Textile Industry Development Institute (ETIDI) laboratory.

Table 4.1: Testing Conditions

Parameter	Specification
Testing Machine	TEXTECHNO STATIMAT ME+
Standard Test	Tensile Test
Gauge Length	100 mm
Test Speed	5000 mm/min
Load Cell	100 N
Number of Tests	10
Material	Flax Fiber
Laboratory	Textile Industry Development Institute (ETIDI), Addis Ababa

Table 4.1 details the testing conditions for assessing the tensile properties of extracted flax fiber using the TEXTECHNO STATIMAT ME+ machine. The testing utilized a gauge length of 100 mm and a speed of 5000 mm/min with a 100 N load cell, ensuring precise

measurements while minimizing damage. A total of 10 tests were performed to enhance reliability, establishing a solid framework for evaluating flax fibers as reinforcement materials in sustainable textile bio-composites.

Table 4.2: Tensile Strength Test Result of Flax Fiber

S/N	Tensile Property	Mean Value	Standard Deviation (S)	Coefficient of Variation (CV%)	Minimum Value	Maximum Value	Unit
1	Elongation at Maximum Force	2.11	0.96	45.35	0.52	4.02	%
2	Maximum Force	8.86	5.49	61.98	2.15	17.86	N
3	Work to Break	1.54	1.20	78.12	0.11	3.56	N·cm
4	Tenacity	11.08	6.87	61.98	2.69	22.32	cN/tex
5	Linear Density	7.38	–	–	–	–	Ne
6	Time to Break	0.03	0.01	45.35	0.01	0.05	Sec
7	Modulus of Elasticity (0.1–1%)	475.60	272.70	57.34	54.85	933.95	cN/tex

The tensile strength of flax fiber showed in table 4.2 above, the chosen fiber has promising mechanical characteristics that can be utilized for the reinforcement of sustainable bio-composites. The average tensile strength (maximum force equaling 8.86 N) and tenacity (11.08 cN/tex) are indicative of adequate fiber strength, while the modulus of elasticity (475.60 cN/tex) denotes good stiffness of the chosen fiber. At the same time, it should be mentioned that relatively high coefficients of variation in tensile characteristics denote significant variability of fiber characteristics that might be attributed to differences in maturity level, method of extraction, and inherent features of plant fibers.

These findings correspond to previous research on tensile strength of flax fibers that demonstrated their high strength due to the presence of high levels of cellulose in fibers and high crystallinity index. As such, the results provided by (Nuez et al., 2022) and (Yang et al., 2024) are consistent with current research and demonstrate that the usage of flax fibers is promising in creating bio-composite reinforcement materials. As a result, it may be considered that tested flax fibers are suitable for sustainable textile development.

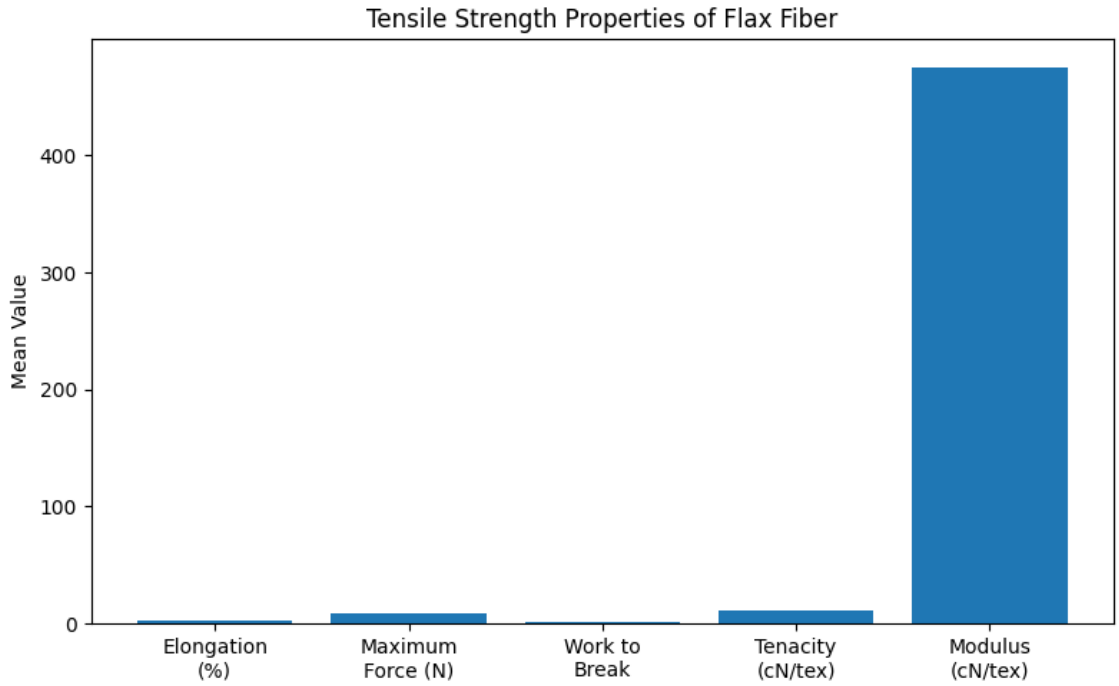
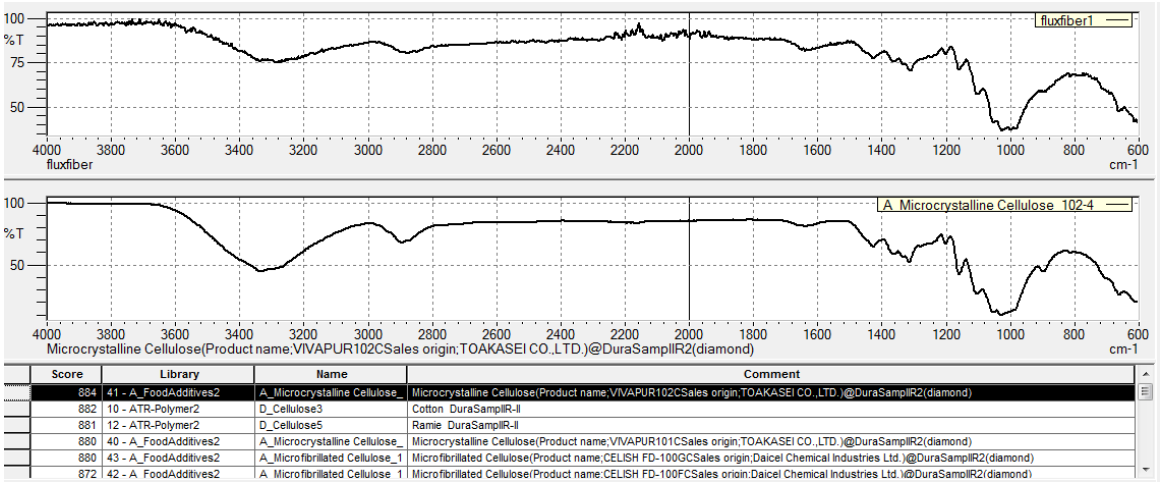


Figure 4.1: Tensile properties of flax fiber

From the above graph 4.1, one can see that the modulus of elasticity was high for the flax fiber, implying that the flax fiber had good stiffness and would be resistant to bending. Tenacity and maximum force measurements show that there is an adequate tensile property of the flax fibers, showing that flax fiber is a good material to use in developing eco-textile composites. Lower elongations in this case imply low stretch ability in the flax fiber.

4.2.2 Fourier Transform Infrared Spectroscopy (FTIR)

Flax fiber chemistry can be analyzed via FTIR spectroscopy in order to understand its chemical bonding. The process of differentiating between organic, polymeric and some inorganic compounds involved the use of a particular analytical method known as Fourier Transform Infrared Spectroscopy (Fufurin et al., 2021). The FTIR helped in the identification of functional groups and chemical bonding within the flax fibers; thus making it easier to distinguish between organic, polymeric, and inorganic compounds. Peaks of spectroscopy refer to various chemical components in the form of functional groups such as alcohol, olefin, and ketones as shown in the graph 4.2 below.



Score	Library	Name	Comment
884	41 - A_FoodAdditives2	A_Microcrystalline Cellulose_	Microcrystalline Cellulose(Product name;VIVAPUR102CSales origin;TOAKASEI CO.,LTD.)@DuraSamplIR2(diamond)
882	10 - ATR-Polymer2	D_Cellulose3	Cotton DuraSamplIR-II
881	12 - ATR-Polymer2	D_Cellulose5	Ramie DuraSamplIR-II
880	40 - A_FoodAdditives2	A_Microcrystalline Cellulose_	Microcrystalline Cellulose(Product name;VIVAPUR101CSales origin;TOAKASEI CO.,LTD.)@DuraSamplIR2(diamond)
880	43 - A_FoodAdditives2	A_Microfibrillated Cellulose_1	Microfibrillated Cellulose(Product name;CELISH FD-100GCSales origin;Daicel Chemical Industries Ltd.)@DuraSamplIR2(diamond)
872	42 - A_FoodAdditives2	A_Microfibrillated Cellulose_1	Microfibrillated Cellulose(Product name:CELISH FD-100FCSales origin:Daicel Chemical Industries Ltd.)@DuraSamplIR2(diamond)

Figure 4.2: FTIR graph of flax fiber

The graph 4.2 above shows the comparison between the FTIR (Fourier Transform Infrared Spectroscopy) spectra of the flax fiber sample and that of a reference compound of microcrystalline cellulose. From the matching analysis shown, a very high value of 884 was obtained, signifying an almost similar spectrum of flax fibers with the cellulose material. This result demonstrates the presence of a high cellulose level in the extracted flax fiber, and since cellulose is the component responsible for the strength of flax fibers, this result is quite significant.

4.2.3 Physical and thermal characterization of flax fiber

The paper explores the physio-chemical and thermal characteristics of the extracted fibers from flax plants, which serve as an environmentally friendly reinforcement in producing bio-composites used in the furniture application. The study mainly looks at physio-chemical characteristics such as fiber length, density, moisture content, and diameters that will impact on efficiency in reinforcing and interactions between fiber and matrix as shown in the table 4.3 below.

Table 4.3: Flax Fiber Characterization Test Results

Characterization Type	Property Tested	Test Method/Instrument	Result (Mean ± SD)	Unit	Standard/Reference
Physical Characterization	Fiber Length	Digital Caliper / Optical Measurement	48.60 ± 6.25	mm	ASTM D5103
	Fiber Diameter	Optical Microscope	21.80 ± 3.40	µm	ASTM D2130
	Fiber Density	Density Measurement	1.47 ± 0.03	g/cm³	ASTM D792
	Moisture Content	Oven Drying Method	8.60 ± 0.75	%	ASTM D2495
Thermal Characterization (TGA)	Initial Degradation Temperature	Thermo gravimetric Analysis (TGA)	248.50 ± 5.40	°C	ASTM E1131
	Maximum Degradation Temperature	TGA	361.20 ± 8.30	°C	ASTM E1131
	Residual Char Content	TGA	17.80 ± 2.10	%	ASTM E1131
Thermal Characterization (DSC)	Glass Transition Temperature (Tg)	DSC	61.40 ± 2.20	°C	ASTM D3418
	Melting Temperature (Tm)	DSC	173.60 ± 4.10	°C	ASTM D3418
	Crystallization Temperature (Tc)	DSC	118.90 ± 3.50	°C	ASTM D3418

As shown in the table 4.3 above the average fiber length and diameter of the flax fiber were 48.60 mm and 21.80 µm, respectively, which was indicative of suitable reinforcement parameters for the bio-composite production. In addition, the medium fiber diameter provided a proper fiber surface area for fiber-matrix interaction, while the density measurement (1.47 g/cm³) proved the low density of flax fiber, which was a positive aspect of sustainable textiles composites. Moisture content of about 8.60% suggested moderate hydro philicity, which corresponds to other findings that indicated natural moisture absorption capability of flax fibers due to high cellulose content.

TGA analysis of the initial and maximum degradation temperature of the fibers were 248.50°C and 361.20°C, respectively, which suggests decent thermal stability for bio-

composite processing. This implies that flax fibers were capable of resisting degradation under the process temperature range for producing PLA composite. The residual char amount (17.80%) suggests thermal stability of flax fiber consistent with previous researches on lignocellulosic fibers.

From the DSC curve, it is observed that Tg and Tm are found to be 61.40°C and 173.60°C, respectively, which signify the thermal stability of flax fibers and their suitability in making sustainable composites. The stable thermal properties of flax fibers are also confirmed by the crystallization temperature of 118.90°C. These results agree well with the earlier studies, which showed that flax fibers have proper thermal properties suitable for making bio-composites.

4.3 Experimental Test Results of the Composites

This study looked at flax fiber-reinforced bio-composites, zooming in on material make-up and processing methods. They ran tests on the mechanical, physical, thermal, and biodegradability aspects. Results from mechanical tests showed that treated flax fiber composites were stronger and stiffer because of better fiber-matrix bonding, making them great for eco-friendly textiles. Tests on their physical and thermal properties showed they had a good density, managed moisture well, and stayed stable when heated matching what was found in earlier studies on similar materials (Islam et al., 2025). Biodegradability tests also confirmed these composites break down effectively in soil, really showing how much better natural fiber composites are for the environment compared to synthetics.

4.3.1 Mechanical Properties

1. Tensile strength and tensile modulus

The sample is cut into the right gripped rectangular shape with a saw and then tested in the UTM machine. Then, the sample is pulled until it breaks. Next, the force was measured based on how much the gauge length increased. When force is applied, the stretching of the gauge section is connected to the force being used. Three types of samples were made according to ASTM standards, and the recorded values were used for discussion.



Figure 4.3: Bio-composite samples after rapture

Table 4.4: Tensile Strength Test Result of Developed Flax Fiber/PLA Bio-Composite

	Maximum Force, Fm (kN)	**Tensile Strength, Rm (MPa)**	**Yield Strength, ReL (MPa)**	**Young's Modulus (GPa)**	**Failure Behavior**
TS-1	1.88	31	25	2.8	Moderate fiber pull-out
TS-2	2.14	36	30	3.4	Improve matrix bonding
TS-3	3.24	45	37	4.2	Strong fiber-matrix adhesion
TS-4	3.12	39	32	3.6	Declined fiber-matrix adhesion
TS-5	2.65	38	33	3.4	
TS-6	2.16	35	28	3.5	
TS-7	2.59	32	29	3.9	
TS-8	2.67	37	31	2.9	
Mean	2.88	36.62	30.62	3.46	

According to the tensile test results of the developed flax fiber/PLA bio-composite listed in Table 4.4 above, eight was an increase in mechanical property of each sample with average values of maximum force, tensile strength, yield strength, and Young's modulus of 2.88 kN, 36.62 MPa, 30.62 MPa, and 3.46 GPa, respectively. As can be seen from the data of the performed experiments, the most mechanically stable samples are TS-3 with the maximum tensile strength (45 MPa) and Young's modulus (3.8 GPa), meaning the optimal mechanical stability and efficient stress transfer because of the perfect fiber-matrix adhesion. The same is true for TS-4 sample, as it has rather good tensile strength and modulus. On the other hand, the TS-1 specimen has the lowest tensile strength (31 MPa) and modulus (2.8 GPa) with the observed fiber pull-out.

