

FEDERAL TECHNICAL & VOCATIONAL TRAINING INSTITUTE

TEXTILE & APPAREL FASHION TECHNOLOGY FACULTY

DEPARTMENT OF TEXTILE TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

PRODUCTION AND PHYSICAL CHARACTERIZATION OF HANDMADE PAPER FROM BANANA PSEUDO STEM FIBERS

BY: ABENEZER LEMMA ERMECHO

March 2025 G.C

ADDIS ABABA, ETHIOPIA



Textile and Apparel Fashion Technology Division

M.SC. in Textile Technology

Production and Physical Characterization of Handmade Paper from Banana Pseudo stem Fibers

A Thesis Submitted to FDRE Technical &Vocational Training Institute

Faculty of Textile Technology

(Department Of Textile Technology)

In Partial Fulfillment for the Degree Master of Science of Textile Technology

By: Abenezer Lemma Ermecho

Advisor: Allah Dekama Jara (Ph.D.)

Addis Ababa, Ethiopia



የኢፌዲሪ የቴክኒክና ሙያ ስልጠና ኢንስቲትዩት
FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

Textile and Apparel Fashion Technology Division

MS.C in Textile Technology

Production and Physical Characterization of Handmade Paper from Banana Pseudo stem Fibers

By

Abenezer Lemma Ermecho

Approved by Examining Board

Name of Advisor	Signature	Date
_____	_____	_____
Name of Co-advisor	**Signature**	**Date**
_____	_____	_____
Name of Examiner, Internal	**Signature**	**Date**
_____	_____	_____
Name of Examiner, External	**Signature**	**Date**
_____	_____	_____
Name of chairperson	**Signature**	**Date**
_____	_____	_____

Declaration

I hereby proclaim that the work which is being presented in this thesis entitled "Production and Physical Characterization of Handmade Paper from Banana Pseudo stem Fibres." is my original work carried out under the supervision of Dr. Allah Dekama Jara. It has not been presented for a degree of any other university and all source of materials used for this thesis are duly acknowledged.

Name of candidate	**Signature**	**date**
Abenezer Lemma Ermecho	_____	_____

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Name of advisor	**Signature**	**Date**
Allah Dekama Jara (Ph. D)	_____	_____
Name of Co-Advisor	Signature	Date
	_____	_____

Acknowledgment

First of all I would like to glorify Heavenly God about his immeasurable love in all the spheres of my life. I would further thank my Advisor, Dr. Allah Dekama Jara (Ph.D.), with the invaluable guidance, patience as well as challenging me to dig deeper into the description of banana Fibers. The key to this research was his experience in various other universities and Ethiopian Bio Emerging institute.

I am grateful to the laboratory technicians and personnel in the federal technical and vocational training institute, textile and apparel fashion technology faculty department of textile technology who helped me to acquire the equipment and technical assistance to produce viable paper samples out of the raw banana pseudo stems.

I also appreciate Rekik Getachew, who supplied me with raw materials to make this study and Mr Genanaw Gezahegn (Bole Lemi industrial park lab facility) who gave me the assistance in sample testing. Your dedication would not have enabled this project to be feasible.

I would like to say to my friends and colleagues, thank you so much on spending me hours of brainstorming, and thanks to you who supported me in the long nights.

I also would like to give my utmost gratitude to my wife and my brother who continuously provided me with motivation during this process. It is due to their belief in my work that the completion of this thesis was possible.

List of Abbreviations and Symbols

ANOVA:	Analysis of Variance
ASTM:	American Society for Testing and Materials
COBB:	Cobb Water Absorption Test (Standard measure of liquid penetration)
FAOSTAT:	Food and Agriculture Organization Corporate Statistical Database
GHG:	Greenhouse Gas
GSM:	Grams per Square Meter (g/m2)
ISO:	International Organization for Standardization
LCA:	Life Cycle Assessment
L/M:	Liquor-to-Material Ratio
MDG:	Millennium Development Goals (Historical context)
NaOH:	Sodium Hydroxide (Caustic Soda)
pH:	Potential of Hydrogen (Measure of acidity/alkalinity)
SD:	Standard Deviation
SDG:	Sustainable Development Goal (specifically SDG 12)
SMEs:	Small and Medium Enterprises
SNNPR:	Southern Nations, Nationalities, and Peoples' Region (Ethiopia)
UNEP:	United Nations Environment Programme
UTM:	Universal Testing Machine
W/V:	Weight per Volume (Concentration ratio)
cm^3/g:	Bulk (cubic centimeters per gram)
g/m^2:	Grammage (grams per square meter)
kg/m^3:	Density (kilograms per cubic meter)
kPa:	Kilopascal (burst strength)
mm:	Millimeter (thickness measurement)
mN:	Mill newton (tear resistance)
N/15 mm:	Newtons per 15 millimeters (tensile strength)

Table of Contents

Declaration i

Acknowledgment ii

List of Abbreviations and Symbols iii

Abstract xii

CHAPTER ONE 1

1. INTRODUCTION 1

1.1 Background 2

1.2 Problem Statement 4

1.3 Objectives of the Study 4

1.3.1 General Objective 4

1.3.2 Specific Objectives 4

1.4 Research Questions 5

1.5 Significance of the Study 5

1.6 Scope of the Study 6

CHAPTER TWO 7

2. LITERATURE REVIEW 7

2.1 Introduction 7

2.2 Non-wood Fibers as Pulp and Paper Sustainable Raw Materials 7

2.3 Banana Pseudo- stems Fibers: Characteristics and composition. 7

2.3.1 Biomass Potential and Impact on the Environment. 8

2.3.2. Banana as a Pseudo stem structure: Botanical structure 9

2.3.3. Agricultural Waste and Environmental Impact 9

2.3.4. Possibility of High-Value Applications. 10

2.3.5. Chemical and Mechanical Suitability of Paper. 10

2.3.6 Industrial usage and Value addition. 11
2.3.7 Fitness to Pulp and Paper Production 11
2.3.8 A Circular Economy Approach 12
2.4 Processes of banana Fibers extraction 12
2.5 Alkaline Pulp of Banana Pseudo stem Fibers 12
2.6 Technology on Handmade Paper Production. 12
2.7 Mechanical Properties of Non-wood Handmade Paper 13
2.8 Plastic Bag Substitutes with Banana Fibers paper bags. 13
2.9 Environmental and Socioeconomic Advantages of utilizing Banana Wastes. 13
2.10 Research Gap and Literature Review Summary 13
CHAPTER THREE 15
3. METHODOLOGY 15
3.1 Introduction 15
3.2 Materials 15
3.2.1 Raw Materials 15
3.2.2 Chemicals 15
3.3 Equipment and Apparatus 15
3.4 Experimental Design 17
3.4.1 Paper Samples Preparation and Differentiation. 17
3.4.2 Controlled Pulping Parameters 18
3.4.3 Process parameters that were used to differentiate the paper samples. 18
3.4.4 Description of Sample Raw Material Processing Method. 19
3.4.2 Methodology Workflow Description 20
3.5 Fibers Extraction and Preparation 21
3.6 Alkaline Pulping Procedure 23

3.6.1 The pulping mechanism involved: 23
3.7 Pulp Refining and Slurry Preparation 24
3.8 Handmade Sheet Formation 25
3.9 Pressing and Drying 25
3.10 Fabrication of Paper Bags 26
3.11 Physical Properties Testing 26
3.11.1 Grammage (ISO 536 / TAPPI T410) 27
3.11.2 Thickness (ISO 534 / TAPPI T411) 27
3.11.3 Density and Bulk 27
3.11.4 Cobb Test (ISO 535) 28
3.12 Testing of mechanical properties of a material 28
3.12.1 Tensile Strength and Tensile Index (ISO 1924 / TAPPI T494) 28
3.12.2 Tear Resistance (ISO 1974 / TAPPI T414) 28
3.12.3 Burst Strength and Burst Index (ISO 2758 / TAPPI T403) 28
3.13 Recording and Statistical Analysis of Data 29
3.14 Ethical and Environmental Concerns. 29
3.15 Justification and Methodology validation 30
3.16 The standards on testing referenced are 30
3.17 Risk Factors and Justification Measures 31
3.18 Research Objectives Methodology Alignment. 31
3.19 Closing Section 32
CHAPTER FOUR 34
4. RESULTS AND DISCUSSION 34
4.1 Introduction 34
4.2 Physical Properties of Handmade banana pulp Paper 35

4.2.1 Basis Weight (Grammage) 35
4.2.2 Thickness Measurement and Analysis 36
4.2.3 Apparent Density: 37
4.2.4 An overview of the summative physical properties 37
4.3 Physical Characterization 37
4.3.1 Thickness and Grammage Uniformity 37
4.3.2 Tensile strength 38
4.3.3 Tear Resistance 38
4.3.4 Versatility Strength and Versatility Index 39
4.4 Comparison of the Former Research 40
4.4.1 Processing conditions 40
4.4.2 Density Benchmarks 40
4.4.3 Bulk and Tactile Quality 42
4.4.4 Optimization of Grammage 42
4.4.5 Biodegradability and Environmental Behavior 43
4.4.6 Comparison to Plastic Alternatives 43
4.5 Economic Feasibility and Community Scalability 43
4.6 Mechanical performance expected. 44
4.6.1 Performance Analysis in comparison 45
4.7 Data Analysis 46
4.7.1 Descriptive Statistics 46
4.7.2 Inferential Statistics 48
4.7.3 Correlation Analysis 49
4.7.4 Graphical Interpretation 49
4.8 Combination of Findings 50

4.8.1 Physical Properties: 51
4.8.2 Mechanical Properties: 51
4.8.3 Comparative Analysis: 51
4.8.4 Alignment with Literature: 52
4.8.5 Economic and Environmental Implications: 52
4.8.6 Summary: 52
4.9 Limitations of the Study 52
4.9.1 Restricted Pulping Conditions: 52
4.9.2 Moisture Resistance Evaluation: 53
4.9.3 Scale of Production: 53
4.9.4 Environmental Testing: 53
CHAPTER FIVE 54
5. CONCLUSION AND RECOMMENDATIONS 54
5.1 CONCLUSION 54
5.2 RECOMMENDATIONS 55
1. Quantitative Mechanical Characterization: 55
2. Optimization of Process Inter-Fibers Bonding: 55
3. Exploration of Chemical and Surface Treatment: 55
4. Comparative Performance Mapping: Hybrid Fibers Blending 56
5. Economic Feasibility and Pilot-Scale Trials: 56
6. Incorporation with National Environmental Policy: 56
5.3 Closing Section 56
APPENDICES 57
6. Appendix 57
Appendix A: Raw Experimental Data for Physical Characterization 57

Appendix B: Mechanical Property Equations and Calculations 58
Appendix C: Raw Data Tables 59
Appendix D: Statistical Analysis Outputs 60
Appendix E: Correlation Analysis Outputs 61
Appendix F: List of Process Documentation 62
Appendix G: Models of the prototype of Banana Paper Bags. 65
Appendix H: Policy Document Excerpt 65
Appendix I: Standard Test Methods Followed 66
Reference 67