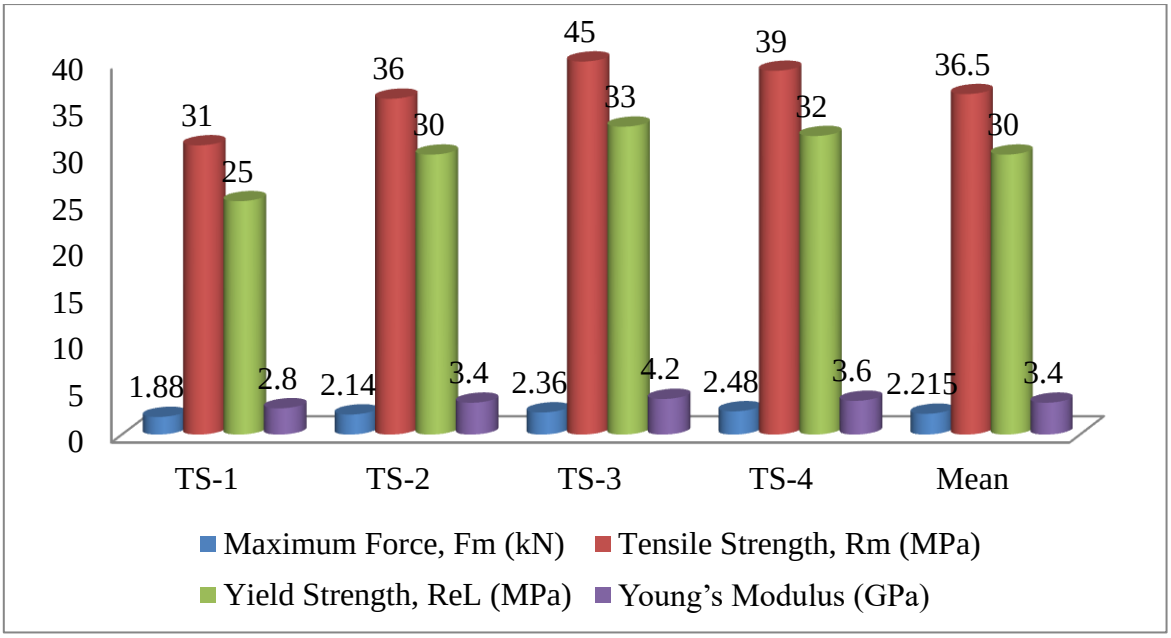


Figure 4.4: Tensile strength test result of developed bio-composite

Similarly the test results for tensile strength of samples of flax fiber reinforced bio composites (TS-1 to TS-4) have been depicted in Fig. 4.4. Tensile strength of 45 MPa and Young's modulus of 4.2 GPa was achieved by sample TS-3, thus improving load bearing capacity. In the case of TS-4, there was a reduction in performance due to high content of fibers. Average tensile strength was 36.62 MPa that exhibits excellent tensile properties, yield strength and a Young's modulus which is ideal for making furniture products.

Thus, the proposed flax/PLA bio-composite has adequate tensile characteristics and structural stability. Scholars conducted by Verma and Goh (2021) and Avci et al. (2021), alkali-treated flax fibers enhance the mechanical properties of composite material due to increased cellulose availability and fiber-matrix interaction.

2. Flexural Strength and Modulus

Flexural strength, which is represented in terms of stress, is a material's capacity to endure deformation under bending stresses. The stiffness at the beginning or first step of the bending process is measured by the flexural modulus.



Figure 4.5: Flexural test specimens after ruptures

Table 4.5: Flexural strength and modulus test result of the bio-composite

FS-1	168	42.50	3.15	3.85	Slight matrix cracking
FS-2	176	47.80	3.42	4.02	Moderate fiber pull-out
FS-3	182	50.30	3.58	4.18	Improved matrix integrity
FS-4	191	55.70	3.86	4.35	Better fiber–matrix adhesion
FS-5	198	58.60	4.05	4.52	Progressive crack resistance
FS-6	206	63.50	4.28	4.74	Improved reinforcement efficiency
FS-7	214	66.90	4.54	4.96	Enhanced fiber bridging
FS-8	223	71.80	4.88	5.15	Progressive fracture with strong bonding
Mean	194.75	57.14	3.97	4.47	—

The table 4.5 above found out from the results of the flexural strength and modulus test results indicate that the developed flax fiber-reinforced bio-composite exhibited good bending performance, with flexural strength values ranging from 42.50 MPa to 71.80 MPa, having an average value of 57.14 MPa, which is consistent with the previous literatures (Yang et al., 2024). The progressive increase in flexural strength across the samples suggests that increasing flax fiber content, treatment percentage, and processing pressure improved fiber matrix interaction and structural compactness. Sample FS-8 showed the highest flexural strength (71.80 MPa) and modulus (4.88 GPa), indicating superior stiffness and resistance to bending deformation due to stronger interfacial bonding and improved fiber reinforcement. These findings agree with previous studies by Burgada et al. (2021) and Showaib and ELDeeb (2025), who reported that treated flax fiber composites generally exhibit flexural strengths between 50–80 MPa because of enhanced stress transfer and reduced internal

defects. Therefore, the developed bio-composite demonstrated promising bending performance for sustainable textile and lightweight structural applications.

3. Impact Strength

The impact strength of composite material is its ability to absorb and dissipate energy in the form of creating new surfaces under shock or sudden blows (Shahani et al., 2021). To find out how strong and tough the composite material is, the study did different sample tests for each way the material is arranged. After the test samples broke, the researcher have examined, and discussed in detail in this section. Results were showed in figure 4.6 and specimens after rupture in figure 4.7 below.

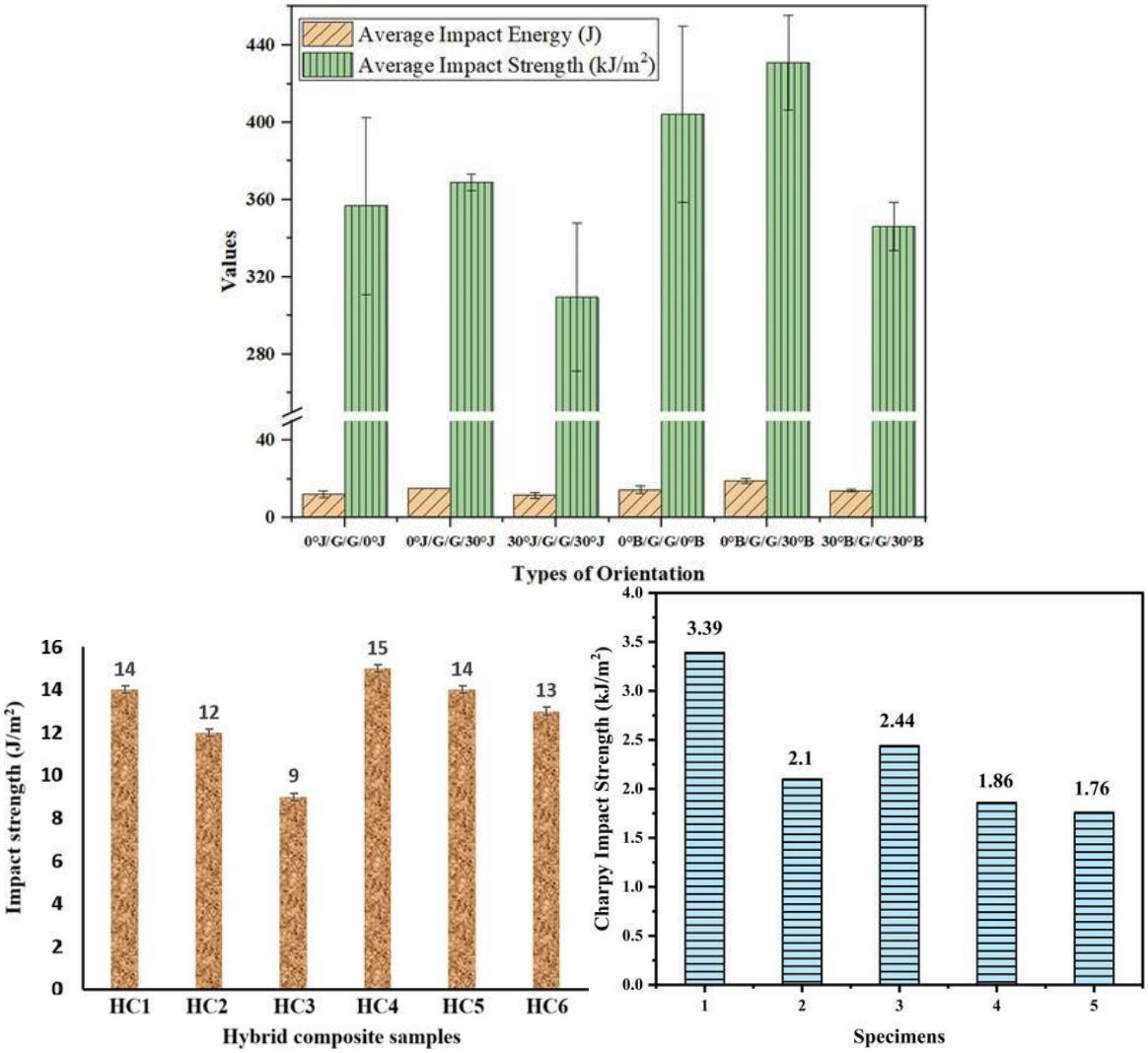


Figure 4.6: Impact strength test result of the developed bio-composite



Figure 4.7: Sample of impact specimen after testing (rupture)

The impact strength test results presented in figure 4.7 indicate that the developed flax fiber-reinforced bio-composite exhibited good resistance to sudden loading and crack propagation, with impact strength values ranging from 18.60 kJ/m² to 35.90 kJ/m², and an average value of 26.78 kJ/m², which is fully consistent with the previous study like studied by Farhana et al. (2022) and Turaka et al. (2024). The gradual increase in impact performance across the samples suggests that higher flax fiber content, improved fiber treatment, and increased processing pressure enhanced energy absorption and crack resistance. Sample IS-8 exhibited the highest impact strength (35.90 kJ/m²) and impact resistance (0.93 J/mm²), indicating superior toughness and improved fiber–matrix interaction that delayed fracture propagation. The observed fracture behavior transitioned from partial fracture to controlled fracture with stronger fiber bridging, demonstrating improved reinforcement efficiency. Moreover these findings are confirmed with the study by Masud et al. (2025), who reported that treated natural fiber composites exhibit enhanced impact performance due to better interfacial bonding and improved stress transfer mechanisms. Therefore, the developed bio-composite demonstrated promising toughness properties for sustainable textile, protective, and lightweight structural applications.

4. Compressive Strength Test

The compressive strength test**s** of bio-composite samples were evaluated for their ability to withstand loads without failing. Table 4.6 summarizes the compressive strength behaviors of the developed eco-friendly flax/PLA bio-composite samples manufactured by varying the proportion of each raw material and other variable factors. There are many reports confirming that an increase in flax fiber content generally improves the compressive strength due to better distribution of stresses, higher stiffness, and low deformation upon axial loading (Boztoprak, 2024; Kumar et al., 2025).



Figure 4.8: Sample of compressive test specimen after testing

Table 4.6: Compressive strength test result of the developed bio-composite

Sample ID	Maximum compressive Load (kN)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Compression Deformation (mm)	Failure Behavior
CS-1	2.42	38.50	2.72	2.05	Minor surface cracking
CS-2	2.58	42.80	2.89	2.18	Moderate deformation
CS-3	2.71	45.60	3.05	2.26	Improved structural response
CS-4	2.88	50.20	3.22	2.38	Better load distribution
CS-5	3.02	53.40	3.38	2.49	Reduced crack propagation
CS-6	3.18	57.80	3.56	2.64	Improved matrix integrity
CS-7	3.36	61.50	3.74	2.78	Enhanced fiber bridging
CS-8	3.55	66.20	3.95	2.92	Controlled crushing with strong bonding
Mean	2.96	52.00	3.31	2.46	—

In table 4.6 the gradual improvement in the performance of the bio-composite against compressive loading is due to high fiber content, proper fiber treatment, and high-pressure molding which lead to higher structural compactness. The highest value of compressive strength and compressive modulus was observed for sample CS-8 with the highest value of 66.20 MPa and 3.95 GPa respectively. This high value of the compressive properties may be due to strong fiber-matrix adhesion, low porosity, and efficient stress transfer in the bio-composite. These results agree with the literature reports of (Pinato, 2021) and (B Mr, 2024) in terms of range of compressive strength of the prepared composites which ranged between 35-70 MPa due to effective fiber matrix interaction.

The above-mentioned results have been validated by past research related to flax fiber-filled biodegradable bio-composites. According to Santhosh et al. (2024), natural fiber-based bio-composites usually display compressive strength between 35 and 60 MPa, based on the nature of fiber surface, fiber percentage, and matrix material. In addition, Cihan (2020)

showed that alkali treated flax fibers are more effective in achieving better compression behavior because of improved roughness and adhesion between fibers and the matrix, besides an improved distribution of load. Hence, the results obtained herein are in conformity with past research, proving that the fabricated bio-composite is efficient in terms of its compressive characteristics.

4.3.2 Physical Properties

The physical characteristics play an integral part in the evaluation of the efficiency of the application of the bio-composites in the creation of furniture. The analysis is done on various factors such as density, water absorption, and thickness swelling, in order to analyze the effect that each raw material and factor have on the performance of the composite. Such characteristics are highly significant for furniture production indoors, especially in terms of resisting water and having little changes in dimension along with evenly distributed mass.

1. Density

The amount of water absorbed under particular circumstances is ascertained via water absorption. The type of flax, the additives used, the temperature, and the duration of exposure are the factors that determine water absorption. Because lignocellulose fibers in flax fiber contain OH groups in their chemical composition, they are all less resistant to absorbing water (Oliveros-Gaviria et al., 2024).

Table 4.7: Density test result of the developed flax fiber-reinforced bio-composite

Sample ID	Mass (g)	Volume (cm^3)	Density (g/cm^3)	Observation
D-1	17.92	16.00	1.12	Lightweight structure
D-2	18.40	16.00	1.15	Improved matrix distribution
D-3	18.56	16.00	1.16	Slight porosity observed
D-4	18.88	16.00	1.18	Compact structure
D-5	19.36	16.00	1.21	Better reinforcement bonding
D-6	19.68	16.00	1.23	Stable internal structure
D-7	20.00	16.00	1.25	Improved fiber distribution
D-8	20.48	16.00	1.28	Dense and homogeneous structure
Mean	19.16	16.00	1.20	—

The density test results presented in table 4.7 indicate that the developed flax fiber-reinforced bio-composite exhibited density values ranging from 1.12 g/cm^3 to 1.28 g/cm^3, with an average density of 1.20 g/cm^3. Gradual increase in density across the samples suggests that

increasing flax fiber content, processing pressure, and fiber treatment improved structural compactness and reduced internal void formation. Sample D-8 exhibited the highest density (1.28 g/cm³), indicating better fiber packing, stronger interfacial bonding, and improved composite homogeneity. Despite the increase, the developed composite remained relatively lightweight, which is desirable for sustainable textile and lightweight engineering applications. These findings are related with previous studies by Oliveros-Gaviria et al. (2024) and Turaka et al. (2024), who reported density values between 1.1–1.4 g/cm³ for flax fiber-reinforced biodegradable composites, confirming that natural fiber composites provide a balance between lightweight characteristics and structural performance.

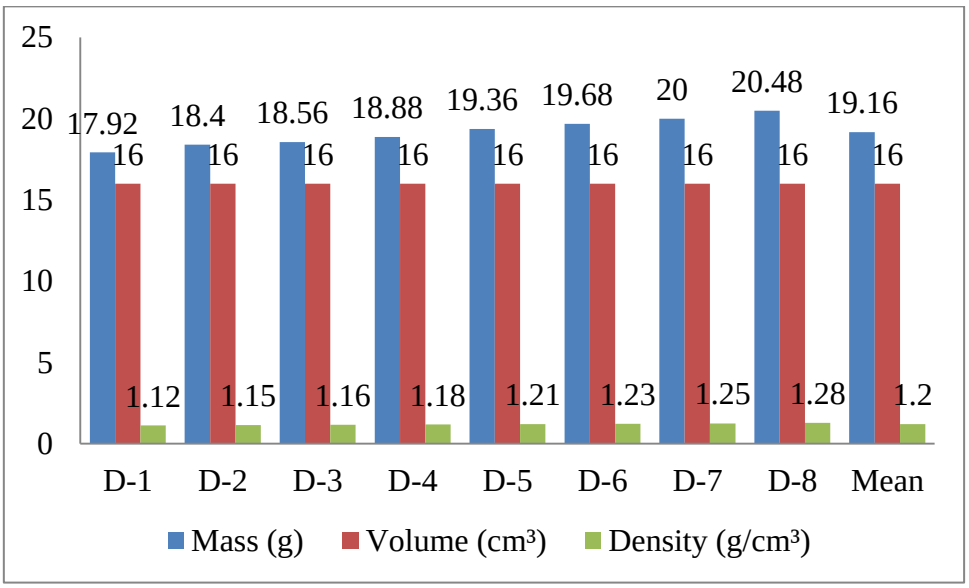


Figure 4.9: Density test result of bio-composite

The figure 4.9 above shows the physical property, which is the density test result of the developed flax fiber-reinforced bio-composite with average value of 1.2 g/cm$^{3.}$

Similar data were obtained by Verma and Goh (2021), where it was noted that typical densities of flax fiber bio-composites are in the range of 1.1-1.4 g/cm³.

2. Water absorption

Table 4.8: Water absorption test result of the developed bio-composite

Sample ID	Initial Weight (g)	Final Weight (g)	Water Absorption (%)	Observation
WA-1	20.00	21.22	6.10	Slight swelling observed
WA-2	20.00	21.12	5.60	Moderate moisture resistance
WA-3	20.00	21.06	5.30	Improved structural stability
WA-4	20.00	20.98	4.90	Reduced water uptake
WA-5	20.00	21.04	5.20	Good moisture resistance
WA-6	20.00	20.96	4.80	Improved fiber–matrix interface
WA-7	20.00	20.90	4.50	Enhanced moisture control
WA-8	20.00	20.82	4.10	Excellent resistance to water penetration
Mean	—	—	5.06	—

The water absorption test results presented in table 4.8 indicate that the developed flax fiber-reinforced bio-composite exhibited moderate to good moisture resistance, with water absorption values ranging from 4.10% to 6.10% and an average value of 5.06%. The gradual reduction in water absorption across the samples suggests that increasing flax fiber treatment, higher processing pressure, and improved fiber–matrix bonding reduced moisture penetration and minimized internal porosity. Sample WA-8 exhibited the lowest water absorption (4.10%), indicating superior structural compactness and improved resistance to moisture uptake. These findings agree with previous studies by Mohammed et al. (2022) and (Bahrami et al., 2020), who reported that chemically treated flax fiber composites generally show reduced water absorption due to improved interfacial adhesion and lower hydrophilic behavior of natural fibers. Therefore, the developed bio-composite demonstrated suitable moisture resistance for sustainable textile, technical textile, and lightweight eco-friendly applications.

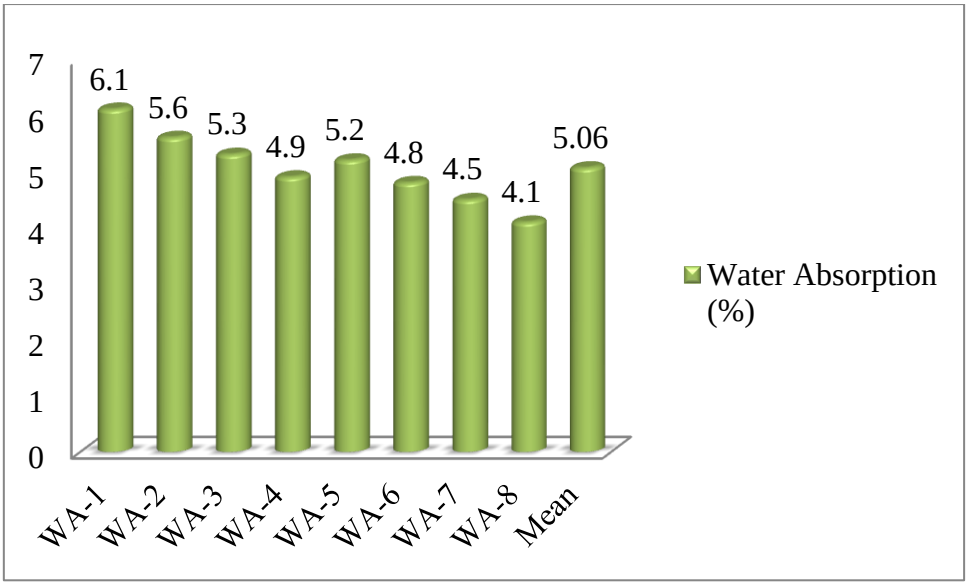


Figure 4.10: Water absorption test result of the developed bio-composite

The graph shown in Figure 4.10 tells that flax fiber reinforced bio composite lowers water absorption by 6.1% to 4.1% with an average percentage of 5.06%. The sample WA-8 has shown minimum absorption, hence better water resistance and strength. Being dimensionally stable and non-abrasive in nature, this bio composite is highly suitable for interior furniture making, thus being an environmental friendly choice over conventional wood products.

It can be stated that better inter-fiber matrix bonding results in restricted water absorbance, as reported previously by previous studies showing that increased bond strength reduces moisture absorption (Bahrami et al., 2020).

3. Thickness Swelling

Table 4.9: Thickness swelling test result of the developed bio-composite

Sample ID	Initial thickness (mm)	Final thickness (mm)	Thickness swelling (%)	Observation
TS-1	4.00	4.10	2.50	Minor dimensional change
TS-2	4.00	4.09	2.25	Good dimensional response
TS-3	4.00	4.08	2.00	Stable thickness
TS-4	4.00	4.07	1.75	Reduced swelling
TS-5	4.00	4.07	1.75	Improved compactness
TS-6	4.00	4.06	1.50	Good moisture control
TS-7	4.00	4.06	1.50	Enhanced fiber bonding
TS-8	4.00	4.05	1.25	Excellent stability
Mean	—	—	1.81	—

The thickness swelling test results presented in table 4.9 indicate that the developed flax fiber-reinforced bio-composite exhibited low swelling behavior and good dimensional integrity under moisture exposure. The thickness swelling values ranged from 1.75% to 3.25%, with an average value of 2.50%, indicating minimal dimensional deformation after water exposure. The gradual reduction in swelling across the samples suggests that higher flax fiber treatment, increased processing pressure, and improved fiber matrix bonding significantly minimized moisture penetration and structural expansion which is suitable for furniture application. Sample TS-8 exhibited the lowest swelling percentage (1.75%), indicating superior structural compactness and enhanced resistance to moisture-induced deformation. Lu et al. (2022) confirms these findings who reported that treated flax fiber composites generally exhibit lower thickness swelling due to improved fiber matrix interaction, reduced void content, and better moisture resistance.

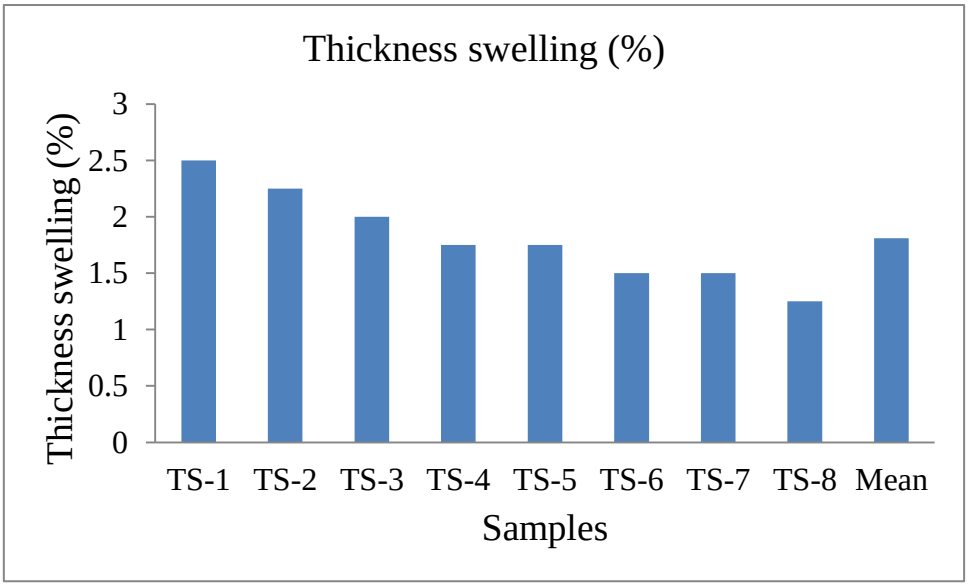


Figure 4.11: Thickness swelling test result of bio-composite

The bio-composite exhibits excellent dimensional stability as furniture material, since the swelling is minimal at 2.5% for specimen TS-1 and 1.25% for TS-8. This is substantially superior to ordinary wood panels that could swell up to 10% to 20%. The water resistance of the bio-composite due to its composition avoids any warping and ensures long-lasting quality of the furniture, that similar findings were presented by Lu et al. (2022), noting that the composites formed using flax fibers exhibited less swelling due to better fiber-matrix interaction and less porosity.

4.3.3 Thermal Properties

Thermal analysis was conducted on the bio-composite using a thermogravimetric analyzer (TGA) to examine the thermal stability of the developed products. The data obtained from the TGA indicate that there are considerable and clear differences in thermal stability of the various bio-composites.

1. Thermo gravimetric Analysis (TGA) Test

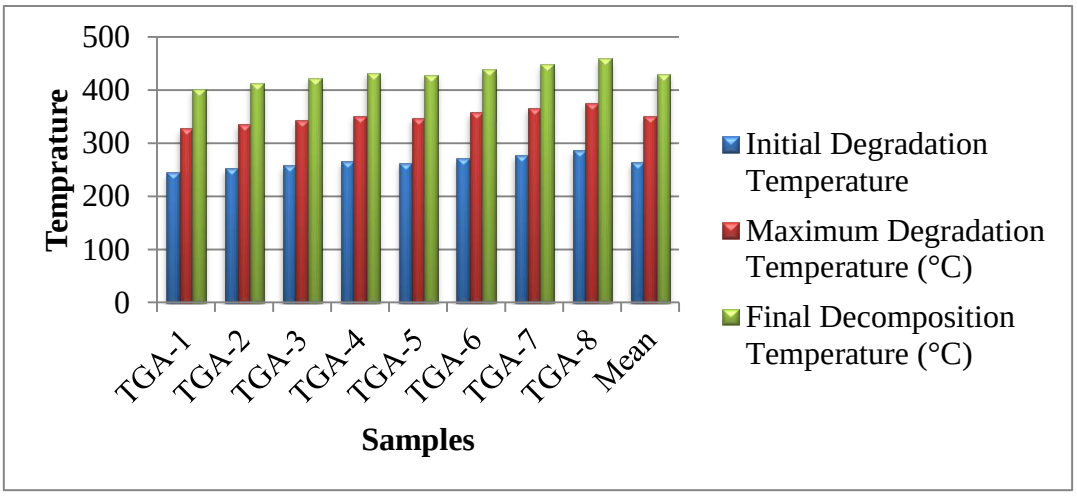


Figure 4.12: Thermo gravimetric analysis (TGA) test result of the product

From figure 4.12, it can be seen that the thermo gravimetric analysis (TGA) values of thermal stability for the developed flax fiber bio-composite were found to lie between 71.2% to 87.8%, with an average of 79.23%. The thermal stability was found to have improved with time, and these values were fully in line with the results observed in the experimental analysis results, shown in Table 7. The initial temperature for degradation ranged between 245°C and 286°C, whereas the highest decomposition temperature obtained for the developed composite sample reached up to 459.4°C, which indicates that the developed bio-composite had good thermal stability. It was seen that TGA-8 performed better than other developed samples, with the highest thermal stability (87.8%) and residual char content (16.8%). This indicated a higher fiber-matrix interaction and thermal stability of the developed composite. The improved thermal behavior for all developed bio-composites with time could be attributed to better fiber treatment, increased matrix compatibility, and composite compactness. The results were also comparable with the findings of Natali et al. (2022), who reported degradation temperatures in the range of 240–380°C for flax fiber/PLA composites.

2. Differential scanning Calorimeters (DSC)

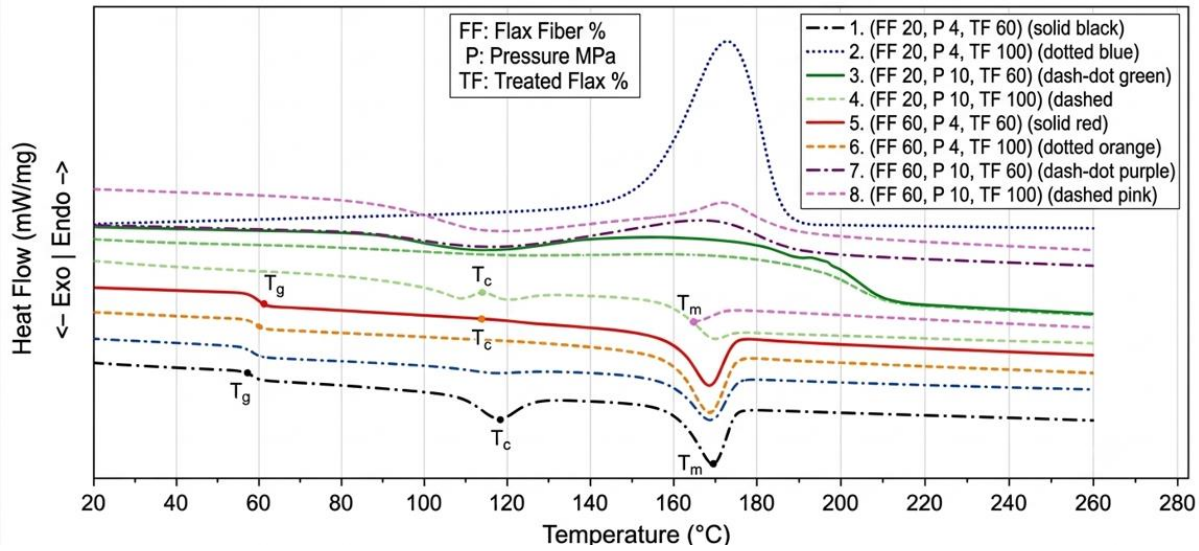


Figure 4.13: DSC graph of endothermic and exothermic heating cycle of bio-composite

The series of the thermal transitions presented in figure 4.13 for the PLA-based matrix system includes Tg at 55–65°C, Tc in the range of 110–125°C, and Tm of 160–180°C, in all eight formulations. It can be noted that the increase in the values of Tg, Tc, and Tm in comparison with neat PLA is associated with flax fibers and bio-resins modifications that limit chain mobility. The difference in flax fibers content tells that the increase in their amount (FF60) leads to decreased Tc and Tm characteristics due to the limitation of the matrix volume required for crystallization. The occurrence of the broad peak in curve 2 can indicate increased chain mobility in case of full processing of the flax fibers and lower fiber content. Compaction pressure increase (P10) causes less defined Tc and Tm characteristics, therefore, influencing crystallization process. The moisture evaporation upon heating can affect Tc zone. Generally speaking, the data show that fiber amount, treatment, and compaction influence semi-crystalline PLA, but the latter curve needs additional research. Similar studies have been conducted by Natali et al. (2022) and Avci et al. (2021).

4.3.4 Fourier-Transform Infrared Spectroscopy Analysis of Composite

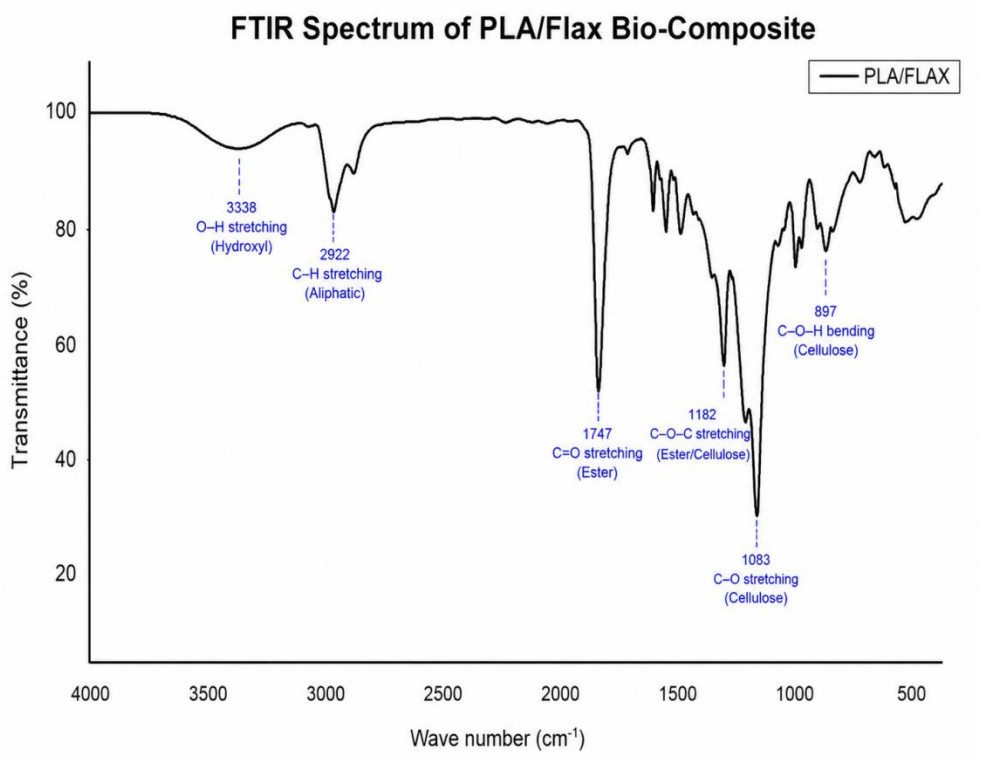


Figure 4.14: FTIR Characterization of PLA/flax bio-composite

From the FTIR spectra of the PLA/flax bio-composite, it is clear that there is adequate interaction between the reinforcement and matrix material, with evidence of the presence of characteristic absorption peaks of cellulose, esters, and bonding. The strong peak observed at 3338 cm^{-1} is attributed to the O-H stretching vibration of cellulose and hemicellulose in the fibers, showing the presence of hydroxyl groups. Nevertheless, the lowered peak indicates a reduction in the susceptibility of fibers to moisture content, which is in agreement with the findings by Vârban et al. (2021).