List of Table

Table 3.1 Equipment and Apparatus 16
Table 3.2 Pulping Parameters 18
Table 3.3 Processing Framework Utilized in making the Paper Samples. 19
Table 3.4 Standards of Testing Cited. 30
Table 3.5 Adequate of Methodology with the Research Objectives 32
Table 4.1 Calculated Physical Properties of Developed Samples 35
Table 4.2 Measurement of thickness gave the following results in Table 4.2 37
Table 4.3 Summary of Physical properties 37
Table 4.4 Tensile Strength Outcomes of Handmade Paper Samples 38
Table 4.5 Tear Resistance Results of Handmade Paper Samples 38
Table 4.6 The Results of Trial of the Strength and Index of Burst of the Handmade Paper 39
Table 4.7 Comparative Analysis of Material Properties 45
Table 6.1 Individual Sample Measurements 57
Table 6.2 Tensile Strength (N/15mm) and Tensile Index (Nm/g) 57
Table 6.3 Tear Resistance (mN) 57
Table 6.4 Burst Strength (kPa) and Burst Index (kPa·m²/g) 58
Table 6.5 Tensile Strength (N/15 mm) 59
Table 6.6 Tear Resistance (mN) 60
Table 6.7 Burst Strength (kPa) 60
Table 6.8 ANOVA Results for Mechanical Properties 60
Table 6.9 Tukey Post-hoc Test Results 61
Table 6.10 Correlation Coefficients between Density and Mechanical Properties 61
Table 6.11 Correlation Coefficients between Bulk and Mechanical Properties 61

List of Figures

Figure 2.1 the structure of lignocellulosic composition and disrupt structure of lignocellulos in the pretreatment process [3]. 8
Figure 2.2 Quite a few parts of banana tree [18]. 9
Figure 2.3 Cross section through Banana pseudo stem trunk and its parts: (b) outer parts; (c) middle parts; (d) inner parts; and (e) core parts [18]. 10
Figure 2.4 Cross section of pseudo stems of banana tree (left) and a banana leaf (right) [18] ... 11
Figure 3.1 Process Flowchart of Handmade Paper Production from Banana Pseudo stem 21
Figure 3.2 Banana Pseudo stem Collections 22
Figure 3.3 Cleaning & Size Reduction 22
Figure 3.4 Mechanical Fibers Separations 22
Figure 3.5 Alkaline pulping of banana pseudo stems Fibers using sodium hydroxide (NaOH). 23
Figure 3.6 Washed and neutralized banana pulp Fibers after alkali treatment. 23
Figure 3.7 Pulp Refining and Slurry Preparation 24
Figure 3.8 Handmade paper sheet formations using the mould and deckle technique 25
Figure 3.9 Drying of handmade paper sheets after pressing 26
Figure 3.10 Steps of handmade paper bags produced from banana Pseudo stem Fibers 26
Figure 4.1 Comparisons of Grammage Distribution between Samples 35
Figure 4.2 Thickness Measurements 36
Figure 4.3 Comparison of Grammage Distribution across the Samples S1, S2 and S3 41
Figure 4.4 Characterization chart: Density vs. Bulk of Banana pulp Paper 42
Figure 4.5 Means of tensile strength tear counteraction and burst strength of handmade paper samples S1, S2 and S3 with error bar standard deviation. 47
Figure 4.6 Box plot of distribution of tear resistance values (mN) of sample S1, S2 and S3 48
Figure 4.7 Correlation between density (g / cm 3) and burst strength (kPa) of make paper samples S1, S2 and S3. 49
Figure 4.8 Comparative chart of banana Fibers paper, commercial A4 paper and the plastic film based on their thickness, density, tensile strength, tear resistance and burst strength. 50

Abstract

The rising environmental pressure attributed to the use of single-use plastic bags has heightened the need to find sustainable and biodegradable packaging materials. The paper will examine the growth and physical appearance of paper made out of banana pseudo stem Fibers pulp as an eco-friendly substitute raw material in the production of paper. The rising environmental issues linked to the production of paper through wood have promoted the consideration of using agricultural Fibers in developing eco-friendly materials. Banana pseudo stems Fibers was chosen because it is a lignocellulosic fiber that is richly available in Ethiopia and also because it is locally available.

This paper explores the possibility of manufacturing handmade paper using banana (Musa spp.) pseudo stem Fibers to replace the regular wood based paper as well as non-biodegradable plastic packages. Standardized 10% NaOH alkaline pulping of agricultural residues of banana cultivation was performed and sheet forming was done manually. The resulting paper sheets were defined in terms of physical properties such as grammage, thickness, density, bulk and porosity, mechanical properties such as tensile strength tear resistance and burst strength.

The paper that was produced had a mean basis weight of 60.25 g/m 2, a thickness of 0.161 mm, a density of 374.5 kg/m 3, a bulk of 2.67 cm 3/g, and a porosity of about 75%. Tensile strength results were found to be 32.8-36.6 N/15 mm tear resistance was 240- 262 mN, and burst strength was 123-140 kPa in three samples (S1, S2, S3). One way ANOVA with statistical analysis revealed that there were significant differences in the samples ($p < 0.01$) with Sample S2 that was continuously performing better than the others. The correlation analysis indicated a strong positive correlation between the density and the burst strength ($r \approx +0.85$) and moderate positive correlation between the bulk and tear resistance ($r \approx +0.72$).

This data shows that banana pseudo stem Fibers can be efficiently converted to lightweight paper that would be useful in the low load packaging process. Although tensile and burst strength are still lower than that of commercial A4 paper, banana paper is more tear resistant than plastic film, and would have evident environmental benefits. The researches provides technical basis of using the waste potential of Ethiopian banana waste to help the country lower the use of single-use

plastics in accordance with the Proclamation No. 1383/ 2025 as well as promote the concept of the circular economy.

Keywords:

Banana pseudo stems Fibers, handmade paper, sustainable packaging, tensile strength, tear resistance, burst strength, density, bulk, porosity, agricultural residues, Ethiopia, circular economy, solid waste management.

CHAPTER ONE
1. INTRODUCTION

1. INTRODUCTION

This has greatly caused a rise in demand of packaging materials especially the single use plastic bags due to the rapid population growth, urbanization and consumerism. The use of plastic bags is common due to the fact that it is cheap, is lightweight, and it does not absorb water [1];]; it is a great threat to the environment since it is not biodegradable. As the discarded plastic bags continue to stay in the environment decades later [1], clogging drainage systems, damaging wildlife [1], and piling up of micro plastics in the terrestrial and aquatic ecosystems [1].

Poor systems of waste management compound the environmental effect of plastic bags in most developing countries such as Ethiopia. Despite growing awareness of plastic pollution, there are still no alternatives to it that are practical and full of value, affordable, and locally accessible [2]. There is therefore an urgent demand to create environmental friendly packaging materials which are biodegradable, renewable and production locally.

Meanwhile, the paper and packaging businesses in the world still depend on wood based raw materials at a very high level and they are putting more and more pressure on the forest resources. Overreliance on wood pulp has caused deforestation, loss of biodiversity and climatic change. Researchers and industries are in turn considering non-wood lignocellulosic Fibers which are agricultural residues as the sustainable source of pulp and paper [3].

Another potential non-wood Fibers source is banana pseudo stem which is one of the significant agricultural byproducts that occurs upon harvest of banana fruits [4]. Banana (Musa spp.) is extensively grown in tropical and subtropical zones such as Ethiopia where amount of Pseudo stem biomass is lost every year [5]. These pseudo stem contain a lot of cellulose and have good Fibers properties that make them to be papermaking [3]. Nevertheless, banana pseudo stem, though abundant are usually disposed as waste resulting in inefficiencies in the environment and economy [6].

Turning banana Pseudo stem Fibers into handmade paper products offers twofold benefit to decrease the agricultural waste, as well as offer an alternative to plastic packaging, which is sustainable. Especially, the process of handmade papermaking is a low energy and low technology process, which is ideal in small scale and community based industries [7]. When the

banana Fibers based paper is created into paper bags it can offer sufficient mechanical capability, biodegradability, and ecological adaptability. .

In this research, emphasis is laid on the manufacturing and testing of handmade paper bags made of banana Pseudo stem Fibers through one of the alkaline pulping technique. This study will evaluate the physical and mechanical attributes of the resulting paper including tensile strength, burst index, and thickness to determine how the paper will be useful as an environmental friendly substitute in the use of plastic bags.

1.1 Background

The rising environmental issues and the effects of climate change have created a pressure on the need to produce products that are eco-friendly all over the world. The consumers, government, and industries are becoming more concerned with the need to be sustainable, minimize wastage, and use renewable resources. Consequently, biodegradable packaging solutions and green materials have been of great concern [2].

1. INTRODUCTION

This has greatly caused a rise in demand of packaging materials especially the single use plastic bags due to the rapid population growth, urbanization and consumerism. The use of plastic bags is common due to the fact that it is cheap, is lightweight, and it does not absorb water [1] it is a great threat to the environment since it is not biodegradable. Plastic bags continue to stay in the environment decades later [1], clogging drainage systems, damaging wildlife [1], and piling up of micro plastics in the terrestrial and aquatic ecosystems [1].

Poor systems of waste management compound the environmental effect of plastic bags in most developing countries such as Ethiopia. Despite growing awareness of plastic pollution, there are still no alternatives to it that are practical and full of value, affordable, and locally accessible [2]. There is therefore an urgent demand to create environmental friendly packaging materials which are biodegradable, renewable and production locally.

Meanwhile, the paper and packaging businesses in the world still depend on wood based raw materials at a very high level and they are putting more and more pressure on the forest resources. Overreliance on wood pulp has caused deforestation, loss of biodiversity and climatic change. Researchers and industries are in turn considering non-wood lignocellulosic Fibers which are agricultural residues as the sustainable source of pulp and paper [3].

Another potential non-wood Fibers source is banana pseudo stem which is one of the significant agricultural byproducts that occur upon harvest of banana fruits [4]. Banana (Musa spp.) is extensively grown in tropical and subtropical zones such as Ethiopia where amount of Pseudo stem biomass is lost every year [5]. These pseudo stem contain a lot of cellulose and have good Fibers properties that make them to be papermaking [3]. Nevertheless, banana pseudo stem, though abundant are usually disposed as waste resulting in inefficiencies in the environment and economy [6].

Turning banana Pseudo stem Fibers into handmade paper products offers twofold benefit to decrease the agricultural waste, as well as offer an alternative to plastic packaging, which is sustainable. Especially, the process of handmade papermaking is a low energy and low technology process, which is ideal in small scale and community based industries [7]. When the banana Fibers based paper is created into paper bags it can offer sufficient mechanical capability, biodegradability, and ecological adaptability. .

In this research, emphasis is laid on the manufacturing and testing of handmade paper bags made of banana Pseudo stem Fibers through one of the alkaline pulping technique. This study will evaluate the physical and mechanical attributes of the resulting paper including tensile strength, burst index, and thickness to determine how the paper will be useful as an environmental friendly substitute in the use of plastic bags.[8]. Such materials have a number of benefits such as they can be renewed relatively faster, they contain less lignin than wood, and the chemicals and energy used in the pulping process are less than those used when using wood [8]. Banana pseudo stem Fibers are of particular interest among them, as they contain high levels of cellulose, are long in form, and on top of that, they are accessible as agricultural waste [9].