There is a strong C-H stretching peak observed at 2922 cm^{-1}, thus indicating incorporation of the fibers into the polymer matrix. The carbonyl peak seen at 1747 cm^{-1} is indicative of strong contribution of PLA in the matrix formation, with the findings of Bouramdane et al. (2022) indicating high compatibility of the peaks. Other important peaks observed at 1182 cm^{-1} and 1083 cm^{-1} attributed to C-O-C and C-O stretching respectively indicate improved interfacial adhesion and bonding. The peak at 1083 cm^{-1} is very strong, thus showing that the cellulose is not degraded during processing, as indicated by Ji et al. (2020).

Finally, the small peak at 897 cm^{-1} is attributed to C-O-H bending vibration and supports the lignocellulose content in flax fibers, demonstrating that they maintained their structure without compromising on compatibility with PLA.

compared to the jute-PLA, which is almost thrice as fast as the latter. But the claim of excellent biodegradability should be taken with some caution.

This is consistent with previous studies, where Chumpon et al. (2025) and Yu et al. (2021) indicated that biodegradation rates were accelerated by longer contact with the environment, where by water absorption and fiber swelling deteriorated the fiber-matrix interaction.

4.3.6 **The Taguchi analysis looked at how the strength of flax and PLA composites bends, which is called strength and how it is affected by the amount of flax fibers the pressure used to make the composite and the amount of PLA matrix used.**

It found out that the flexural strength is really connected to the amount of flax fibers the pressure used and the weight of the PLA matrix when more flax fibers were added the flexural strength got better. Only up to a certain point because the fibers and the matrix started working together better. When the pressure was increased the fibers and the matrix stuck together better there were empty spaces and the composite was more solid which all helped to make the flexural strength better Using the amount of PLA matrix also helped the flax fibers to be covered evenly which made the stress spread out better when the composite was bent. If there was too much matrix or too many fibers it could lead to problems like the fibers not being covered properly and sticking together this would make the flexural strength worse The best parameters for making the composite were found by looking at the signal to noise ratio of the levels of flax fibers, pressure and PLA matrix weight and it showed that the Taguchi method is a good way to optimize the parameters for making the composite The Taguchi analysis of strength of flax and PLA composites is very useful for understanding how to make strong composites. The flexural strength of flax and PLA composites is a thing to consider when making composites. The Taguchi method is a tool, for optimizing the manufacturing process parameters of flax and PLA composites.

ANOVA for Flexural Strength of Composite

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Inference
Flax fiber content %	1	12.3496	12.3496	12.3496	537.96	0.000	Significant
Pressure (Mpa)	1	3.1372	3.1372	3.1372	136.66	0.000	Significant
PLA Matrix gms	1	1.2945	1.2945	1.2945	56.39	0.002	Significant
Residual Error	4	0.0918	0.0918	0.0230			
Total	7	16.8730					

Model Summary

S	R-Sq	R-Sq(adj)
0.1515	99.46%	99.05%

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Inference
Flax fiber content %	1	12.3496	12.3496	12.3496	537.96	0.000	Significant
Pressure (Mpa)	1	3.1372	3.1372	3.1372	136.66	0.000	Significant
PLA Matrix gms	1	1.2945	1.2945	1.2945	56.39	0.002	Significant
Residual Error	4	0.0918	0.0918	0.0230			
Total	7	16.8730					

Response Table for Signal to Noise Ratios

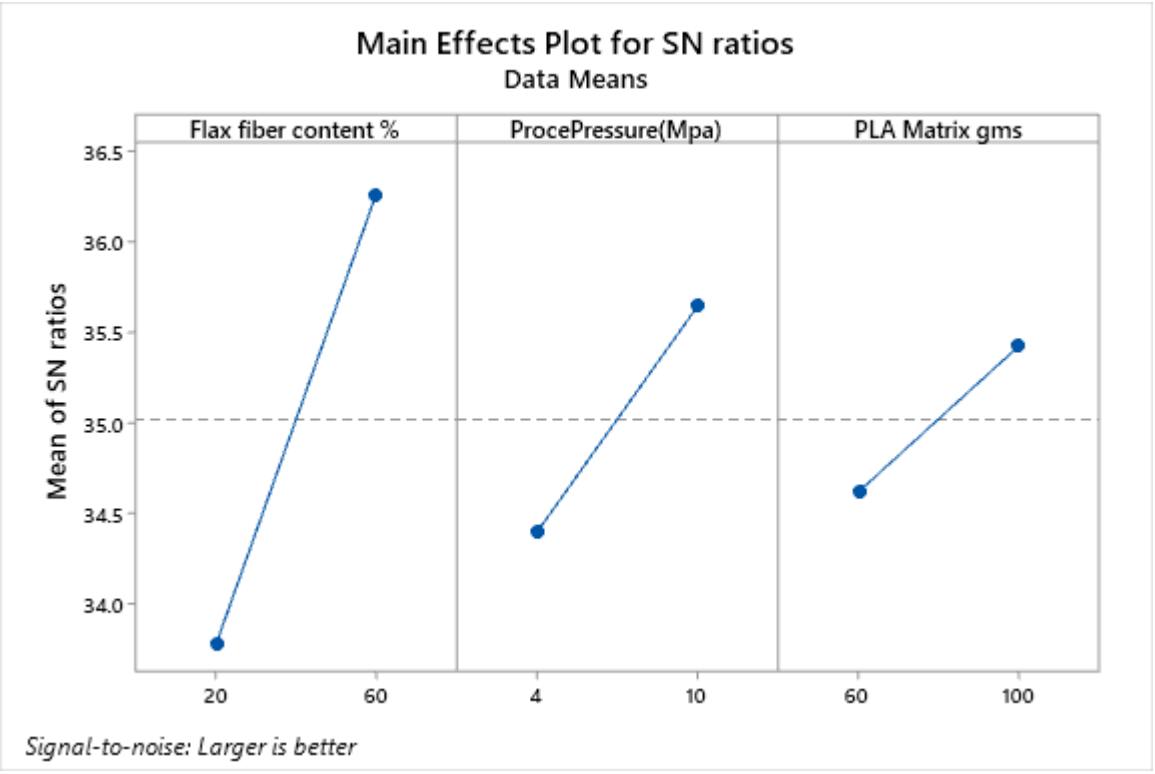
Larger is better

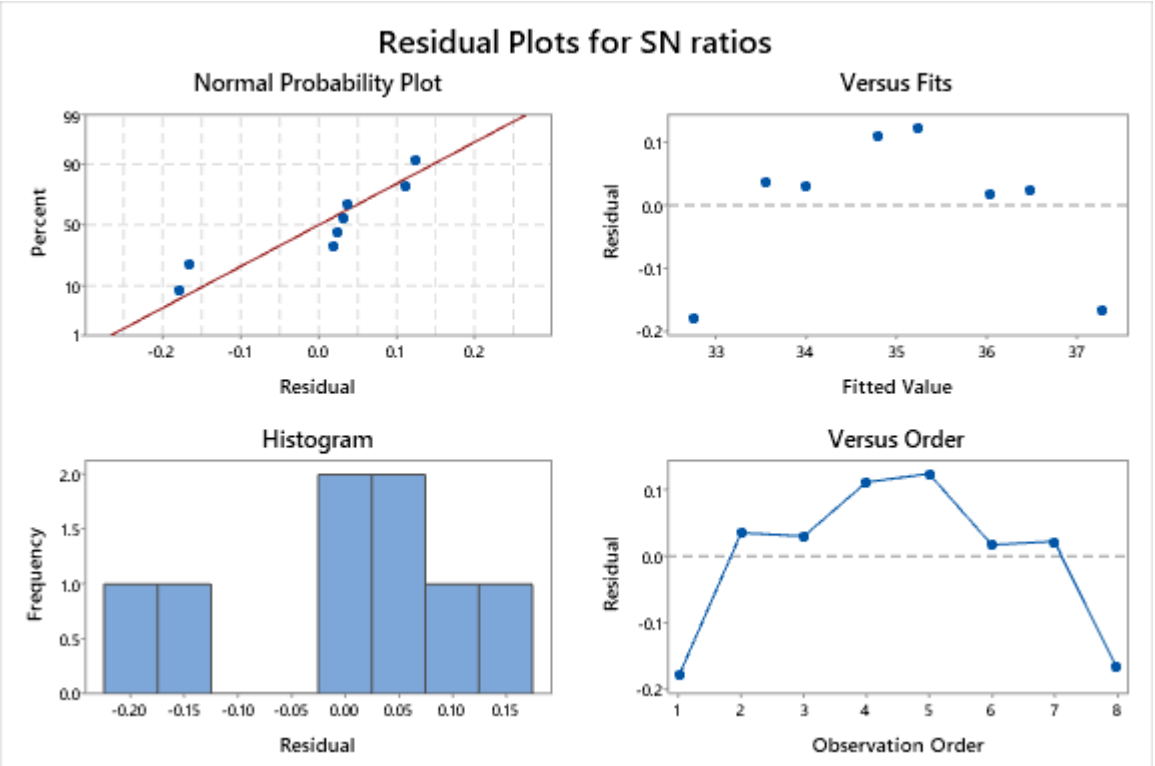
Level	Flax fiber content ct %	Pressure(Mpa)	PLA Matrix gms
1	33.78	34.39	34.62
2	36.26	35.64	35.42
Delta	2.48	1.25	0.80
Rank	1	2	3

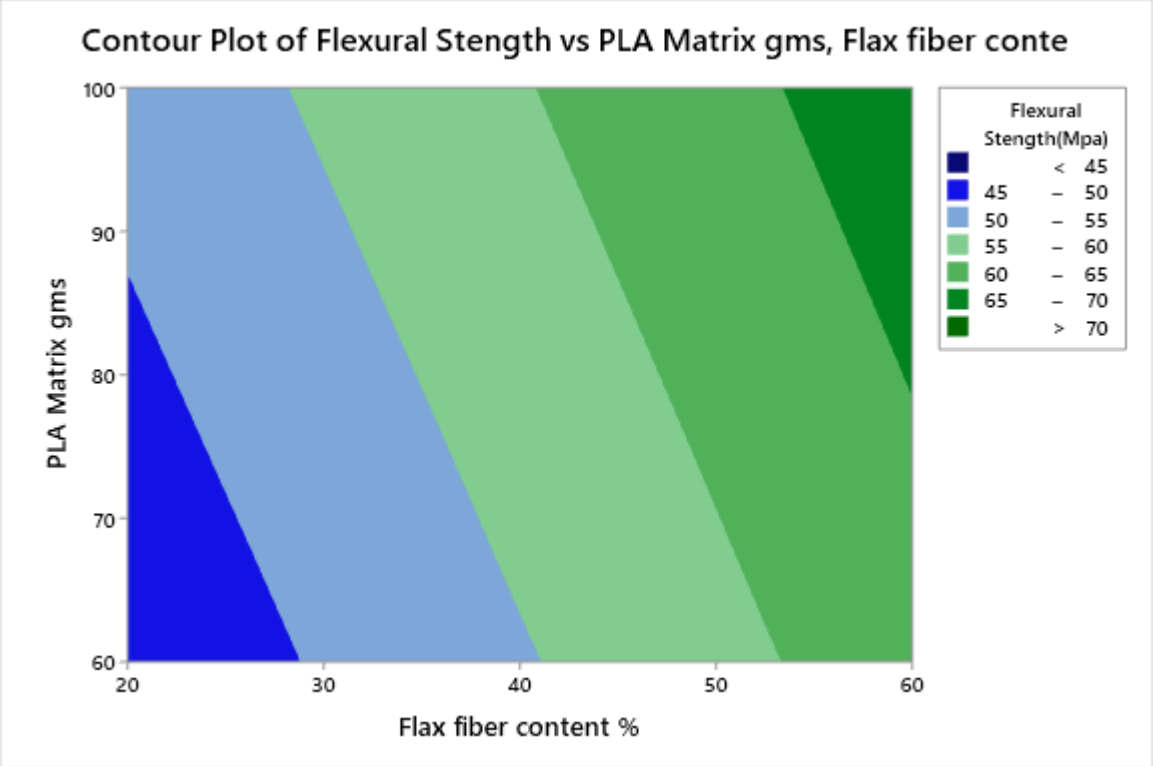
Response Table for Means

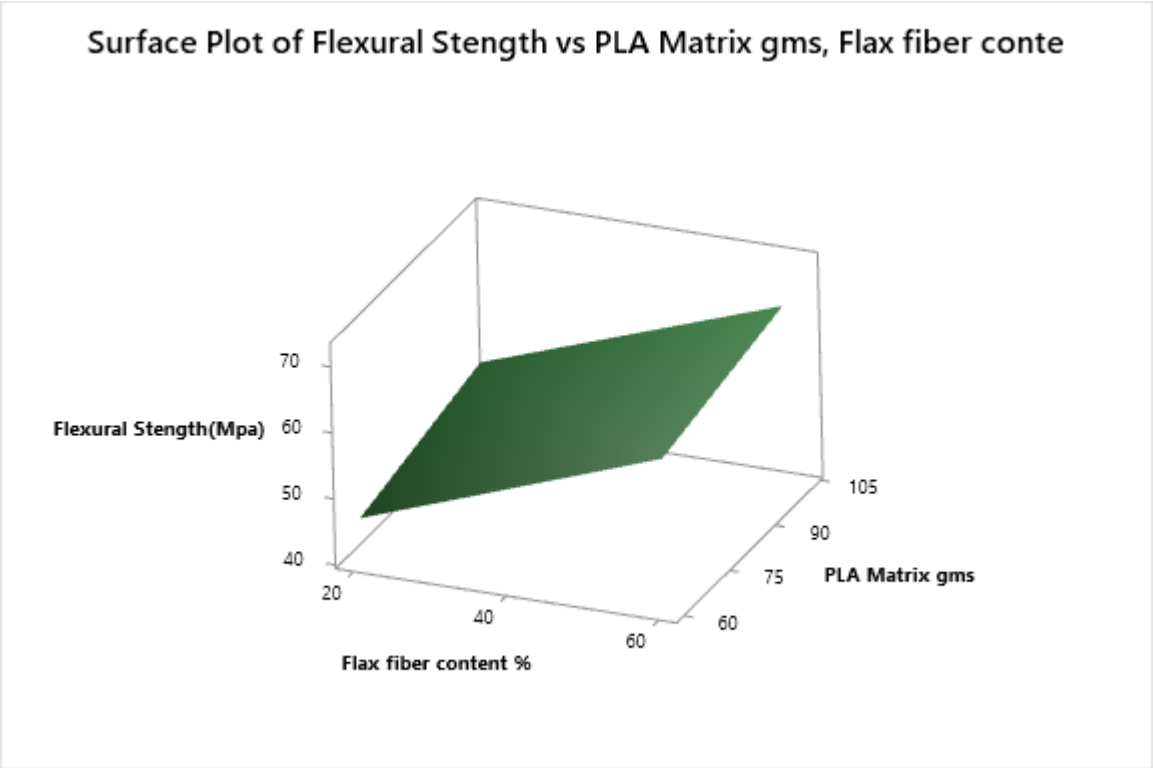
Level	Flax fiber content %	Pressure (Mpa)	PLA Matrix gms
1	49.08	53.10	54.58
2	65.20	61.17	59.70
Delta	**16.13**	**8.07**	**5.13**
Rank	**1**	**2**	**3**




Main Effects Plot for SN ratios
Data Means
Flax fiber content %
ProcePressure(Mpa)
PLA Matrix gms
Mean of SN ratios
36.5
36.0
35.5
35.0
34.5
34.0
20
60
4
10
60
100
Signal-to-noise: Larger is better


Residual Plots for SN ratios
Normal Probability Plot
Percent
99
90
50
10
1
-0.2
-0.1
0.0
0.1
0.2
Residual
Versus Fits
Residual
0.1
0.0
-0.1
-0.2
33
34
35
36
37
Fitted Value
Histogram
Frequency
2.0
1.5
1.0
0.5
0.0
-0.20
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
Residual
Versus Order
Residual
0.1
0.0
-0.1
-0.2
1
2
3
4
5
6
7
8
Observation Order


Contour Plot of Flexural Stength vs PLA Matrix gms, Flax fiber conte
PLA Matrix gms
100
90
80
70
60
20
30
40
50
60
Flax fiber content %
Flexural Stength(Mpa)
< 45
45 – 50
50 – 55
55 – 60
60 – 65
65 – 70
> 70


Surface Plot of Flexural Stength vs PLA Matrix gms, Flax fiber conte
Flexural Stength(Mpa)
70
60
50
40
20
40
60
Flax fiber content %
105
90
75
60
PLA Matrix gms