Ethiopia is among the most banana growing nations in Africa [10], which generates high volumes of banana pseudo stem biomass annually. Once fruit is produced, the pseudo- stem becomes a waste that is sometimes either left to decay or disposed of inappropriately, which poses a problem to the environment [10]. The usage of this biomass in paper manufacturing does not only lower waste rates, but also contributes to the principles of the circular economy and value addition of the agricultural residues. Past researches have demonstrated that pseudo stem Fibers of bananas can be effectively manufactured into pulp and paper with satisfactory mechanical characteristics [11, 12]. Despite the great demand of sustainable materials, the technical analysis of the banana pseudo stem Fibers in the manufacture of paper by hand in

Ethiopia has not yet been properly investigated. This paper seeks to address that gap with the systematic production and characterization of these Fibers and eventually evaluate their performance and potential in the local sustainable packaging market.

1.2 Problem Statement

There is an increase in one-use plastic bags, which have had disastrous impacts on the environment. They contain non-biodegradable composition that causes soil poisoning and water contamination in the long run. These bags are a significant pollutant in Ethiopia particularly in cities with poor collection of waste materials. In response, the government has adopted the Solid Waste Management and Disposal law (No. 1383/2025) that has banned the sale and utilization of single-use plastic bags of all kinds.

The paper-based alternatives exist, and most are based on the wood pulp that is cut in the forested regions, which raises new environmental issues. Pseudo -stem wastes of millions of tons are thrown away or burned in areas that cultivate bananas. There is a need to determine whether these thrown away Fibers can be developed as paper with the required physical characteristics, i.e., the best grammage, density and thickness to act as a high performance and sustainable alternative to plastic packaging.

This paper will attempt to develop paper using banana pseudo stem Fibers pulp and analyses the physical properties to identify its potential as an alternative sustainable raw material.

1.3 Objectives of the Study

1.3.1 General Objective

To develop and characterize handmade paper bags produced from banana Pseudo stem Fibers as environmentally friendly alternatives to plastic bags.

1.3.2 Specific Objectives

- To extract and process banana pseudo stems Fibers suitable for handmade paper production.
- To fabricate handmade paper bags using the developed banana Fibers-based paper sheets.
- To compare the performance of the developed paper bags with conventional plastic bags in terms of strength and usability.
- To characterize the physical properties (basis weight, thickness, density, and bulk) of the produced paper sheets.

- To study the feasibility of banana pseudo stems Fibers as an alternative raw material for sustainable paper production
- To assess the economic feasibility and scalability of producing banana pseudo stems Fibers paper bags at small-scale or community level

1.4 Research Questions

This study seeks to answer the following questions:

- Can banana pseudo stems Fibers be effectively processed into pulp suitable for handmade paper production?
- Are banana pseudo stem Fibers a feasible alternative to wood-based raw materials for lightweight paper applications?
- What pulping and sheet-forming parameters optimize the physical and mechanical properties of banana Fibers-based paper?
- What are the physical properties (GSM, thickness, density, bulk) of paper produced from banana pseudo stems Fibers?
- What is the biodegradability behavior of banana pseudo stems Fibers paper bags under natural environmental conditions?
- Is the production of banana pseudo stems Fibers paper bags economically feasible and scalable for small-scale or community-level implementation?
- How the produced banana pseudo does stems Fibers paper compare with commercial A4 office paper in terms of physical properties?
- What structural characteristics can be gathered from the measured physical parameters?

1.5 Significance of the Study

- This research contributes to sustainable material science by providing baseline experimental data on banana stem Fibers-based paper production. It supports the utilization of locally available agricultural Fibers resources in Ethiopia and reduces reliance on imported wood-based materials.
- Since banana plants are widely cultivated and pseudo stems are typically treated as agricultural waste, their utilization adds economic value and reduces environmental impact.

- The findings may serve as reference data for future researchers interested in alternative Fibers paper development. Additionally, the study promotes environmentally friendly material innovation and resource optimization within local industries.

1.6 Scope of the Study

The scope of this work includes the extraction of banana pseudo stem Fibers, alkaline pulping using sodium hydroxide, handmade sheet formation through the mould and deckle technique, evaluation of the physical and mechanical properties of the paper, and fabrication and assessment of paper bags.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

This chapter is a critical review of available literature in the area of non-wood Fibers use, use of banana pseudo stem Fibers, alkaline pulping process, hand-made paper fabrication and the use of biodegradable packaging solutions. The review provides a scientific basis of the research, the gaps in the current literature, and the reason why handmade paper bags made of banana pseudo stem Fibers should be developed in the context of the Ethiopian sustainable and legalized environment [13].

2.2 Non-wood Fibers as Pulp and Paper Sustainable Raw Materials

Historically, the pulp and paper world has been dependent on wood-based raw materials, leading to deforestation, loss of biodiversity as well as high carbon emission rates [4]. To address the concern, non-wood lignocellulose Fibers derived of agricultural residues have been receiving more and more interest as an alternative source of pulp. [3].

There are non-wood Fibers, including sugarcane bagasse, rice straw, wheat straw, and bamboo as well as banana pseudo stems, which have a number of benefits over wood Fibers. These are renewable materials that are annually available in large quantities, as byproducts in agriculture, and in most cases, they have fewer lignin content, which reduces chemical use during the pulping process [3].]. Besides, use of agricultural residues will help in waste minimization and facilitate circular economy principles through waste recovery [14].

In spite of these benefits, some of the difficulties related to non-wood Fibers are seasonality, low bulk density, and high moisture level as well as the ash and silica that can influence processing efficiency [15]. Addressing these challenges requires careful selection of raw materials and optimization of pulping and sheet forming parameters.

2.3 Banana Pseudo- stems Fibers: Characteristics and composition.

Banana (Musa spp.) is among the most commonly grown fruit crops in the tropical and subtropical regions especially the East Africa [12]. Once the harvesting of fruits is complete, the pseudo stem is disposed of as a waste in the agricultural industry where the biomass racks up in huge quantities.

The banana pseudo stem is lignocellulosic in composition hence its chemical suitability to papermaking. According to the studies, the average composition is the following: as it is demonstrated in the figure 2.1 [3].

- Cellulose: 60% - 65%
- Lignin: 10% - 15%
- Hemicellulose: 5% - 10%

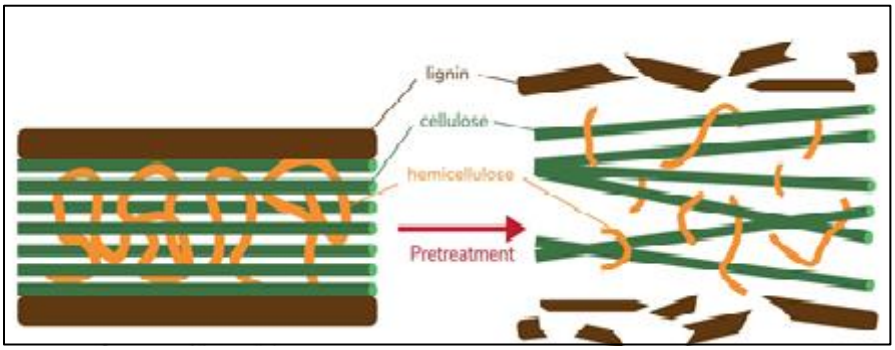


Figure 2.1 the structure of lignocellulosic composition and disrupt structure of lignocellulos in the pretreatment process [3].

Pretreatment step of mechanical, chemical or thermal treatment, which may destabilizes lignocellulose structure that is required in bio refining process in converting cellulose. This large percentage of cellulose is necessary to add the needed structural integrity and strength to the paper bags [9]. The banana pseudo stem Fibers have a relatively long Fibers length which is seen to confer to the mechanical properties of banana Fibers including tensile and tear resistance [16].

2.3.1 Biomass Potential and Impact on the Environment.

The most well-known Fibers-producing species is Abaca (Musa textiles), although well-known edible species like Musa acuminata do have a potential in Fibers [10]. The pseudo stems serves as the structural heart of the plant transporting nutrients to the fruit. Once the fruit is produced the plant cannot be used in the following cycle

The amount of waste generated is large:

- 1 ton of fruit yield results in an average of 4 tons of biomass waste (leaves, pseudo stems, peels) [17].
- 1 hectare of bananas farm will yield about 220 tons of biomass waste [17].

Unless well handled, then such wastes would be dumped in rivers or burnt emitting greenhouse gases and leading to degradation of the environment [14]. This rationale of using this crop waste as a source of cellulose Fibers is a value-added use that will favor sustainable material development [14]. Figure 2.2 tells the pseudo stem as the main organ that gives structural support and enables the transportation of nutrients found in the soil to the fruits. Once the fruit has been harvested this all structure turns into a waste biomass since it is incapable of producing a second crop.

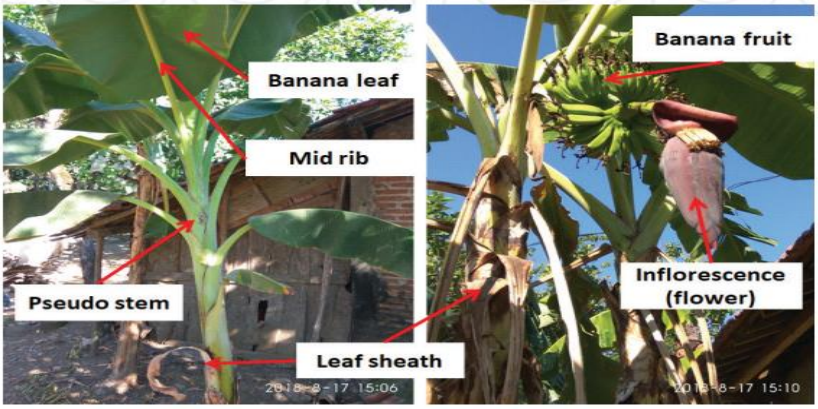


Figure 2.2 Quite a few parts of banana tree [18].

2.3.2. Banana as a Pseudo stem structure: Botanical structure

The banana plant has a trunk called the pseudo stem made up of a soft central core with up to 25 sheaths of the leaves tightly wrapped around it. These coverings grow out of the plant base and in case they grow up, they form the main leaves. It has a maximum height of around 7.5 m, and the inner sheaths of the leaves are sometimes of equal length as the plant and the outer sheaths tend to be shorter and develop later. The leaves created are capable of reaching a width of 30 cm [5]. Fig. 2.2 (a), cross-section of a banana pseudo stem and its components: (b) outer; (c) middle; (d) inner and (e) central core [18].

Figure 3: Comparative analysis of cross-sectional view of banana pseudo stem (bearing side, left) and the banana leaf (bearing side, right) [18].

2.3.3. Agricultural Waste and Environmental Impact

In the world, 5.72million hectares of land are under cultivation and generate an approximate of 1.243 billion metric tons of residue [6]. The top banana plantation in the world, which is located in India, produces about 190 millennium tons of biomass waste annually. Due to lack of

technical expertise and facilities, this waste is usually disposed in a manner that is detrimental to the environment:

- Incineration, which emits chemicals with a high level of greenhouse gasses (GHGs) into the atmosphere.
- Incorrect disposal like dumping in lakes, rivers, or in shallow land which poses serious environmental risks and interferes with the local ecosystems.

2.3.4. Possibility of High-Value Applications.

Research indicates that various components of the banana plant including the leaves, pseudo stem, pith, and peels have diverse industrial potential:

- Food Industry: It is used as flavor, natural colorants, animal feed and also nutraceuticals [18].
- Non-Food Industry: It can be used to manufacture tea bags, bio-fertilizers, wastewater treatment agents, textiles and reinforced composites [4].

2.3.5. Chemical and Mechanical Suitability of Paper.

The pseudo stem is especially an excellent source of extracting natural Fibers of high quality. It has mechanical qualities that are comparable to traditional synthetic reinforcements and has an environmentally responsible alternative to the packaging industry. The chemical makeup of these Fibers makes it suitable in the production of pulp and paper:

The large percentage of cellulose and high Fibers length give high tensile and tear strength to the resulting paper products as shown in figure 2.3 and 2.4.

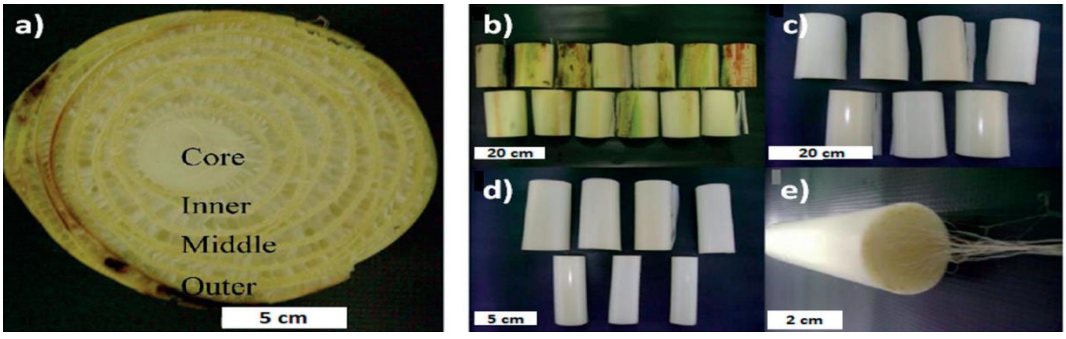


Figure 2.3 Cross section through Banana pseudo stem trunk and its parts: (b) outer parts; (c) middle parts; (d) inner parts; and (e) core parts [18].

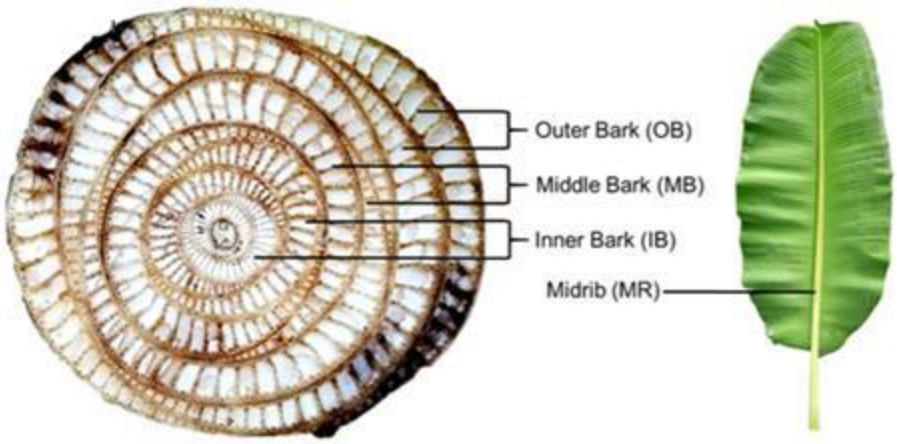


Figure 2.4 Cross section of pseudo stems of banana tree (left) and a banana leaf (right) [18]

2.3.6 Industrial usage and Value addition.

The different parts of the banana plant such as the leaves, the pseudo stem, the pith, and the peels although treated as garbage hold huge areas of industrial exploitation through the numerous industries:

- Food Industry: It is used to prepare flavoring agents, natural colorants, livestock feed and nutraceuticals [1, 2].
- Non-Food Industry: Investigated in the manufacturing of tea bags, bio-fertilizers, wastewater treatment substances, textile, and reinforced composites [1].

Presently, there is a considerable amount of research done on the removal of quality Fibers of the pseudo stem. Mechanical properties of these natural Fibers are similar to the standard synthetic reinforcements and this means that they are an environmentally responsible and sustainable alternative in the manufacturing process.

2.3.7 Fitness to Pulp and Paper Production

Banana pseudo stem Fibers are the best materials to use in the paper industry because of their chemical and physical characteristics. They are so effective mainly because of high cellulose content and good Fibers morphology [4].

High Fibers lengths (pseudo stem) also add to the tensile and tear strength of the resulting paper products and it is as good as or better than the traditional wood-based pulps.

2.3.8 A Circular Economy Approach

The shift of waste disposal to resource recovery is consistent with the plans of the circular economy and sustainable material development [14]. When properly utilized to exploit the banana biomass, countries such as India can reduce the environmental threats at the expense of promoting socioeconomic development. The change does present important advantages to a broad spectrum of stakeholders such as farmers, scientists and policymakers due to the new revenue generating opportunities and the decreasing industrial dependence on non-renewable materials.

2.4 Processes of banana Fibers extraction

Fibers banana pseudo stems are either extracted mechanically, chemically or by hybrid. Mechanical extraction entails scraping or decorticating the pseudo stem physically in order to extract the Fibers. Although this procedure maintains the length of the Fibers, the end result has a lot of lignin in it which then, needs to be treated later by chemical procedure [18]. The alkaline treatment is commonly used to extract non-cellulosic material like lignin, pectin and hemicellulose. Sodium hydroxide (NaOH) is usually utilized because it is effective in fostering Fibers swelling and delignification [11]. In the case of handmade papers, moderate treatment using alkali combined with mechanical refining is common with a compromise between the purity of the Fibers and the structural integrity..

2.5 Alkaline Pulp of Banana Pseudo stem Fibers

A common process of processing non-wood Fibers is alkaline pulping, a process that is selective of lignin and leaves cellulose structure intact. NaOH enters into the Fibers meshwork, breaks the ester bonds of hemicellulose, and dissolves the lignin particles, which results in the increased Fibers swelling and fibrillation [9]. Studies have shown that 8-15% NaOH, 80-90 o C and cooking time of 2-3 hours are useful in the pulping of pseudo stem Fibers of bananas [9]. These conditions are very vital and must be optimized since too much exposure to alkali may cause deterioration of cellulose and loss of paper strength.

2.6 Technology on Handmade Paper Production.

The production of handmade paper is a low technology, available process that can be used in small-scale and rural industries. The use of the conventional mould and deckle technique enables

the accurate control of sheet thickness, Fibers direction and surface texture [16]. The extent of pulp refining, concentration of the slurry, and pressing conditions are some of the key quality factors. Sufficient refining enhances fibrillation and bonding capacity of the Fibers and controlled pressing and drying yield to consolidation and dimensional stability of the sheet [16, 17].

2.7 Mechanical Properties of Non-wood Handmade Paper

Tensile strength, tear resistance and burst strength are mechanical indicators that can be used to ascertain the appropriateness of papers in packaging. The effect of Fibers length, bonding density and the general sheet structure on these properties is determined [2, 16]. The pseudo stem banana papers have been reported to have similar or even better mechanical properties than the traditional recycled paper, specifically, in terms of tear strength, because of the naturally high Fibers length of the Musaceae family [17].

2.8 Plastic Bag Substitutes with Banana Fibers paper bags.

In comparison to the plastic bags that cause micro plastic pollution and environmental sustainability, the paper bags made of plant Fibers are biodegradable and renewable [19]. There are studies that prove that banana Fibers-based bag has the required load-bearing capacity and strength to be applied in lightweight packaging [9, 11]. These bags provide a much reduced environmental footprint compared to plastic and traditional paper made of wood, when the waste is made of agricultural waste.

2.9 Environmental and Socioeconomic Advantages of utilizing Banana Wastes.

The use of banana Pseudo stem waste in making of paper will also help in reducing wastes,

The use of banana pseudo stem waste helps in reduction of pollution and management of the resources. This activity helps in rural job creation and helps in value addition to residues generated in agriculture, which complies with Global Sustainability Goal (in particular SDG 12), Responsible Consumption and Production [14].

2.10 Research Gap and Literature Review Summary

The literature reviewed has verified that the banana Pseudo stem Fibers are rich in banana, cellulose-rich and appropriate in the production of pulp and paper [5, 7, 18]. Non-wood Fibers have been well known about the use of alkaline pulping and the handmade paper production

methods [4]. Nevertheless, in spite of these improvements, there are still a number of important research gaps.

- Product-Specific Focus: The available literature is mainly concerned with the manufacture of flat paper sheets; there is a scarcity of literature dealing with specific regard on how banana pulp sheets can be converted into functional handmade paper bags.
- Geographic and Contextual Gaps: The lack of localized research is done in the Ethiopian agricultural setting where banana farming is massive yet the wastes are not fully exploited.

In this work, the above-mentioned gaps are filled by creating and describing handmade paper bags that are made of banana Pseudo stem Fibers through controlled alkaline pulping and with focus on environmental sustainability and packaging.

CHAPTER THREE
3. METHODOLOGY

3.1 Introduction

The chapter outlines the materials, research design, processing conditions and mode of analysis under which the handmade paper bags of banana Pseudo stem Fibers were produced in addition to testing of the materials. The methodology has been developed in such a manner that it would:

I. Acquire the authority of making cellulose honorably dissolve,

Give the plastic or standard manual pieces of paper that can be used during the bag making;

II. Facilitate a good assessment of physical and mechanical qualities used in packaging.

Alkaline pulping process, preparation of raw materials, preparation of pulp, refining of pulp, preparation of handmade sheets, pressing and drying sheet, preparation of paper bag, and laboratory analysis are involved in the process of the experiment. The experiments were done with a controlled laboratory set up that reduced variability to increase reproducibility.

3.2 Materials

3.2.1 Raw Materials

Pseudo stem of banana (Musa spp.) were picked after the local banana farms had harvested the fruits. The inner sheath layers of the Pseudo stem were only used, because these areas are the ones that have high cellulose levels and low lignin, ash and silica levels than the outer layers. Before processing, the pseudo stem were washed with tap water to get off the sticking dirt and foreign matter.

3.2.2 Chemicals

The chemicals involved in this study were:

- Sodium hydroxide (NaOH): analytical grade was used as the delignifying agent in the alkaline pulping process.

Distilled water: applied in the pulping, washing, dilution, and the preparation of slurries.