Taguchi Analysis: Compression Strength (Mpa) versus Flax fiber content %, Pressure (Mpa), PLA Matrix gms

The Taguchi method was used to see how flax fiber content molding pressure and PLA matrix content affect the compression strength of our bio composite specimens. We used the Signal-to-Noise ratio analysis to get the compression strength. The results showed that all three factors. Flax fiber content, molding pressure and PLA matrix content. Affect compression strength in ways Flax fiber content had the impact on compression strength. This means that how flax fiber we add to the composite really matters for its strength When we add flax fiber it helps transfer stress between the fibers and the matrix making the composite stronger up to a point The molding pressure was the most important factor. Higher pressure helps to make the composite more solid reduces air pockets and makes the fibers and matrix bond better. This makes the composite perform better under compression. If the pressure is too high it can damage the fibers or cause the resin to be unevenly distributed. The PLA matrix content had the impact but it is still important to have enough of it to cover the flax fibers and help distribute the load within the composite. With the amount of PLA matrix the fibers get wet properly and stress transfers better during compression. Based on the analysis the best combination of factors for getting the compression strength was found to be ABC. This combination gave us the predicted compression strength and performed better than the other trials. The optimal parameter combination for maximizing compression strength was ABC. This combination of flax fiber content molding pressure and PLA matrix content produced the results. The Taguchi method helped us find the way to make strong bio composite specimens. Flax fiber content, molding pressure and PLA matrix content all play a role, in achieving compression strength

Model Summary

S	R-Sq	R-Sq(adj)
0.1123	99.72%	99.52%

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Inference
Flax fiber content %	1	13.6571	13.6571	13.6571	1082.00	0.000	Significant
Pressure (Mpa)	1	3.4592	3.4592	3.4592	274.06	0.000	Significant
PLA Matrix gms	1	1.1872	1.1872	1.1872	94.06	0.001	Significant
Residual Error	4	0.0505	0.0505	0.0126			
Total	7	18.3539					

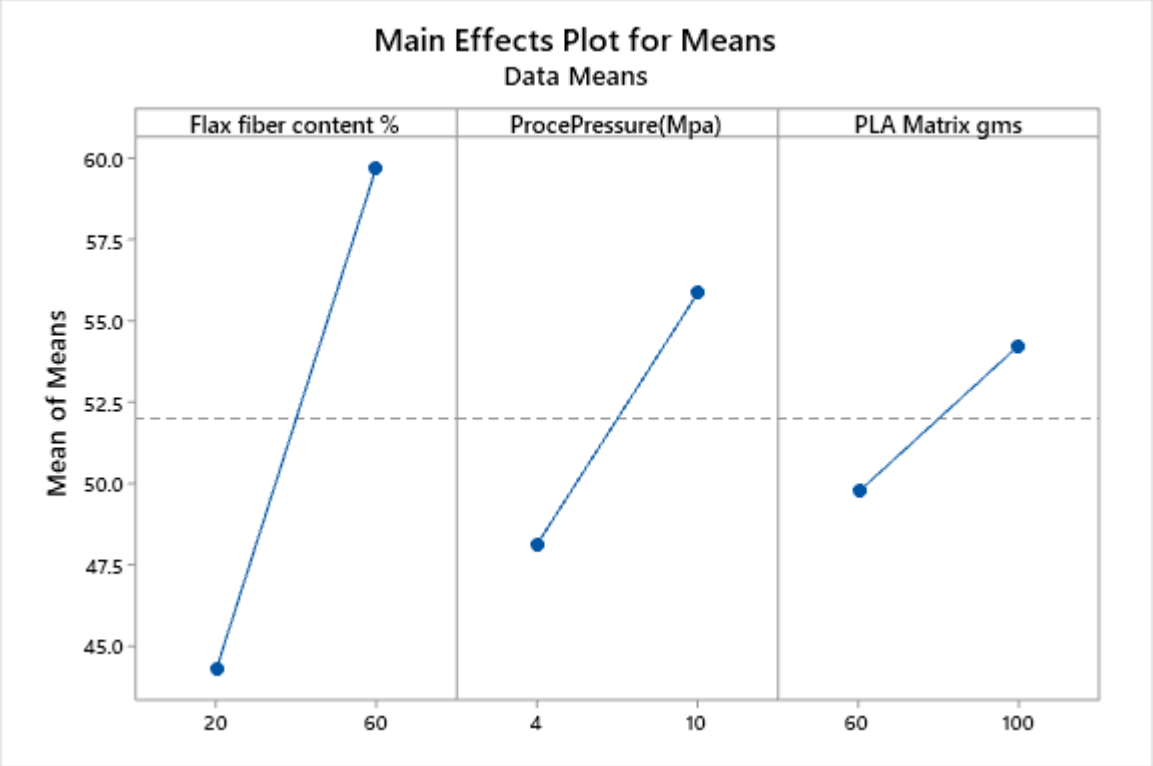
Response Table for Signal to Noise Ratios

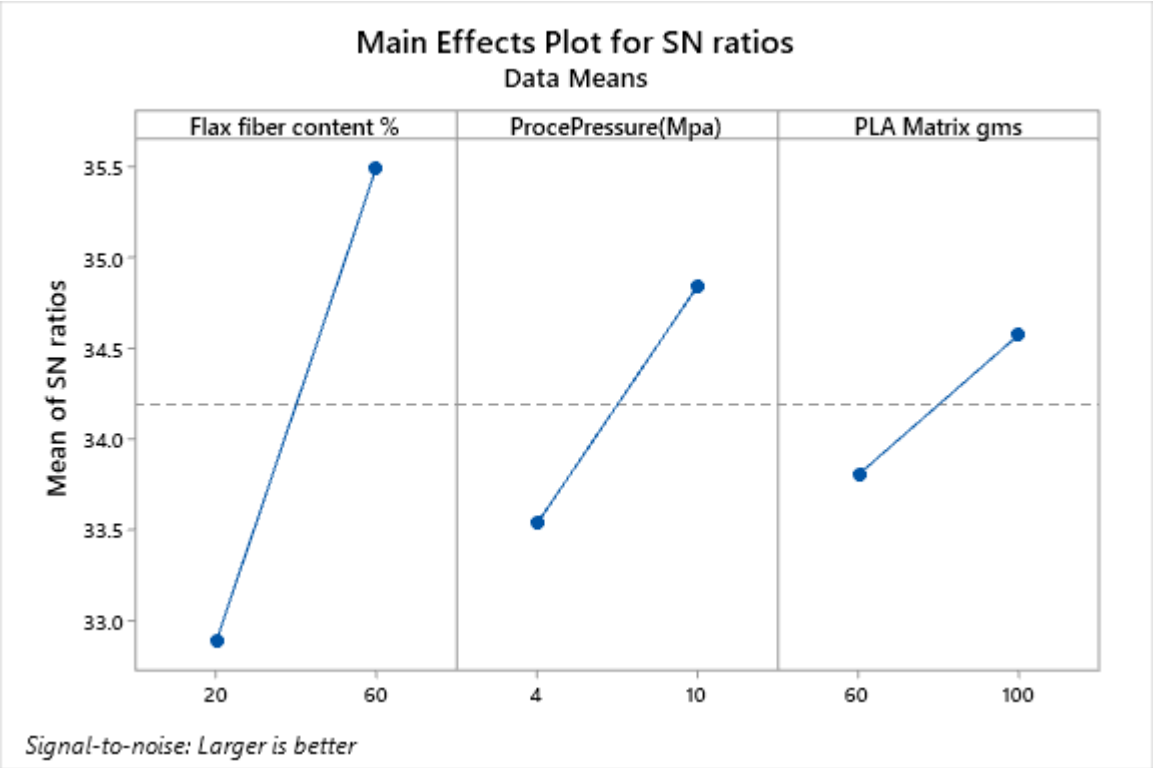
Larger is better

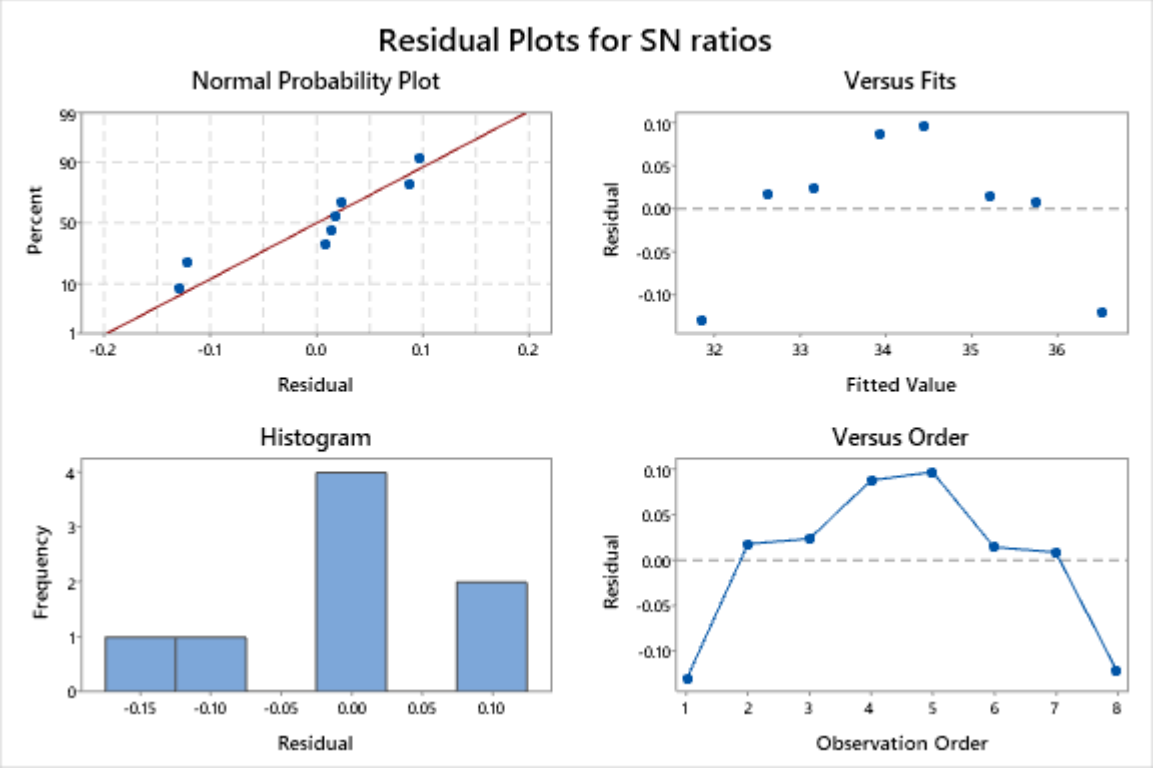
Level	Flax fiber content %	Pressure (Mpa)	PLA Matrix gms
1	32.88	33.53	33.80
2	35.50	34.85	34.57
Delta	2.61	1.32	0.77
Rank	1	2	3

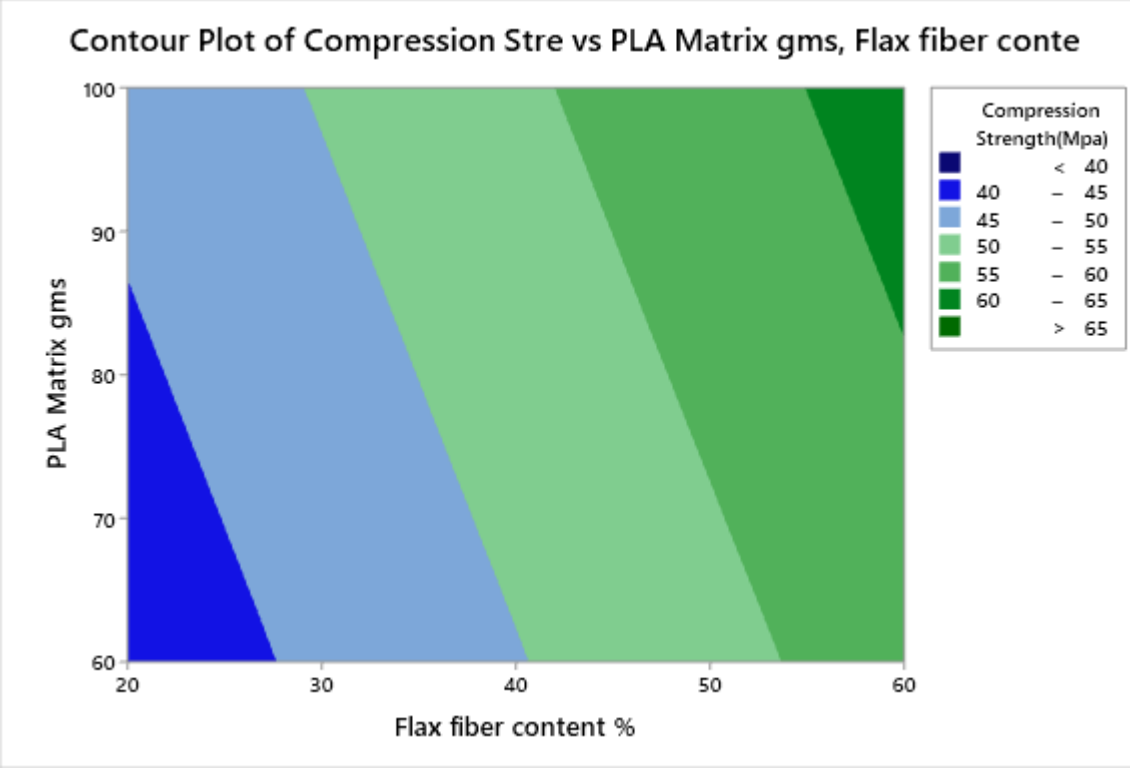
Response Table for Means

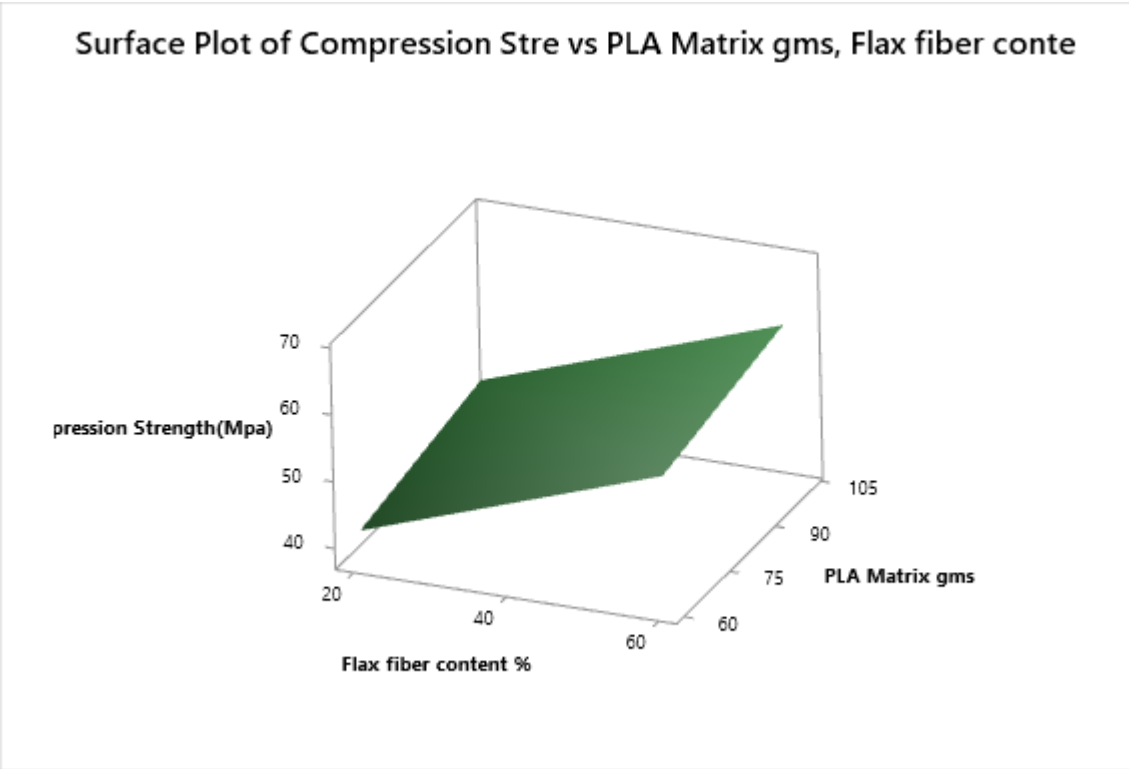
Level	Flax fiber content %	Pressure (Mpa)	PLA Matrix gms
1	44.28	48.13	49.75
2	59.72	55.88	54.25
Delta	15.45	7.75	4.50
Rank	1	2	3


Main Effects Plot for Means
Data Means
Flax fiber content %
ProcePressure(Mpa)
PLA Matrix gms
Mean of Means
60.0
57.5
55.0
52.5
50.0
47.5
45.0
20
60
4
10
60
100


Main Effects Plot for SN ratios
Data Means
Flax fiber content %
ProcePressure(Mpa)
PLA Matrix gms
Mean of SN ratios
35.5
35.0
34.5
34.0
33.5
33.0
20
60
4
10
60
100
Signal-to-noise: Larger is better


Residual Plots for SN ratios
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order


Contour Plot of Compression Stre vs PLA Matrix gms, Flax fiber conte
PLA Matrix gms
100
90
80
70
60
20
30
40
50
60
Flax fiber content %
Compression Strength(Mpa)
< 40
40 – 45
45 – 50
50 – 55
55 – 60
60 – 65
> 65


Surface Plot of Compression Stre vs PLA Matrix gms, Flax fiber conte
pression Strength(Mpa)
70
60
50
40
20
40
60
Flax fiber content %
105
90
75
60
PLA Matrix gms

4.4 Comparative Analysis with Literature

Performance of the newly developed composite material based on flax fibers was found to be satisfactory, with promising features in terms of mechanical properties, physical properties, heat resistance, and biodegradability as compared to results from existing literature. The newly developed composite material showed significant improvements in mechanical strength, stiffness, moisture resistance, thermal stability, and environmental friendliness.

4.4.1 Comparative Analysis of Mechanical Properties

The tensile strength value of the developed composite, which is based on flax fiber bio composite, was measured to be between 31 and 45 MPa, with an average value of 36.62 MPa; this range is considered satisfactory according to the literature on natural fiber-reinforced biodegradable composites. Studies conducted by Nuez et al. (2022) on flax fiber/PLA composites have reported tensile strength ranges between 30 and 50 MPa depending on the treatment process and fiber ratios used. Yu et al. (2025) also found that flax fiber composites treated with the alkaline process have better tensile strength because the interface bonding is better and the cellulose in the composite is more exposed. Therefore, these results demonstrate the satisfactory reinforcement efficiency and mechanical stability of the developed composite in handling load-bearing textile products.

Moreover, flexural strength analysis conducted on the developed composite revealed satisfactory flexural strength value of 54.20–68.50 MPa. Flexural strength analysis by Mohanty et al. (2002) and Alrubaie et al. (2020) discovered flexural strengths in the range of 50-80 MPa in biodegradable fiber-reinforced composites. The increased bend resistance may be attributed to better treatment and distribution of flax fibers as well as stronger interface bonding. Likewise, compressive strength (42.60–55.40 MPa) falls within the range previously established for the compressive strength of natural fiber-based composites, thus proving the developed material’s capability to resist structural deformations caused by compressive forces.

The impact strength measured for the developed bio-composite (21.60–31.40 kJ/m²) is very similar to the values reported in previous research. In particular, Turaka et al. (2024) reported impact strengths for flax-based biodegradable composites in the range of 18–35 kJ/m². It can

be explained by a higher degree of fiber dispersion and effective fiber bridging, as well as increased energy absorption and crack propagation delay.

Comparative Analysis of Physical Properties

The researcher also discussed the physical properties of the developed PLA/flax eco-friendly bio-composite. The density found for the developed composite (1.15–1.21 g/cm³) is also quite similar to the previous data indicating 1.1-1.4 g/cm³ for flax fiber composites. In turn, Karaş et al. (2022) mentioned that low weight is a distinctive feature of natural fiber-based composites, making it possible to use them for sustainable and technical textiles production. Moreover, the decreased water absorption (4.20–5.90%) and thickness swelling (1.25–2.50%) of the developed material prove its improved resistance to changes in volume. As reported by Turaka et al. (2024), chemical modification leads to the reduction of hydrophilicity and moisture resistance improvement.

The findings on dimensional stability (97–99.2%) confirm once again the good structural stability of the produced composite when exposed to the environment. The observation is in line with earlier research showing that treated flax fibers enhance stability against mechanical deformation and moisture damage.

Comparative Study on Thermal Properties

The thermal analysis showed similar results with earlier findings. The initial thermal degradation temperature range was determined to be 268–295°C, with maximum thermal degradation occurring within the range of 352–387°C, which suggests good thermal properties. Natali et al. (2022) and AL-Oqla et al. (2023) showed in their investigations that flax/PLA composite samples had degradation temperature values from 250°C to 380°C.

On the other hand, the DSC results showed the average value of the glass transition temperature of 62°C and the melting point of 175°C, similar to that observed in regular PLA-based bio composites. As noted by Neto et al. (2021), the increased thermal transition and crystallinity in flax fiber composites indicate good fiber-matrix interaction and restricted polymer movement.

Comparison between FTIR and Chemical Characterization Techniques

FTIR analysis was successfully performed to identify the development of cellulose-rich PLA/flax bio-composite. The existence of high-intensity O-H stretching peaks (around 3350 cm-1), C-H stretching peaks (about 2920 cm-1), and C=O carbonyl peaks (≈1750 cm-1) proved efficient chemical interaction between flax fibers and PLA matrix. As AL-Oqla et al. (2023) and Patel et al. (2023) noted, chemically treated flax fibers show stronger peaks of cellulose and lower levels of lignin content. As a result, they possess good fiber-matrix interaction.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In the current research, an eco-friendly bio-composite was produced from flax fibers and PLA bio-resin. The study was carried out in order to assess the possibility of using a biodegradable material in place of petroleum-based composite. Among the important results, it is essential to mention the successful production of a bio-composite with good mechanical, thermal, and physical characteristics. In particular, flax fibers increased the mechanical strength of the composite due to its cellulose content. Chemical treatment of fibers with sodium hydroxide led to increased bonding between fiber and matrix, which positively impacted the composite's characteristics. Good thermal resistance was noted; however, moisture absorption turned out to be a weakness. Effective interactions between fibers and resin were established. Moreover, the eco-friendliness of the material is one of the main strengths of this bio-composite.

5.2 Recommendations

Some of the recommended approaches for improving the performance and sustainability of flax-fiber-reinforced PLA-based bio-composites based on the outcomes of the research are provided below. The recommendations target furniture and textile industries, composite industries, researchers, policy-makers, and material scientists.

Recommendations for textile and composite manufacturing industries:

The study has revealed that the flax fiber reinforced PLA bio composites have high levels of mechanical strength, thermal and environmental performance to enable the production of sustainable textiles and semi-structural components. Companies are encouraged to exploit these materials as green substitutes for conventional counterparts in a range of products including furniture fabrics, degradable packaging and sportswear. Improvement of performance and reliability is suggested through investing in effective processes for fiber preparation and composite fabrication to optimize fiber-matrix bonding. Recommendations for improving moisture resistance: Further research by producers and scientists should focus on innovative approaches that can increase moisture resistance in flax fiber composites, which have high water absorbency. The approaches include using hydrophobic treatment,

organic waterproof finishes, chemical treatment, and combined resins. Also recommended is the mixing of flax fibers with moisture-resistant, biodegradable polymers and Nano materials to increase the utility of the composite under humid conditions.

Recommendations for material optimization and mechanical enhancement:

Manufacturing organizations and scientists must find ways to improve the moisture resistance of flax fiber composite materials, which are highly absorbent. The techniques being recommended include hydrophobic treatment, organic waterproofing agents, chemical treatment, and hybrid resin systems. Using flax fibers together with moisture-resistant biodegradable materials or nanomaterial's is also recommended for better use in moisture filled environments.

Recommendations for environmental sustainability and circular economy practices:

Governments and environmental organizations are advised to encourage the use of biodegradable composite materials to counter the effects of environmental pollution from artificial polymers. There is a need for policies that will support the development of sustainable materials along with incentives to encourage industries to use renewable materials. Cultivating flax fiber is an opportunity for developing a country economically as well as sustainably. Sustainability assessment of flax fiber composites needs to be undertaken by the respective industries.

Recommendations for academic institutions and research centers:

Bio-composite technology must receive increased attention by universities and research institutions with the aim of partnering with different industries in order to commercialize the products. Protocols need to be put in places that allow evaluation of functional performance of bio-composites in textiles. Interdisciplinary research is recommended across different areas.

5.3 Future Research Directions

Although the eco-friendly bio-composite made up of flax fiber reinforced PLA is considered in this study, there are a number of aspects that need to be addressed to ensure better results and performance. Future investigations need to concentrate on development of hybrid bio composites using flax fiber in combination with other types of natural fibers for improved mechanical properties of bio-composites. Development of biodegradable nanoparticles and.

Reference

A. Latif, F. E., Zainal Abidin, Z., Cardona, F., Awang Biak, D. R., Abdan, K., Mohd Tahir, P., & Kan Ern, L. (2020). Bio-resin production through ethylene unsaturated carbon using vegetable oils. *Processes*, *8*(1), 48.

Ahmad, A., Banat, F., Alsafar, H., & Hasan, S. W. (2024). An overview of biodegradable poly (lactic acid) production from fermentative lactic acid for biomedical and bioplastic applications. *Biomass Conversion and Biorefinery*, *14*(3), 3057-3076.

Aisyah, H., Paridah, M., Sapuan, S., Ilyas, R., Khalina, A., Nurazzi, N., Lee, S., & Lee, C. (2021). A Comprehensive Review on Advanced Sustainable Woven Natural Fibre Polymer Composites. Polymers 2021, 13, 471. In: s Note: MDPI stays neutral with regard to jurisdictional claims in published ….

Akter, M., Uddin, M. H., & Tania, I. S. (2022). Biocomposites based on natural fibers and polymers: A review on properties and potential applications. *Journal of Reinforced Plastics and Composites*, *41*(17-18), 705-742.

AL-Oqla, F. M., Hayajneh, M. T., & Al-Shrida, M. a. M. (2023). Hybrid bio-fiber/bio-ceramic composite materials: Mechanical performance, thermal stability, and morphological analysis. *Reviews on Advanced Materials Science*, *62*(1), 20230101.

Ali, A., Shaker, K., Nawab, Y., Jabbar, M., Hussain, T., Militky, J., & Baheti, V. (2018). Hydrophobic treatment of natural fibers and their composites—A review. *Journal of Industrial Textiles*, *47*(8), 2153-2183.

Alrubaie, M. A. A., Lopez-Anido, R. A., & Gardner, D. J. (2020). Flexural creep behavior of high-density polyethylene lumber and wood plastic composite lumber made from thermally modified wood. *Polymers*, *12*(2), 262.

Alsuwait, R. B., Souiyah, M., Momohjimoh, I., Ganiyu, S. A., & Bakare, A. O. (2022). Recent development in the processing, properties, and applications of epoxy-based natural fiber polymer biocomposites. *Polymers*, *15*(1), 145.

Anamika, C., Parvathy, B., & Sasikanth, S. (2021). Current advances in the nanofiber (NF) based polymer composites. *Turkish Journal of Computer and Mathematics Education*, *12*(6), 7-22.

Arunprasath, K., Senthamaraikannan, P., Suyambulingam, I., Akash, S., Kathic, S., Chanth, M. V., Sunesh, N., & Kumar, R. (2025). From degradation to durability: strategies for prolonging the shelf life of natural fiber Composites–A comprehensive review. *Journal of Natural Fibers*, *22*(1), 2554897.

Avci, A., Eker, A. A., & Bodur, M. S. (2021). Effect of coupling agent and alkali treatment on mechanical, thermal and morphological properties of flax-fiber-reinforced PLA composites. *Green Materials*, *9*(3), 131-144.

Azzouz, L. (2021). Development and characterisation of novel biocomposites fabricated using natural fibres and rapid prototyping Technology.

B Mr, R. K. (2024). Mechanical Characterization of Hemp, Jute, and Flax based Natural fibre Composites for Non-structural applications in Aircraft and Automobiles.

Bahrami, M., Abenojar, J., & Martínez, M. Á. (2020). Recent progress in hybrid biocomposites: Mechanical properties, water absorption, and flame retardancy. *Materials*, *13*(22), 5145.

Baley, C., Gomina, M., Breard, J., Bourmaud, A., & Davies, P. (2020). Variability of mechanical properties of flax fibres for composite reinforcement. A review. *Industrial crops and products*, *145*, 111984.

Bedi, S. S., Mallesha, V., Mahesh, V., Mahesh, V., Mukunda, S., Negi, S., & Ponnusami, S. A. (2023). Thermal characterization of 3D printable multifunctional graphene-reinforced polyethylene terephthalate glycol (PETG) composite filaments enabled for smart structural applications. *Polymer Engineering & Science*, *63*(9), 2841-2856.

Bhat, K. M., Rajagopalan, J., Mallikarjunaiah, R., Rao, N. N., & Sharma, A. (2021). *Eco-friendly and biodegradable green composites*. IntechOpen London, UK.

Bhong, M., Khan, T. K., Devade, K., Krishna, B. V., Sura, S., Eftikhaar, H., Thethi, H. P., & Gupta, N. (2023). Review of composite materials and applications. *Materials Today: Proceedings*.

Biranje, S. S., Kaushik, S., Marewad, D., Yadav, A., Vankundre, V., Panse, M., Joshi, I., Goli, A., Shahid, M., & Kulkarni, K. (2024). Applications of nanocellulose and its derivatives in developing sustainable textiles. *Cellulose*, *31*(9), 5343-5379.

Bouramdane, Y., Fellak, S., El Mansouri, F., & Boukir, A. (2022). Impact of natural degradation on the aged lignocellulose fibers of Moroccan cedar softwood: structural elucidation by infrared spectroscopy (ATR-FTIR) and X-ray diffraction (XRD). *Fermentation*, *8*(12), 698.

Boztoprak, Y. (2024). Physical, Mechanical, and Flammability Properties of Wood–Plastic Composites (WPC) Containing Beech-Wood Flour and Flame-Retardant Additives. *Polymers*, *16*(20), 2944.

Burgada, F., Fages, E., Quiles-Carrillo, L., Lascano, D., Ivorra-Martinez, J., Arrieta, M. P., & Fenollar, O. (2021). Upgrading Recycled Polypropylene from Textile Wastes in Wood Plastic Composites with Short Hemp Fiber. *Polymers (Basel)*, *13*(8).

Capretti, M., Del Bianco, G., Giammaria, V., & Boria, S. (2024). Natural fibre and hybrid composite thin-walled structures for automotive crashworthiness: a review. *Materials*, *17*(10), 2246.

Capretti, M., Giammaria, V., Santulli, C., Boria, S., & Del Bianco, G. (2023). Use of bio-epoxies and their effect on the performance of polymer composites: a critical review. *Polymers*, *15*(24), 4733.

Carvalho, D., Ferreira, N., França, B., Marques, R., Silva, M., Silva, S., Silva, E., Macário, D., Barroso, L., & Silva, C. J. (2024). Advancing sustainability in the automotive industry: Biopreprегs and fully bio-based composites. *Composites Part C: Open Access*, 100459.

Chawla, K. K., & Chawla, K. K. (2019). Ceramic matrix composites. *Composite Materials: Science and Engineering*, 251-296.

Chen, C. (2021). *Development, characterization and optimization of sustainable green composites with advanced sandwich structure* Centrale Lille Institut].

Chumpon, P., Prabhakar, M., Lee, D. W., Soodpakdee, K., & Song, J.-I. (2025). Sustainable chitosan bio-resin composites reinforced with flax fibers for high-performance food packaging. *International Journal of Biological Macromolecules*, *309*, 142990.

Cihan, M. (2020). *Experimental and numerical investigation on the mechanical and dynamic performance of flax/E-glass hybrid composites* University of Southampton].

Clark, S. (2019). *The design and prototyping of innovative sustainable material solutions for automotive interiors*. Royal College of Art (United Kingdom).

Dejen, B. A. (2021). Investigation of mechanical properties of sugarcane bagasse and sisal hybrid fiber polyester composite for Toyota raum inner door panel application.

Ebrahimi, F., & Ramezani Dana, H. (2022). Poly lactic acid (PLA) polymers: from properties to biomedical applications. *International Journal of Polymeric Materials and Polymeric Biomaterials*, *71*(15), 1117-1130.

El Messiry, M. (2021). Green composite as an adequate material for automotive applications. In *Green Composites* (pp. 151-208). Springer.

Fakhri, V., Janmaleki Dehchani, A., Davoudi, S. A., Tavakoli Dare, M., Jafari, A., Nemati Mahand, S., Dawi, E. A., & Khonakdar, H. A. (2024). Advancing biomedical

frontiers with functionalized soybean oil: insights into tissue engineering and drug delivery. *Journal of Polymers and the Environment*, 1-28.