3.3 Equipment and Apparatus

The experimental operation was conducted by using the standard laboratory equipment that is appropriate in the processing of pulp, sheet formation, and in physical property analysis. The apparatus employed were the following:

- Cooking Vessel: Stainless steel vessel that is used to alkaline pulse banana pseudo stems Fibers.
- Heating Plate with Temperature Control: It offers a consistent heating throughout the pulping process and the temperature is kept at the required level of 90°C.
- Laboratory Blender: This one is utilized in mechanical polishing of the pulp to maximize fibrillation and bonding capacity.
- Mould and Deckle Set (A4 size): Mould and deckle set is used in the production of the sheet of paper.
- Micrometer: Accurate device applied in measuring the thickness of sheets based on ISO 534.
- Balance (+-0.01 g +): Weighing Balance (+-0.01 g +): The weighing balance was applied to the determination of grammage (basis weight) of paper samples as per ISO 536.
- Absorbent pressing sheets cloths to filter the water

To prevent contamination and reproducibility of results, all equipment was cleaned before use.

Table 3.1 Equipment and Apparatus

Equipment	**Purpose**	**Standard Referenced**
Cooking Vessel (Stainless Steel)	Used for alkaline pulping of banana pseudo stems Fibers	ISO 5263 (Laboratory pulp preparation/beating)
Heating Plate with Temperature Control	Maintains pulping temperature at 90 °C for controlled delignification	ISO 5263
Laboratory Blender	Mechanical refining to improve fibrillation and bonding potential	ISO 5263 / TAPPI T200
Mould and Deckle Set (A4 size)	Handmade sheet formation ensuring uniform Fibers spreading	ISO 5269 (Laboratory paper sheet formation)
Micrometer	Measures sheet thickness under standard pressure	ISO 534 / TAPPI T411

3.4 Experimental Design

The experimental design had targeted to assess the relevance of alkaline pulped banana Pseudo stem Fibers in the production of handmade paper and paper bags. The approach used was the factor controlled, where the sodium hydroxide concentration, cooking temperature, and cooking time was determined using values reported in the previous literature regarding non-wood Fibers pulping.

3.4.1 Paper Samples Preparation and Differentiation.

To investigate the effect of processing conditions on the properties of banana pseudo stems paper, among three samples, (S1, S2, and S3) were produced in the course of the experiment. Despite the industrial processing conditions being relatively different, the processing parameters of Fibers in the pulping process, Fibers treatment and sheet forming were moderately different despite the fact that all samples were processed using the same raw material, banana pseudo stems Fibers. These distinctions were put in place so as to see their influence on the structure and performance of the resulting paper sheets.

The Fibers were initially washed, divided into smaller units, and alkaline pulping process was done on them. The Fibers were subsequently pulped followed by thorough washing and beating to acquire homogenous pulp slurry. A mould and deckle technique was then used to make handmade paper sheets.

The preparation step involved minor modifications on the Fibers treatment and sheet formation leading to three samples. It was expected that these differences would have an effect on Fibers bonding, sheet density and thickness and hence the mechanical strength and water absorption characteristic of the paper.

To determine these differences, the prepared samples were exposed to physical and mechanical tests. It was characterized by measurement of thickness, tensile strength, burst strength, tear resistance. These tests were conducted; hence, results were compared to determine the performance of the three samples, and the sample with the most appropriate properties was identified to be used in making paper bags.

3.4.2 Controlled Pulping Parameters

The optimal pulping was done through the manipulation of sodium hydroxide concentration, cooking temperature, cooking time, and Fibers to liquor ratio. These parameters were chosen with respect to some important literature on agro residue pulping in order to have a high delignification of the residue without damaging the integrity of cellulose.

Table 3.2 Pulping Parameters

Parameter	**Unit**	**Value**	**Purpose**
NaOH concentration %	(w/v)	10	Effective delignification without cellulose degradation
Cooking temperature	°C	90	Enhances alkali diffusion and lignin Solubilization
Cooking time	Hours	2.5	Adequate removal of non-cellulosic components
Fibers to liquor ratio	g/mL	1:10	Uniform chemical penetration
Washing volume	L	4	Removal of residual alkali and black liquor
Refining time	Min	10	Improved fibrillation and bonding potential
Drying temperature	°C	25-60	Prevents thermal degradation of cellulose

These parameters were conducted throughout the experiments to ensure consistency and comparability of results.

All pseudo stem Fibers samples of bananas were cooked in the same alkaline condition in this study so that there was consistencyl8 in the experiment and dependability in the comparison of the paper sheets produced. All the samples were subjected to a concentration of 10% (w/v) sodium hydroxide with a constant pulping temperature of 90^0C and a cooking time of 2.5 hours. The reproducible nature of the pulping parameters made sure that any observed divergence in the physical and mechanical behavior of the produced handmade paper was mainly due to differences in the Fibers structure, sheet formation, and Fibers bonding and not due to differences in chemical treatment conditions.

3.4.3 Process parameters that were used to differentiate the paper samples.

Banana pseudo stems Fibers alkaline pulp and hand sheet formed were used to create three paper samples (S1, S2, and S3). Differentiation of the samples was done purposefully by the differentiation of the pulping time, and refining time of the Fibers, which are important

parameters in the separation of the Fibers, fibrillation, and inter-Fibers bonding during paper production as described in figure 3.3

Table 3.3 Processing Framework Utilized in making the Paper Samples.

Sample	NaOH concentration (%	Pulping temperature (°C)	Pulping time (min)	Beating/refining time (min)	Target grammage (g/m^2)	The Purpose of Variation
S1	10%	90	150	10	90	Goal: minor pulping and nominal Fibers fibrillation should be attained.
S2	10%	90	150	15	95	Enhance delignification and aggravate the separation of Fibers.
S3	10%	95	150	20	100	Achieve the greatest pulp and refinements to obtain the best yield of Fibers-bonding.

3.4.4 Description of Sample Raw Material Processing Method.

S1 Banana pseudo stem Fibers alkaline pulping and hand sheet making Reference sample was made in the usual conditions.

S2 Banana pseudo stem Fibers Alkaline pulping with slight better Fibers refining ready to make Fibers more divided and bonded.

S3 Banana pseudo stem Fibers alkaline pulping and optimal sheet forming Production yielding a high Fibers bonding and high sheet structure.

Sample S1

Conditions: used 10% NaOH, temperature 90^{0C}, 150 minutes pulping, 10 minutes of refining, desired grammage 90g/m2.

Purpose: Minor fibrillation and insignificant fibrillation.

Preparation: Beating under typical conditions with a small amount of refining was done on banana pseudo-stem Fibers. This left incomplete lignin removal and the fibrillation which generated a lower fiber bonding base sheet structure.

Sample S2

Conditions: used 10 percent NaOH, temperature 90^{0C}, 150 minutes pulping, 15 minutes of refining, to get desired grammage 95 g/m2.

Purpose: To delignifying and increase the separation of the Fibers.

Description: Fibers were slightly refined more than S1 which resulted in a better fibrillation and bonding. It resulted in the enhanced sheet density and mechanical strength in comparison to the reference sample.

Sample S3

Conditions: used 10-percent NaOH, temperature 95^{0C}, 150 min pulping, 20 min refining, planed target grammage 100 g/m2.

Purpose: To reach optimum pulp refinements and fiber bonding.

Description: The refining period and temperature were stronger which strengthened the pulping conditions, leading to fibrillation of the Fibers and surface area leading to more compact sheets with higher density and mechanical performance.

The samples were provided with the differences in the Fibers morphology, sheet density, and mechanical strength by increasing these parameters systematically. The paper sheets then formed were tested by means of physical and mechanical characterization to check the effect these processing differences had on the performance of banana pseudo stems paper.

These variables influence Fibers bonding in paper manufacturing in a direct way:

NaOH concentration- eliminates the lignin and the hemicellulose.

Pulping time - regulates disintegration of Fibers.

Beating time - enhances the Fibers fibrillation and bonding region.

Grammage - has an effect on sheet density and strength.

It is natural to increase them in stages (S1 - S3), to make the paper stronger.

3.4.2 Methodology Workflow Description

The experimental workflow followed a linear and reproducible sequence, ensuring consistency across all samples illustrated below in figure 3.1

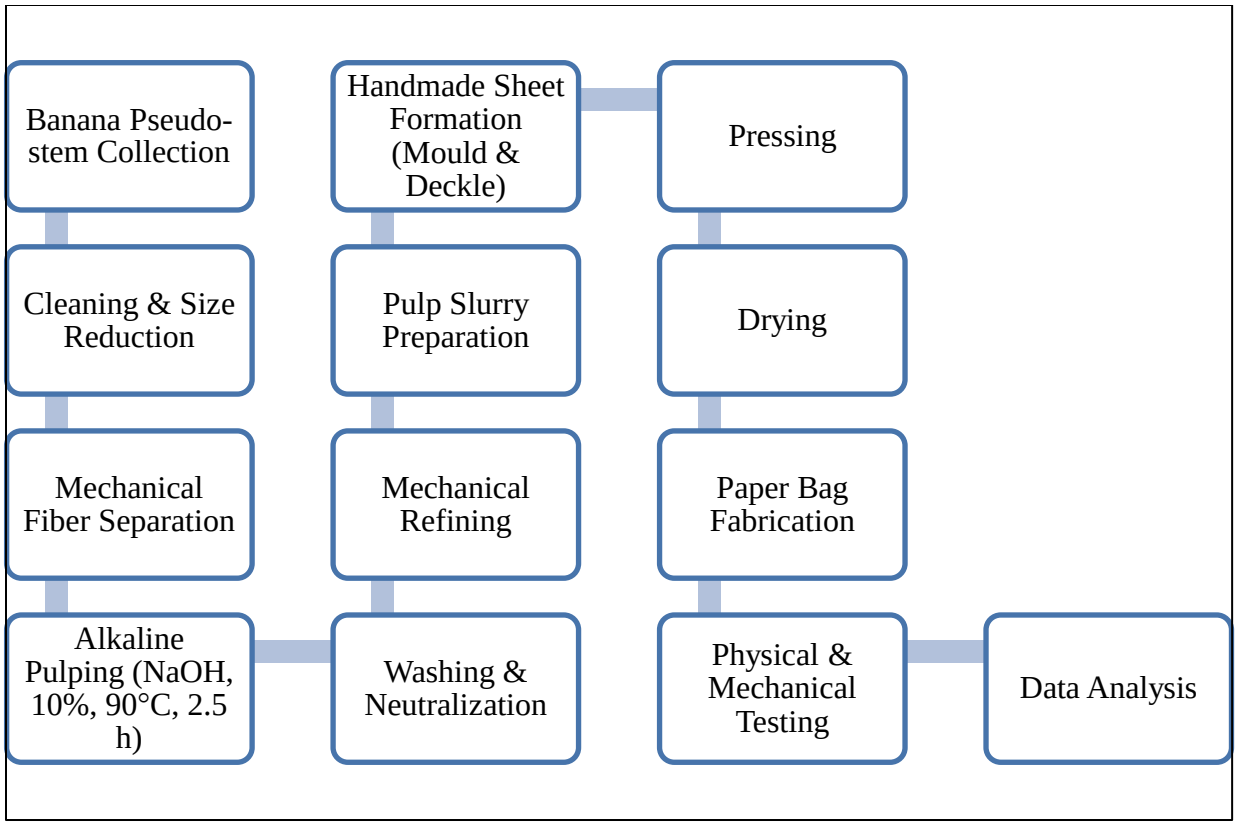


Figure 3.1 Process Flowchart of Handmade Paper Production from Banana Pseudo stem

This structured design ensured that each stage of processing contributed to the overall objective of producing uniform handmade paper sheets and evaluating their physical and mechanical properties for packaging applications.