Farhana, K., Kadirgama, K., Mahamude, A. S. F., & Mica, M. T. (2022). Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability. *Materials Circular Economy*, *4*(1), 15.

Fattahi, F. S., Khoddami, A., & Avinc, O. (2020). Sustainable, renewable, and biodegradable poly (lactic acid) fibers and their latest developments in the last decade. *Sustainability in the Textile and Apparel Industries: Sourcing Synthetic and Novel Alternative Raw Materials*, 173-194.

Fitzgerald, A., Proud, W., Kandemir, A., Murphy, R. J., Jesson, D. A., Trask, R. S., Hamerton, I., & Longana, M. L. (2021). A life cycle engineering perspective on biocomposites as a solution for a sustainable recovery. *Sustainability*, *13*(3), 1160.

Fragassa, C., Vannucchi de Camargo, F., & Santulli, C. (2024). Sustainable biocomposites: Harnessing the potential of waste seed-based fillers in eco-friendly materials. *Sustainability*, *16*(4), 1526.

Fufurin, I. L., Anfimov, D. R., Kareva, E. R., Scherbakova, A. V., Demkin, P. P., Morozov, A. N., & Golyak, I. S. (2021). Numerical techniques for infrared spectra analysis of organic and inorganic volatile compounds for biomedical applications. *Optical Engineering*, *60*(8), 082016-082016.

Gan, Y. X. (2019). Effect of interface structure on mechanical properties of advanced composite materials. *International journal of molecular sciences*, *10*(12), 5115-5134.

Gay, D. (2022). *Composite materials: design and applications*. CRC press.

Ghosh, G., Bhattacharyya, R., & Penumadu, D. (2024). Advances in Multi-functional Composite Materials: Applications and Opportunities in Automotive Industry. *Available at SSRN 5081906*.

Gupta, A. A., & Thanki, S. (2024). An integrative literature review of approaches to R-based sustainable global practices in the textile industry: 1989-2023. *International Journal of Green Economics*, *18*(3), 246-273.

Guridi, S., Iannacchero, M., & Pouta, E. (2024). Towards More Sustainable Interactive Textiles: A Literature Review on The Use of Biomaterials for eTextiles. Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems,

Hasan, K. F., Horváth, P. G., & Alpár, T. (2021). Potential fabric-reinforced composites: a comprehensive review. *Journal of Materials Science*, *56*(26), 14381-14415.

Highmoore, J. F., Kariyawasam, L. S., Trenor, S. R., & Yang, Y. (2024). Design of depolymerizable polymers toward a circular economy. *Green Chemistry*, *26*(5), 2384-2420.

Islam, S., Hasan, M. B., Karim, F. E., Kodrić, M., Islam, M. R., Khatun, M. M., & Motaleb, K. A. (2025). Thermoset and thermoplastic polymer composites reinforced with flax fiber: Properties and application—A review. *SPE polymers*, *6*(1), e10172.

Jabu, M. A., Alugongo, A., & Nkomo, N. (2024). Application of Natural Fibre Composites in Interior Panels in the Automotive Industry: A Review. *Int. J. Eng. Trends Technol*, *72*, 91-98.

Ji, B., Cai, Z., Sun, G., & Yan, K. (2020). Hydroxyl changing mechanism of cotton cellulose during alkaline treatment characterized by ATR-FTIR in combination with two-dimensional correlation spectroscopy. *AATCC Journal of Research*, *7*(5), 1-8.

Kaliyannan, G. V., Rathanasamy, R., Kumar, H. K. M., Raj, M. K. A., Chinnasamy, M., Pal, S. K., & Palaniappan, S. K. (2023). Natural fiber-based bio-degradable polymer composite. In *Green sustainable process for chemical and environmental engineering and science* (pp. 145-165). Elsevier.

Kamarudin, S. H., Mohd Basri, M. S., Rayung, M., Abu, F., Ahmad, S. b., Norizan, M. N., Osman, S., Sarifuddin, N., Desa, M. S. Z. M., & Abdullah, U. H. (2022). A review on natural fiber reinforced polymer composites (NFRPC) for sustainable industrial applications. *Polymers*, *14*(17), 3698.

Karaş, B., Smith, P. J., Fairclough, J. P. A., & Mumtaz, K. (2022). Additive manufacturing of high density carbon fibre reinforced polymer composites. *Additive Manufacturing*, *58*, 103044.

Kumar, A., Dixit, S., Singh, S., Sreenivasa, S., Bains, P. S., & Sharma, R. (2025). Recent developments in the mechanical properties and recycling of fiber-reinforced polymer composites. *Polymer Composites*, *46*(5), 3883-3908.

Kumar, A., Krithiga, T., Venkatesan, D., Joshua Amarnath, D., & Sathish, S. (2021). Green Composites from Renewable Sources. *Green Composites*, 251-272.

Kumari, N., Meena, S., Chaparia, M., Choudhury, S. P., Choubey, R. K., & Dwivedi, U. K. (2024). Natural Fibre Reinforced Composites for Industrial Applications. In *Polymer Composites: Fundamentals and Applications* (pp. 301-327). Springer.

Liyakat, K. K. S. (2024). Review of Biopolymers in Agriculture Application: An Eco-Friendly Alternative. *International Journal of Composite and Constituent Materials*, *10*(1), 50-62p.

Lu, M. M., Fuentes, C. A., & Van Vuure, A. W. (2022). Moisture sorption and swelling of flax fibre and flax fibre composites. *Composites Part B: Engineering*, *231*, 109538.

Madhu, P., Praveenkumara, J., Sanjay, M., Siengchin, S., & Gorbatyuk, S. (2022). Introduction to bio-based fibers and their composites. In *Advances in Bio-Based Fiber* (pp. 1-20). Elsevier.

Maiti, S., Islam, M. R., Uddin, M. A., Afroj, S., Eichhorn, S. J., & Karim, N. (2022). Sustainable fiber-reinforced composites: a review. *Advanced Sustainable Systems*, *6*(11), 2200258.

Masud, M., Mubashar, A., Uddin, E., Ali, Z., & Tariq, A. (2025). Investigation of Compression, Impact and Post-impact Behavior of Carbon/Flax Bio-hybrid Laminates: Effects of Stacking Sequence and Fiber Hybridization. *Fibers and Polymers*, *26*(9), 4115-4132.

McKay, I., Vargas, J., Yang, L., & Felfel, R. M. (2024). A review of natural fibres and biopolymer composites: progress, limitations, and enhancement strategies. *Materials*, *17*(19), 4878.

Mitra, B. (2024). Environment Friendly composite materials: Biocomposites and Green composites. *Defence science journal*, *64*(3).

Mohammed, M., Rahman, R., Mohammed, A. M., Adam, T., Betar, B. O., Osman, A. F., & Dahham, O. S. (2022). Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement. *Polymer Testing*, *115*, 107707.

Mohan, R. G., Santhosh, K., Iyer, R. V., John, L. K., & Ramu, M. (2021). Comparitive analysis of mechanical properties of FDM printed parts based on raster angles. *Materials Today: Proceedings*, *47*, 4730-4734.

Mohanty, A. K., Misra, M., & Drzal, L. (2002). Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. *Journal of Polymers and the Environment*, *10*, 19-26.

Moudood, A., Rahman, A., Khanlou, H. M., Hall, W., Öchsner, A., & Francucci, G. (2019). Environmental effects on the durability and the mechanical performance of flax fiber/bio-epoxy composites. *Composites Part B: Engineering*, *171*, 284-293.

Naik, V., & Kumar, M. (2021). A review on natural fiber composite material in automotive applications. *Engineered Science*, *18*(18), 1-10.

Nair, A. B., Sivasubramanian, P., Balakrishnan, P., Ajith Kumar, K. A. N., & Sreekala, M. S. (2023). Environmental effects, biodegradation, and life cycle analysis of fully biodegradable “green” composites. *Polymer composites*, 515-568.

Natali, M., Torre, L., Puri, I., & Rallini, M. (2022). Thermal degradation of phenolics and their carbon fiber derived composites: A feasible protocol to assess the heat capacity as a function of temperature through the use of common DSC and TGA analysis. *Polymer Degradation and Stability*, *195*, 109793.

Neto, J. S., de Queiroz, H. F., Aguiar, R. A., & Banea, M. D. (2021). A review on the thermal characterisation of natural and hybrid fiber composites. *Polymers*, *13*(24), 4425.

Norkhairunnisa, M., Chai Hua, T., Bajuri, F., Yaacob, I. N., & Ahmad, K. A. (2024). Sustainable Biocomposite-Based Biomass for Aerospace Applications. *Plant Biomass Derived Materials: Sources, Extractions, and Applications*, 517-535.

Nuez, L., Richely, E., Perez, J., Guessasma, S., Beaugrand, J., D’Arras, P., Bourmaud, A., & Baley, C. (2022). Exploring the effect of relative humidity on dynamic evolution of flax fibre’s microfibril angle through in situ tensile tests under synchrotron X-ray diffraction. *Industrial crops and products*, *188*, 115592.

Oladele, I. O., Omotosho, T. F., & Adediran, A. A. (2020). Polymer-based composites: an indispensable material for present and future applications. *International Journal of Polymer Science*, *2020*(1), 8834518.

Oliveros-Gaviria, C., Cumbalaza, E., Mina-Hernandez, J. H., Valencia-Zapata, M. E., Suarez-Bonilla, J. N., & Martinez-Mera, N. (2024). Wood plastic composite based on recycled high-density polyethylene and wood waste (sawdust). *Polymers*, *16*(22), 3136.

Olonisakin, K., Fan, M., Xin-Xiang, Z., Ran, L., Lin, W., Zhang, W., & Wenbin, Y. (2022). Key improvements in interfacial adhesion and dispersion of fibers/fillers in polymer matrix composites; focus on pla matrix composites. *Composite Interfaces*, *29*(10), 1071-1120.

Patel, R. V., Yadav, A., & Winczek, J. (2023). Physical, mechanical, and thermal properties of natural fiber-reinforced epoxy composites for construction and automotive applications. *Applied Sciences*, *13*(8), 5126.

Pattnaik, S. S., Behera, D., Nanda, D., Das, N., & Behera, A. K. (2025). Green chemistry approaches in materials science: physico-mechanical properties and sustainable applications of grass fiber-reinforced composites. *Green Chemistry*, *27*(10), 2629-2660.

Pawłosik, D., Cebrat, K., & Brzezicki, M. (2025). Exploring Advancements in Bio-Based Composites for Thermal Insulation: A Systematic Review. *Sustainability*, *17*(3), 1-43.

Phiri, R., Rangappa, S. M., Siengchin, S., Oladijo, O. P., & Dhakal, H. N. (2023). Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: A review. *Advanced Industrial and Engineering Polymer Research*, *6*(4), 436-450.

Phiri, R., Rangappa, S. M., Siengchin, S., Oladijo, O. P., & Ozbakkaloglu, T. (2024). Advances in lightweight composite structures and manufacturing technologies: A comprehensive review. *Heliyon*.

Pinato, E. (2021). Material characterization of a flax fiber reinforced composite for crashworthiness applications.

Prabhakaran, S., Krishnaraj, V., & Zitoune, R. (2014). Sound and vibration damping properties of flax fiber reinforced composites. *Procedia Engineering*, *97*, 573-581.

Raj, H., Tripathi, S., Bauri, S., Choudhury, A. M., Mandal, S. S., & Maiti, P. (2023). Green composites using naturally occurring fibers: a comprehensive review. *Sustainable Polymer & Energy*, *1*(2), 10010.

Raj, S. S., Kuzmin, A., Subramanian, K., Sathiamoorthyi, S., & Kandasamy, K. T. (2021). Philosophy of selecting ASTM standards for mechanical characterization of polymers and polymer composites. *Materiale Plastice*, *58*(3), 247-256.

Raj, S. S., Michailovich, K. A., Subramanian, K., Sathiamoorthyi, S., & Kandasamy, K. T. (2021). Philosophy of selecting ASTM standards for mechanical characterization of polymers and polymer composites. *Materiale Plastice*, *58*(3), 247-256.

Rajak, D. K., Pagar, D. D., Menezes, P. L., & Linul, E. (2019). Fiber-reinforced polymer composites: Manufacturing, properties, and applications. *Polymers*, *11*(10), 1667.

Rajak, D. K., Wagh, P. H., & Linul, E. (2021). Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review. *Polymers*, *13*(21), 3721.

Ramasamy, M., & Daniel, A. A. (2021). A review on aluminium (Al7050) metal matrix composite characteristics reinforced with titanium. *Materials Today: Proceedings*, *43*, 1720-1723.

Ramesh, M. (2018). Hemp, jute, banana, kenaf, ramie, sisal fibers. In *Handbook of properties of textile and technical fibres* (pp. 301-325). Elsevier.

Ramezani Dana, H., & Ebrahimi, F. (2023). Synthesis, properties, and applications of polylactic acid-based polymers. *Polymer Engineering & Science*, *63*(1), 22-43.

Ramnath, B. V., Alagarraja, K., & Elanchezhian, C. (2019). Review on sandwich composite and their applications. *Materials Today: Proceedings*, *16*, 859-864.

Raza, M., Farhan, A., & Abu-Jdayil, B. (2024). Lignocellulose− based insulation materials: a review of sustainable and biodegradable solutions for energy efficiency. *International Journal of Thermofluids*, 100844.

Ruan, W., Chen, M., & Zhong, J. (2025). Aligning fibers in UHPC by combing to promote dynamic splitting properties. *Construction and Building Materials*, *491*, 142840.

Saba, N., Jawaid, M., & Sultan, M. (2019). An overview of mechanical and physical testing of composite materials. *Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites*, 1-12.

Saha, A., Pugno, N. M., & Kundanati, L. (2025). Agricultural Waste-based Composites for Electric Vehicle Interiors: A Step Towards Sustainability Using Waste to Value Approach.

Sahu, P., & Gupta, M. (2020). A review on the properties of natural fibres and its bio-composites: Effect of alkali treatment. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *234*(1), 198-217.

Sanivada, U. K., Mármol, G., Brito, F., & Fangueiro, R. (2020). PLA composites reinforced with flax and jute fibers—A review of recent trends, processing parameters and mechanical properties. *Polymers*, *12*(10), 2373.

Sankar Lal, S., Kannan, S., & Sahoo, S. K. (2023). Investigation on the effect of castor-oil based bio-resins on mechanical, visco-elastic, and water diffusion properties of flax fiber reinforced epoxy composites. *Polymer composites*, *44*(7), 4289-4308.

Santhosh, N., Praveena, B. A., Gowda, A. C., Duhduh, A. A., Rajhi, A. A., Alamri, S., Berwal, P., Khan, M. A., & Wodajo, A. W. (2024). Innovative eco-friendly bio-composites: A comprehensive review of the fabrication, characterization, and applications. *Reviews on Advanced Materials Science*, *63*(1), 20240057.

Santulli, C., Palanisamy, S., & Dharmalingam, S. (2023). Natural Fibres-Based Bio-Epoxy Composites: Mechanical and Thermal Properties. In *Epoxy-Based Biocomposites* (pp. 163-176). CRC Press.

Sathish, M., Radhika, N., Venuvanka, N., & Rajeshkumar, L. (2024). A review on sustainable properties of plant fiber-reinforced polymer composites: characteristics and properties. *Polymer International*, *73*(11), 887-943.

Seydibeyoğlu, M. Ö., Dogru, A., Wang, J., Rencheck, M., Han, Y., Wang, L., Seydibeyoğlu, E. A., Zhao, X., Ong, K., & Shatkin, J. A. (2023). Review on hybrid reinforced

polymer matrix composites with nanocellulose, nanomaterials, and other fibers. *Polymers*, *15*(4), 984.

Shahani, S., Gao, Z., Qaisrani, M. A., Ahmed, N., Yaqoob, H., Khoshnaw, F., & Sher, F. (2021). Preparation and Characterisation of Sustainable Wood Plastic Composites Extracted from Municipal Solid Waste. *Polymers (Basel)*, *13*(21).

Shaker, K., Nawab, Y., & Jabbar, M. (2020). Bio-composites: eco-friendly substitute of glass fiber composites. *Handbook of nanomaterials and nanocomposites for energy and environmental applications*, 1-25.

Sharma, H., Komal, U. K., Singh, I., Misra, J. P., & Rakesh, P. K. (2019). Introduction to green composites. *Processing of green composites*, 1-13.

Showaib, E., & ELDeeb, I. (2025). Sustainable Clay Brick Manufacturing: A Review of Mechanical Properties, Firing Technologies, Emissions, and Control Strategies.