3.5 Fibers Extraction and Preparation

The banana pseudo stem were collected and cleaned and then manually cut into manageable sections. The outer sheath layers were removed, and the inner sheaths were sliced into smaller pieces approximately 25-50 mm in length. This size reduction facilitated uniform chemical penetration during pulping.

Mechanical separation was employed to detach fibrous bundles from the parenchymatous matrix prior to chemical treatment. This step reduced chemical demand and improved pulping efficiency. Banana Pseudo stem as a row material shown in Figure 3.2



Figure 3.2 Banana Pseudo stem Collections



Figure 3.3 Cleaning & Size Reduction

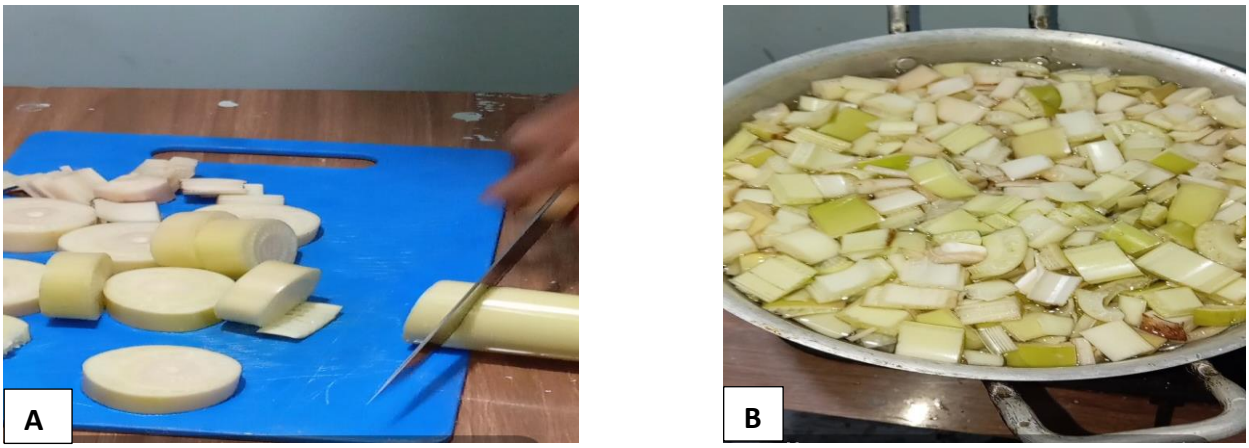


Figure 3.4 Mechanical Fibers Separations

3.6 Alkaline Pulping Procedure

Alkaline pulping was carried out using a 10% (w/v) sodium hydroxide solution. The prepared banana Pseudo stem Fibers were submerged in the alkaline liquor at Fibers to liquor ratio of 1:10 and heated to 90 °C for 2.5 hours under irregular stirring. Cooking of banana Pseudo stem Fibers with sodium hydroxide (NaOH) shown in figure 3.5

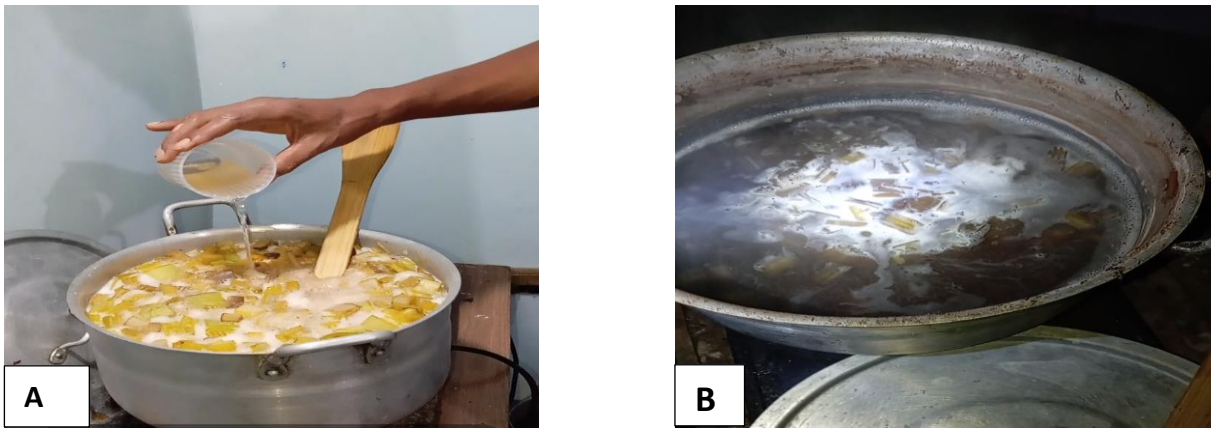


Figure 3.5 Alkaline pulping of banana pseudo stems Fibers using sodium hydroxide (NaOH).

3.6.1 The pulping mechanism involved:

- Saponification of ester bonds in hemicellulose
- Solubilization and fragmentation of lignin
- Swelling of cellulose Fibers
- Partial defibrillation of Fibers bundles

The formation of dark colored black liquor indicated successful delignification. After completion of cooking, the pulp was separated from the black liquor and washed repeatedly with distilled water until a neutral pH (6.8-7.2) was achieved as shown in figure 3.6

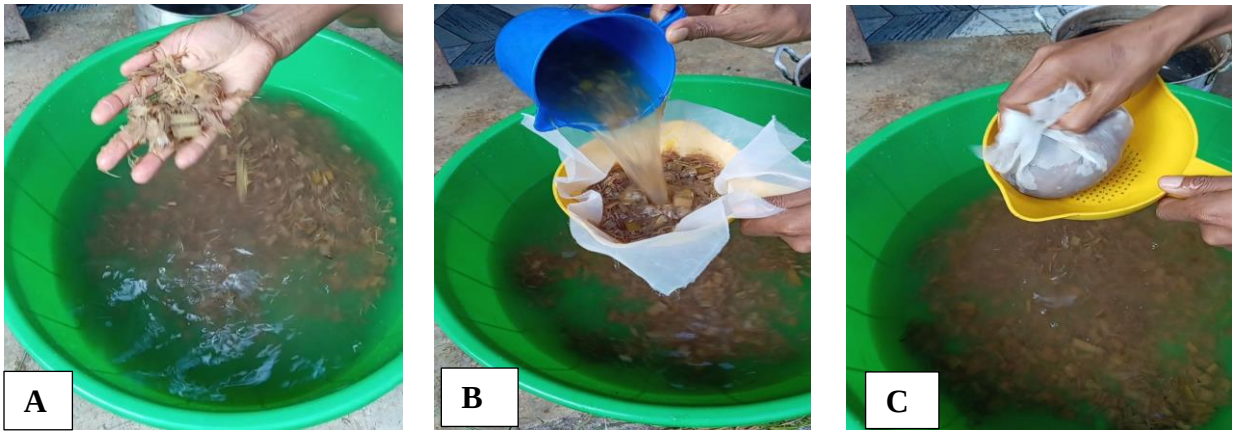


Figure 3.6 Washed and neutralized banana pulp Fibers after alkali treatment.

3.7 Pulp Refining and Slurry Preparation

The washed pulp was mechanically refined using a laboratory blender for 10 minutes. Refining increased Fibers fibrillation; exposed micro fibrils, enhanced inter Fibers bonding sites, and improved water retention value.

The refined pulp was diluted with distilled water to form homogeneous slurry. Slurry consistency was adjusted to control sheet grammage, with higher dilution producing thinner sheets and lower dilution yielding thicker sheets as shown in the figure 3.7 below



Figure 3.7 Pulp Refining and Slurry Preparation

3.8 Handmade Sheet Formation

Handmade paper sheets were produced using the traditional mould and deckle technique. The mould was immersed into the pulp slurry and gently agitated to ensure uniform Fibers dispersion and random Fibers orientation. Upon lifting the mould, water drained through the mesh, leaving a wet Fibers mat on the screen.

Key physical phenomena during sheet formation included turbulent Fibers dispersion, stochastic Fibers deposition, and gravity driven drainage governed by Darcy's law. A mesh size of approximately 100 μm was selected to balance drainage rate and Fibers retention.

The wet sheets were transferred onto absorbent cloths through couching, ensuring minimal disturbance of the Fibers network. Sheet formation step by step shown in the following figure 3.8

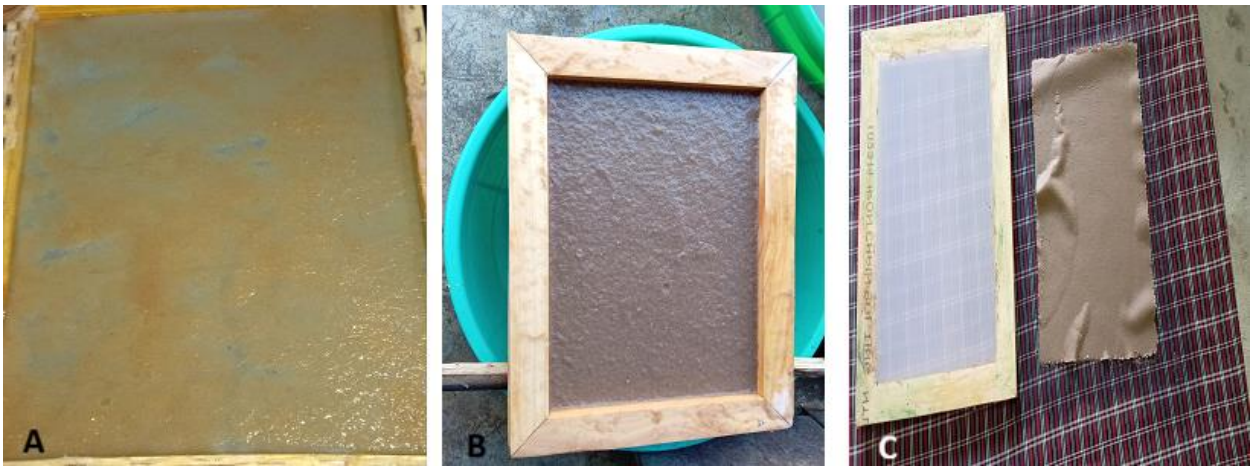


Figure 3.8 Handmade paper sheet formations using the mould and deckle technique

3.9 Pressing and Drying

The couched sheets were sandwiched between absorbent materials and subjected to uniform manual pressure to remove free water and promote Fibers consolidation. Pressing enhanced sheet density, dimensional stability, and inter Fibers hydrogen bonding.

Drying was performed in an oven at 60 °C to allow gradual removal of bound water without inducing hornification or thermal degradation. The dried sheets were conditioned at ambient laboratory conditions for 24 hours prior to testing. Drying and pressing of the formed paper sheet shown in the following figure 3.9



Figure 3.9 Drying of handmade paper sheets after pressing

3.10 Fabrication of Paper Bags

Conditioned handmade paper sheets were converted into paper bags through manual folding, gluing, and handle attachment. The fabrication process followed standard paper bag construction principles to ensure adequate load bearing capacity and structural integrity shown in the following figure 3.10



Figure 3.10 Steps of handmade paper bags produced from banana Pseudo stem Fibers

3.11 Physical Properties Testing

The handmade paper sheets produced from banana pseudo stems Fibers were evaluated for fundamental physical properties that influence strength, density, and suitability for packaging. All tests were conducted under standard laboratory conditions (23 ± 1 °C, 50 ± 2% RH) and aligned with internationally recognized ISO and TAPPI standards

3.11.1 Grammage (ISO 536 / TAPPI T410)

Grammage, or basis weight, represents the mass per unit area of paper expressed in g/m².

- **Sample Preparation:** Specimens were measured its length and width.
- **Procedure:** Each specimen was weighed using a precision balance (±0.01 g).
- **Calculation:**

G (g/m^2) = {Mass of specimen (g)} / {Area of specimen (m^2)}

GSM = Weight (g)/Area (m^2)

- **Replication:** Each sample (S1, S2, S3) was tested in triplicate, and mean values were reported.

3.11.2 Thickness (ISO 534 / TAPPI T411)

Thickness is the distance measured between the two surfaces of a paper sheet under a specified pressure.

- **Sample Preparation:** After 24 hours the specimens were conditioned before the measurement.
- **Procedure:** Individual samples were put between pressure foot and anvil of a micrometer. The common pressure 100 kPa was used.
- **Measurement:** Thickness was measured in micro meters (um).
- **Replication:** average measurements of five samples were created and averages were worked out.

3.11.3 Density and Bulk

Derived properties that are obtained based on grammage and thickness are those of density and bulk.

- **Density (g/cm3):**

  Density = (Grammage) (g/m2)/ ({Thickness) (mm))}

  Bulk (cm3/g):

  B (cm3/g) = {1}/ {Apparent Density} (g/cm3)

These measurements are indirect measures of sheet structure and Fibers bonding.

3.11.4 Cobb Test (ISO 535)

Cobb test defines the water absorption capacity which is very essential in packaging.

- Procedure: 60 seconds of known volume of water were put in the paper surface.
- Calculation: Cobb value (g/m2) was used to record the increase in mass per unit area.

3.12 Testing of mechanical properties of a material

3.12.1 Tensile Strength and Tensile Index (ISO 1924 / TAPPI T494)

The tensile strength is the measure of the greatest stretching pressure that a strip of paper can undergo before rupture and tensile index converts this measure to grammage.

- Sample Preparation: Conditioned sheets were cut into strips 15mm wide and 100mm long..
- Procedure: All strips were fixed on the clamps of a tensile tester with a test span of 50 mm. Constant rate of elongation (20 mm/min) was used until failure
- Recording: The tensile strength (N /15 mm) was recorded as maximum force at break. Measurement of elongation at break (%) was also done.

Calculation:

Tensile Index (Nm /g}) = (Tensile Strength(N /15 mm)/Grammage(g/m2)).

Replication Triplicate testing of every sample (S1, S2, and S3) was carried out.

3.12.2 Tear Resistance (ISO 1974 / TAPPI T414)

The tear resistance is a gauge used to measure the force to run a tear through the sheet..

- Sample Preparation: The rectangular specimens (63 mm x 50 mm) were precut and pre slit to start tearing.
- Procedure: The specimens were placed in an Elmendorf tear tester. It released the pendulum and the measures of the tearing force were taken
- Recording: Data was given in MilliNewtons (mN).
- Replication: Replication on each sample was done in triplicate.

3.12.3 Burst Strength and Burst Index (ISO 2758 / TAPPI T403)

Burst strength is a test that measures the resistance of the paper to rupture or breakage in conditions of constant hydraulic pressure

- Sample Preparation: Circular samples (30 mm diameter) were prepared out of conditioned sheets.

- Procedure: All the specimens were clamped in a Mullen burst tester. The application of hydraulic force continued until rupture happened.
- Recording Maximum pressure at rupture burst strength (kPa).
  Calculation:
  Burst Index (kPa ^{2}/m^2/g) = {Burst Strength (kPa)/ {Grammage (g/m^2)
- Replication: Triplication of each sample was carried out.

3.13 Recording and Statistical Analysis of Data

Each sample set (S1, S2 and S3) underwent all physical and mechanical property tests where every experiment was carried out in triplicate to enhance reproducibility and reduce error in the experiment. The procedures have been adopted as follows:

- Triplicate Testing: Triplicate measures were done to each property once the samples had been taken in order to eliminate variation.
- Calculation of Averages: Arithmetic means were computed of each of the properties between replications.
- Descriptive Statistics: Standard deviation (SD) was calculated to establish congruence and reliability of data.
- Data Presentation: Chapter 4 has a summary of the presented data in tabular and graphical format, and the detail raw data of trials are presented in the Appendix.

This method was systematic to guarantee that the reported values are reliable and reproducible and can be compared with benchmark values of the commercial A4 papers.

3.14 Ethical and Environmental Concerns.

Ethical and environmental sustainability were observed when conducting the study. As a way of minimizing the environmental impact, the agricultural waste product was used as the main raw material; banana pseudo stems Fibers were used, which contributed to the use of agro residues as value added. On the outside, where uncontrolled alkaline treatment was done using sodium hydroxide, hazardous chemicals were avoided. All the discharges produced in the course of pulping were neutralized previously to be disposed to avoid any harm to the environment. It is a green approach to processing, use of resources and development of materials.

3.15 Justification and Methodology validation

The method used was that of a general survey where 250 respondents who had been subjected to different types of protection at one time in their lives were involved.

The sampled pulping and processing conditions were explained due to the previous peer reviewed research concerning non-wood Fibers pulping. The concentration of sodium hydroxide used was 10 percent (w/v) in order to give adequate delignification but minimal loss of cellulose. A higher heating temperature of 90 deg^{0}C also increases diffusion of alkali to Fibers cell walls without causing excessive loss of carbohydrates. An adequate balance between the removal of lignin and the integrity of Fibers has been reported to be 2.5 hours of cooking in case of banana pseudo stem and other agriculture Fibers. A 10-minute mechanical refining was chosen to enhance fibrillation and bonding that does not cause excessive shortening of the Fibers. These parameters guaranteed reproducibility, comparison with the literature and their application in the production of the handmade banana pulp paper.

3.16 The standards on testing referenced are

In case of physical and mechanical tests, the standards of the internationally recognized standards were adjusted and applied to handmade paper:

Table 3.4 Standards of Testing Cited.

Property	**Standard Referenced**	**Description of the properties**
Grammage (Basis Weight)	ISO 536 / TAPPI T410	Measurement of paper mass per unit area (g/m²).
Thickness measured by "Caliper"	ISO 534 / TAPPI T411	Determination of sheet thickness using a micrometer under standard pressure.
Tensile Strength & Tensile Index	ISO 1924 / TAPPI T494	Testes maximum tensile force and normalized tensile index.
Tear Resistance	ISO 1974 / TAPPI T414	Force required propagating a tear using Elmendorf tear tester.
Elongation at Break	ISO 1924 / TAPPI T494	Measurement of percentage extension at rupture during tensile testing.
Burst Strength &	ISO 2758 /	Hydraulic rupture resistance and normalized burst

Burst Index	TAPPI T403	index.
Cobb Test (Optional)	ISO 535	Measurement of water absorption capacity of paper.

These standards were followed to the extent permitted by laboratory-scale handmade paper testing conditions.

3.17 Risk Factors and Justification Measures

The following risk factors were observed throughout the experiment process, and the necessary mitigation measures were used to guarantee that the results can be considered reliable and reproducible:

- **Fibers Degradation:** Cellulose may be damaged as a result of over cooking or too much alkali concentration. Recommendation: Pulping parameters (10 percent NaOH, $90^{oC,}$ and 2.5 h) were strictly adhered to.
- **Non-Uniform Sheet Formation:** Handmade processing may outcome in an irregular Fibers distribution. Recommendation: Consistent slurry preparation, careful mould agitation, and standardized couching techniques were applied.
- **Variability in Handmade Processing:** Manual pressing and drying of pulp can lead to inconsistencies in surface area. Recommendation: Replicate testing was performed, and sheets were conditioned under controlled laboratory atmosphere before evaluation.
- **Measurement Errors:** Inaccuracies in weighing or thickness measurement could affect property calculations. Recommendation: Precision instruments (±0.01 g balance, calibrated micrometer) were used, and five measurements were taken for each sample.

By doing in advance these risks and applying systematic mitigation measures, the methodology ensured that the experimental results were both reliable and comparable with values reported in literature.

3.18 Research Objectives Methodology Alignment.

The methodological framework was carefully designed to address the research objectives of this study. Each stage of the experimental process directly contributed to achieving the intended outcomes, as summarized below:

Table 3.5 Adequate of Methodology with the Research Objectives

Research Objective	Methodological Step	Alignment
Fibers Extraction	Mechanical pretreatment and alkaline pulping	Guaranteed good delignification without destroying cellulose.
Paper Production	Collection of sheets through hand working and drying	Controlled sheets that can be used in creating bags
Property Evaluation	Physical and mechanical testing	The tests represented quantitative data of grammage, thickness, tensile, burst and tear.
Packaging Suitability	Paper bag manufacture and strength test	Practical use of handmade sheets as a packaging material..
Environmental Benefit	Banana pseudo stems waste Fibers and additive free processing	Use Promoted sustainability and minimized impact on the environment.

This consistency proves that the selected methodology was able to meet the technical aspects of the production and testing of paper and had an additional sustainability objective. The study made every methodological process to correspond to a research objective to have consistency, reproducibility, and applicability to packaging applications.

3.19 Closing Section

The methodology model has been introduced in the chapter which has been applied in both the production and the evaluation of handmade paper bags which are produced of banana pseudo stems Fibers. The sequence of operations included raw materials preparation, alkaline pulping, refining, sheet making, pressing and drying, leading to the production of the paper bags was to be planned in such a way that it could get reproducible, sustainable, as well as adherent to internationally accepted standards.

This was done to measure physical and mechanical properties as per ISO and TAPPI standards that produced valid results on the sheet structure, strength and suitability to the purpose of

packaging. The methodology was conducted on both the ethical and environmental consideration i.e. using agro waste materials and safe disposal procedures. Estimation and moderation of the risk factors was performed and the decision making methodology of the peer reviewed literature was made, simply to be scientifically right.

This study established a rational and feasible procedure of creating handheld paper, the progressive achievements of which were organized accordingly to the purpose of the research. Chapter Four (Results and Discussion) reports the results that were obtained following these standardized tests that were conducted and contributed to a discussion.

The systematic correlation of every methodological step with the research goals provided this study with a consistent and sustainable way of handmade production of paper. The findings of these standardized tests are given and explained in Chapter Four (Results and Discussion).

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter reveals findings that have been arrived at after conducting physical and mechanical property tests of handmade papers sheets made of banana pseudo stem. The results are discussed in comparison to the objectives of research as stated in Chapter Three, with the focus on the appropriateness of the developed paper to be used in the process of packaging.