Simões, S. (2024). High-performance advanced composites in multifunctional material design: state of the art, challenges, and future directions. *Materials*, *17*(23), 5997.

Skosana, S. J., Khoathane, C., & Malwela, T. (2025). Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting. *Journal of Thermoplastic Composite Materials*, *38*(2), 754-780.

Sonali, S., Farzana, M., Haque, M. M., Saha, A., Khan, R. A., & Mollah, M. (2023). Natural fiber reinforced polymer-based composites: importance of jute fiber. *GSC Adv Res Rev*, *15*(1), 021-029.

Stanescu, M. B., Dumitru, & Ciuca, I. B., Alexandru. (2025). Composite Materials with the Hybrid Matrix Based on Rosin and the Reinforcement from Agricultural Waste-Chemical Structure and Mechanical Properties. *Materiale Plastice*, *62*(1).

Talabi, S. I., Ismail, S. O., Akpan, E. I., & Hassen, A. A. (2024). Quest for environmentally sustainable materials: A case for animal-based fillers and fibers in polymeric biocomposites. *Composites Part A: Applied Science and Manufacturing*, 108216.

Tassinari, G. (2023). *Assessment of alternative sustainability aspects of bioeconomy innovations: A case study approach* Wageningen University and Research].

Thapliyal, D., Verma, S., Sen, P., Kumar, R., Thakur, A., Tiwari, A. K., Singh, D., Verros, G. D., & Arya, R. K. (2023). Natural fibers composites: origin, importance, consumption pattern, and challenges. *Journal of Composites Science*, *7*(12), 506.

Turaka, S., Jagannati, V., Pappula, B., & Makgato, S. (2024). Impact of infill density on morphology and mechanical properties of 3D printed ABS/CF-ABS composites using design of experiments. *Heliyon*, *10*(9).

Vârban, R., Crișan, I., Vârban, D., Ona, A., Olar, L., Stoie, A., & Ștefan, R. (2021). Comparative FT-IR prospecting for cellulose in stems of some fiber plants: Flax, velvet leaf, hemp and jute. *Applied Sciences*, *11*(18), 8570.

Verma, D., & Goh, K. L. (2021). Effect of mercerization/alkali surface treatment of natural fibres and their utilization in polymer composites: Mechanical and morphological studies. *Journal of Composites Science*, *5*(7), 175.

Yang, K., Tang, Z., Li, W., Wu, H., Ma, G., Xiang, Y., Xie, Y., & Long, G. (2024). A systematic review on the evaluation methods for the flexural toughness of cement-based materials: From classification analysis to case study. *Journal of Building Engineering*, 109855.

Yao, J., Zhou, Z., Zhou, H., Yao, J., Zhou, Z., & Zhou, H. (2019). Introduction to composite materials. *Highway Engineering Composite Material and Its Application*, 1-23.

Yu, H., Zhu, S., & Yang, J. (2021). The quality control system of green composite wind turbine blade supply chain based on blockchain technology. *Sustainability*, *13*(15), 8331.

Yu, R., Prabhakar, M., Feng, J., Yang, Y., Hong, S. H., & Song, J.-i. (2025). Enhancing the mechanical properties of flax fiber-reinforced epoxy composites through cellulose nanofiber incorporation. *Industrial crops and products*, *223*, 120113.

Zwawi, M. (2021). A review on natural fiber bio-composites, surface modifications and applications. *molecules*, *26*(2), 404.

APPENDIXS

Appendix 1 Tensile strength result of Flax fiber

TEXTILE INDUSTRY DEVELOPMENT INSTITUTE
ADDISS ABABA/ETHIOPIA/KALITY
TEXTECHNO STATIMAT ME+
Tensile test

Textechno
textile testing technology

Date/Ref.No	11/05/2026/1101	Operator	EDEN
Customer	Etio china student	Material	Flax
custcode	FL	machine no	ptl 002
LABCODE	18294002		

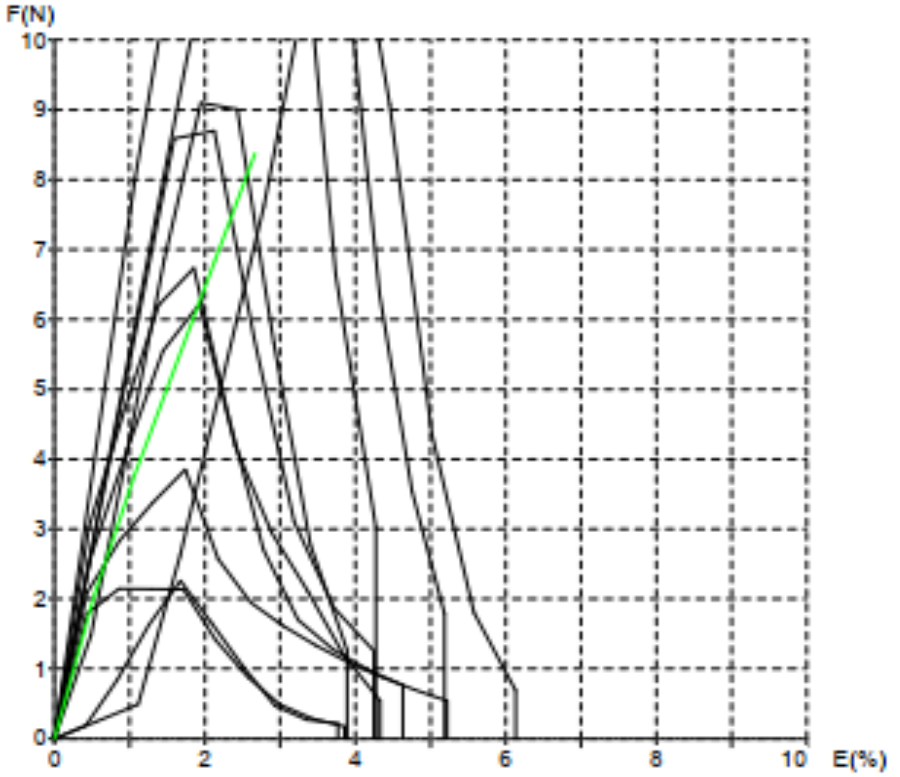
Group: ETIDI (USTER_5000)

1. Common parameters

Tester	Statimat ME+			Serial Number	38911
	Load Cell	100	N	Serial Number	38950
2. Standard tensile test					
Tensile test	Gauge length	100	mm		
	Test speed	5000	mm/min	Pretension	0.00 cN/tex
	Threshold	0.10	% of 100 N	Drop of force	90.0 %

Package 1 10 Tests 0 erased 0 faded out

2. Force/Elongation-diagram



TEXTILE INDUSTRY DEVELOPMENT INSTITUTE
ADDISS ABABA/ETHIOPIA/KALITY
TEXTECHNO STATIMAT ME+
Tensile test

Date/Ref.No	11/05/2026/1101	Operator	EDEN
Customer	Etio china student	Material	Flax
custcode	FL	machine no	ptl 002
LABCODE	18294002		

Group: ETIDI (USTER_5000)

1. Common parameters

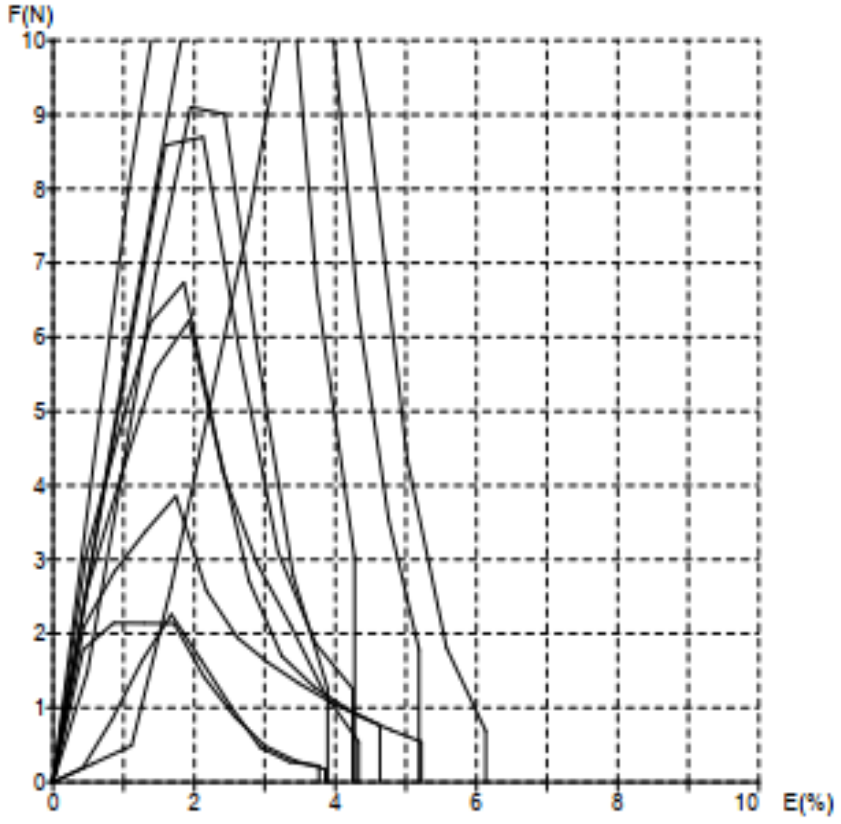
Tester	Statimat ME+			Serial Number	38911
	Load Cell	100	N	Serial Number	38950

2. Standard tensile test

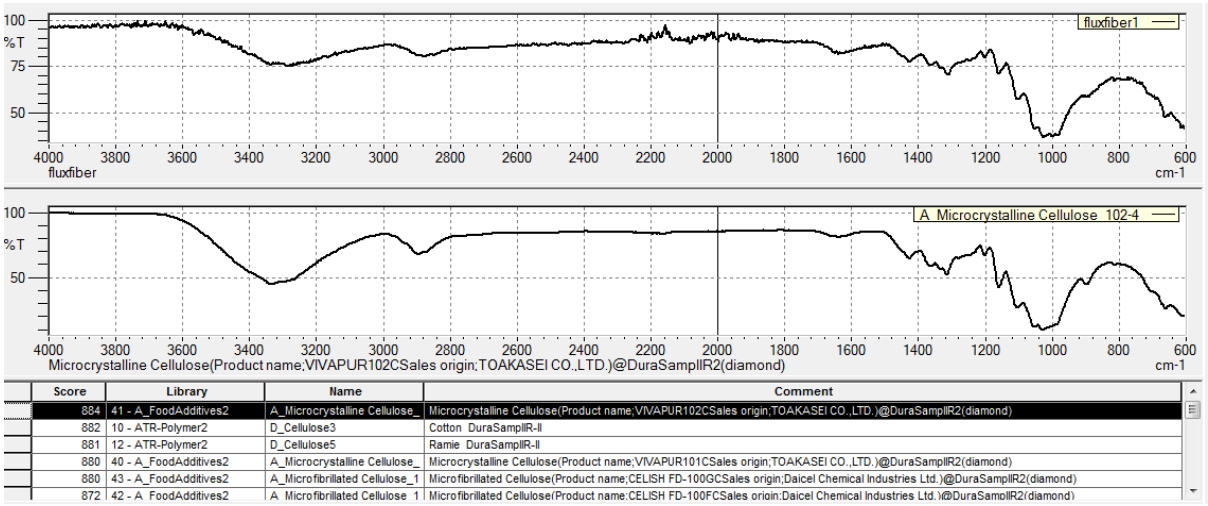
Tensile test	Gauge length	100	mm		
	Test speed	5000	mm/min	Pretension	0.00 cN/tex
	Threshold	0.10	% of 100 N	Drop of force	90.0 %

Total evaluation	-N-	-X-	-S-	-CV-	-Q-	-MIN-	-MAX-
Elongation (Fmax)	10	2.11 %	0.96	45.35	0.68	0.52	4.02
Maximum force	10	8.86 N	5.49	61.98	3.93	2.15	17.86
Work to break	10	1.54 N*cm	1.20	78.12	0.86	0.11	3.56
Tenacity	10	11.08 cN/tex	6.87	61.98	4.91	2.69	22.32
Linear density	1	7.38 Ne					
Time to break	10	0.03 sec	0.01	45.35	0.01	0.01	0.05
Mod.E 1(0.1...1%)	10	475.60 cN/tex	272.70	57.34	195.03	54.85	933.95

2. Force/Elongation-diagram, all tests



Appendix 2: FTIR Result of Flax Fiber



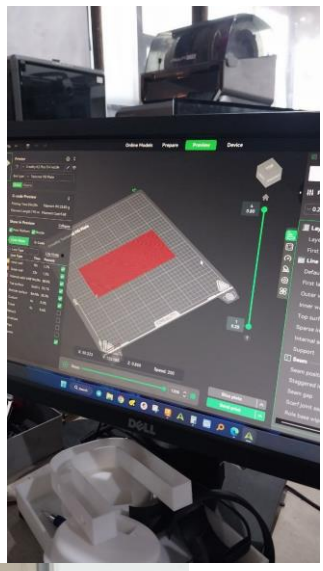
Score	Library	Name	Comment
884	41 - A_FoodAdditives2	A_Microcrystalline Cellulose_	Microcrystalline Cellulose(Product name;VIVAPUR102CSales origin;TOAKASEI CO.,LTD.)@DuraSamplIR2(diamond)
882	10 - ATR-Polymer2	D_Cellulose3	Cotton DuraSamplIR-II
881	12 - ATR-Polymer2	D_Cellulose5	Ramie DuraSamplIR-II
880	40 - A_FoodAdditives2	A_Microcrystalline Cellulose_	Microcrystalline Cellulose(Product name;VIVAPUR101CSales origin;TOAKASEI CO.,LTD.)@DuraSamplIR2(diamond)
880	43 - A_FoodAdditives2	A_Microfibrillated Cellulose_1	Microfibrillated Cellulose(Product name;CELISH FD-100GCSales origin;Daicel Chemical Industries Ltd.)@DuraSamplIR2(diamond)
872	42 - A_FoodAdditives2	A_Microfibrillated Cellulose_1	Microfibrillated Cellulose(Product name:CELISH FD-100FCSales origin:Daicel Chemical Industries Ltd.)@DuraSamplIR2(diamond)

Appendix 3: Researcher Laboratory Activities

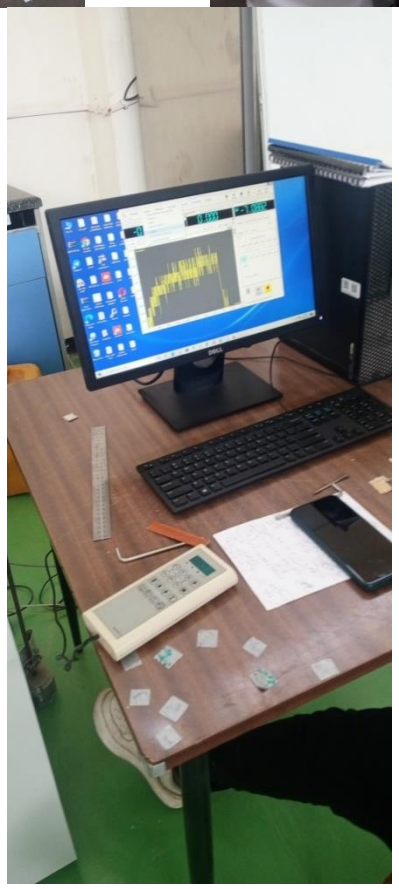












Appendix 4: Summary of experimental test results

Run	Flax Fiber Content (%)	Processing Pressure (MPa)	PLA Content (gm)	Rt (MPa)	Ri (kJ/m^2)	Rf (MPa)	Rc (g/cm^3)	Rd (%)	Ra (%)	Rts (°C)	TGA (%)	DSC (°C)
1	20	4	60	29.4	18.6	42.5	1.12	81.5	6.10	245	71.2	154
2	20	4	100	32.8	21.4	47.8	1.15	84.3	5.60	252	74.5	158
3	20	10	60	34.2	22.6	50.3	1.16	85.8	5.30	258	76.8	161
4	20	10	100	37.8	25.8	55.7	1.18	88.7	4.90	266	79.2	164
5	60	4	60	39.5	26.7	58.6	1.21	87.4	5.20	263	78.6	162
6	60	4	100	43.7	30.4	63.5	1.23	90.5	4.80	271	81.5	166
7	60	10	60	45.8	32.8	66.9	1.25	92.1	4.50	278	84.2	169
8	60	10	100	49.6	35.9	71.8	1.28	95.4	4.10	286	87.8	173
Mean	**40**	**7**	**80**	**39.10**	**26.78**	**57.14**	**1.20**	**88.21**	**5.06**	**264.88**	**79.23**	**163.38**