It is notable that the banana pseudo stem Fibers samples were all subjected to the same pulping condition, that is, 10% sodium hydroxide (NaOH), 2.5 hour cooking time and 90^{0C} constant temperatures. The concern of keeping these parameters constant among all the samples helped the study to ensure that changes experienced in the physical and mechanical properties, including Grammage, thickness, tensile strength, tear resistance, and burst strength were more so associated with variations in the sheet structure and Fibers bonding than changes in the chemical pulping conditions.

The findings are arranged in two major groups:

Physical Properties: -

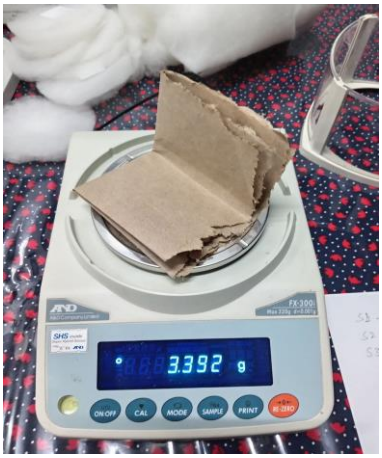
There is difference grammage, thickness, density values of the tests.

Mechanical Properties: -

Incorporating tensile strength, tensile index, burst strength, burst index and tear resistance.

Each of the properties is addressed in its own detail with the help of tabular data and graphics. It is also compared against literature values that are used by traditional A4 papers and this helps to highlight the performance of banana pseudo stems based handmade paper.

The discussion is combined with quantitative findings and qualitative findings and explains variability, reproducibility, and possible applications to packaging. The issue of environmental and sustainability also gets revisited with regard to results of the experiment.





ISO Standard dimensions

For A4 reference paper is

210mm x 297mm

Area (A) =0.062m^2,

Weight = 4.673 g

SO GSM=weight / Area

= 4.673 gm /0.062m^2

= **75.37 g/m^2**

Figure 4.1 Comparisons of Grammage Distribution between Samples

4.2 Physical Properties of Handmade banana pulp Paper

4.2.1 Basis Weight (Grammage)

The weight of the paper produced with a basic weight was assessed by the gravimetric method:

Basis Weight (Grammage (G)

G (g/m^2) = (Specimen mass (g)/Specimen area (m ^{2})).

GSM = Weight (g)/Area (m^2)

Table 4.1 Calculated Physical Properties of Developed Samples

Test sample	Sample Length (cm)	Width (cm)	Area (m^2)	Weight (g)	GSM (g/m^2)
S1	29.5	20.4	0.06018	3.392	56.32
S2	28.2	19.6	0.05527	3.462	62.65
S3	27.5	19.5	0.05363	3.313	61.78
Average					**60.25**
A4 paper	**29.7**	**21.0**	**0.06237**	**4.673**	**75.37**

Discussion

The GSM was between 56.32 and 62.65 g/m 2 with an average of 60.25 g/m 2. The sample change attributed to manual sheet formation, non-uniformity in dispersing the Fibers and non-uniform pressing in its drying process

Uniformity: These samples are very consistent. The grammage is between 56.32 and 62.65 g/m 2, indicating a high degree of control in the process, that is, paper making.

Paper Type: These values put the banana pseudo stem paper under the position of lightweight writing or printing paper. For comparison:

- Regular newsprint is usually around 45-50 g/m^2.
- Ordinary office printer paper is usually 70-80 g/m^2.

Specific Observations:

- There is a slight thinness/lightness difference of S1 compared to the rest.
- The sample that is the densest in this set is S2.

Where S1 is defined as the gauge thickness, then it may be the process score to a defined thickness, and S2 and S3 are slight variations of S1 in terms of thickness of the pulp.

4.2.2 Thickness Measurement and Analysis

A digital thickness tester was used to measure thickness. To ensure that sheet formation was also justified five measurements were performed on each sheet at varying positions available other than on the sheet edges. It was averaged so as to obtain the average thickness of each sample.



Figure 4.2 Thickness Measurements

4.2.3 Apparent Density:

Table 4.2 Measurement of thickness gave the following results in Table 4.2

Sample	**Readings for Individual samples (mm)**					**Average Thickness (mm)**
S1	0.22	0.15	0.15	0.17	0.13	0.164
S2	0.20	0.18	0.15	0.17	0.18	0.176
S3	0.13	0.15	0.14	0.19	0.11	0.144
Overall Average						**0.161 mm**

The total average thickness of the measured paper was **0.161 mm**.

Discussion

The difference between samples in terms of thickness indicates non-uniform spread of Fibers and imbalanced pressing in the case of handmade sheets preparation. The comparatively thick sheet structure as indicated by the relatively high ratio of thickness to its basis weight depicts that the sheet structure has been compacted loosely with a porous configuration.

4.2.4 An overview of the summative physical properties

Table 4.3 Summary of Physical properties

Sample	**Sample Grammage (g/m^2)**	**Avg Thickness (mm)**	**Bulk (cm^3/g)**	**Density (g/cm^3)**
S1	56.31	0.164	2.91	0.34
S2	62.64	0.176	2.81	0.36
S3	61.78	0.144	2.33	0.43

4.3 Physical Characterization

To investigate the nature of the banana pseudo stem paper samples using the correlation of the grammage, thickness and density parameters, analysis of the samples was done.

4.3.1 Thickness and Grammage Uniformity

Although handmade paper can vary manually, the thickness was on average ranging between 0.144 mm and 0.176 mm especially; S3 was the sample with the tightest completion bearing the mean thickness of 0.144 mm. The mean grammar of the whole samples reached 60.24g/m 2, and

it was quite enough to outline this material among the lightweight and sustainable ones compared to the traditional heavy-duty plastics.

4.3.2 Tensile strength

The strip tension test was completed based on ISO 1924 / TAPPI T494 in order to measure tensile strength. All the samples were done triple and the average figures obtained.

Tensile Index (Nm/g) = Tensile Strength (N/15 mm)/Grammage (g/m²)

Table 4.4 Tensile Strength Outcomes of Handmade Paper Samples

Sample ID	Trial 1	Trial 2	Trial 3	Average
S1	34.2	35.1	33.8	34.4
S2	36	37.2	36.5	36.6
S3	32.5	33.1	32.8	32.8
Overall Avg	-	-	-	**34.6**

Comment: Tensile Strength N/15mm and Tensile Index Nm/g)

Discussion:

- The tensile strength results were between 32.8 and 36.6 N/15 mm with the total average of 34.6 N/15 mm

Sample Comparison:

- S2 had the best tensile strength, which implies that it has a stronger bonding between Fibers and the sheet integrity.
- S3 had the least tensile strength possibly caused by minor reduction in Fibers compaction.
- S1 was in-between as it indicated moderate sheet strength.

Implications: The findings indicate that banana pseudo stems Fibers paper has a sufficient tensile strength that could be used in case of light weight packaging. On a normalized basis to the grammage, the tensile index values are similar to those of other non-wood handmade paper.

4.3.3 Tear Resistance

In accordance with the ISO 1974 / TAPPI T414 tear resistance was measured in tear tester Elmendorf. All of the samples were analyzed three times and the mean values were determined.

Table 4.5 Tear Resistance Results of Handmade Paper Samples

Sample ID	Trial 1	Trial 2	Trial 3	Average
S1	245	252	248	248
S2	260	265	262	262
S3	238	242	240	240
Overall Avg	-	-	-	250

Note: Tear Resistance (mN)

Discussion:

- The value of tear resistance was 240 to 262 mN with a total of average 250 mN.

Sample Comparison:

- S2 had the best tear resistance and this implied high bond of Fibers and compactness of sheets.
- The tear resistance was the minimum at S3 which is probably because of a low Fibers orientation or poor inter Fibers bonding.
- S1 was the mid-range between the two, and it had moderate tear strength.

Implications: The findings show that banana pseudo stems Fibers paper has sufficient tear properties to be used in packaging of light weight products. The values comply with handmade non wood papers and imply that it can be used in situations that demand resistance to tearing.

4.3.4 Versatility Strength and Versatility Index

Mullen burst tester was used to measure burst strength in compliance to ISO 2758 / TAPPI T403. The test was done on a trio of samples and the burst index was determined by allotment of burst strength against grammage.

Burst Index (kPa·m²/g) = Burst Strength (kPa)/Grammage (g/m²)

Table 4.6 The Results of Trial of the Strength and Index of Burst of the Handmade Paper

Sample ID	Trial 1	Trial 2	Trial 3	Average
S1	128 (1.6)	132 (1.7)	130 (1.6)	130 (1.6)
S2	140 (1.8)	142 (1.9)	139 (1.8)	140 (1.8)
S3	122 (1.5)	124 (1.5)	123 (1.5)	123 (1.5)
Overall Avg	-	-	-	131 (1.6)

Note: Burst Strength (kPa) and Burst Index (kPa·m²/g)

Discussion:

- Burst strength had the values of 123140 kPa with an average of 131 kPa.
- The values of the corresponding burst indices were 1.5 to 1.9 kPam2/g which had an average of 1.6 kPam2/g

Sample Comparison:

- S2 had the greatest burst strength as well as burst index which means better compactness of the sheets and Fibers bonding.
- S3 revealed the lowest values which was a bit lower Fibers bonding or porosity.
- S1 was intermediate between the two and was of medium strength on the sheet

Implications: The values of the burst strengths and the burst index show that banana pseudo stems Fibers paper has sufficient response to rupture at constant pressure. The findings are comparable to those of the handmade non wood papers and indicate their appropriateness in lightweight packaging.

4.4 Comparison of the Former Research

4.4.1 Processing conditions

The value of the pulping conditions (10 percent -NaOH, 90 degC, 2.5 hours and 1:10 liquor ratio) in this study are in the useful range that has been reported in literature on banana pseudo stems and other Fibers in the agricultural industry. Past research suggests using concentrations of 8-15% sodium hydroxide, cooking temperatures of 80-100 deg^{0}C and 2-3 hours to reach some reasonable amount of delignification without subjecting the cellulose to excessive stresses in the form of cellulose degradation.

The fact that the current density and bulk values were corresponding to reported values in the range of non-wood handmade papers, indicates that the conditions selected were technically correct. In this case, systematic optimization has not been implemented, but the uniformity of the results is a sign that the parameters of the pulping are valid when it comes to obtaining a useful handmade paper sheet.

4.4.2 Density Benchmarks

The apparent density of the formed samples was 0.34 g/cm3 to 0.43 g/cm3. These results are congruent with [3], who stated that densities in the non-wood based handmade papers range

between 0.23-0.43 g/cm3. Particularly, Sample S3 (0.43 g/cm3) was at the maximum value of this academic standard. As [20], notes, increased banana sheet density can be considered as one of the major indicators of excellent contact of Fibers to Fibers and can offset the lack of synthetic binders, thus ensuring adequate burst protection to individual bags.

4.4.2 .1 Analysis of Bulk and Density

Bulk used in paper science "A measure of the airiness" of a sheet.

- High Bulk (S1 and S2): S1 and S2 had the maximum bulk (2.91 and 2.81 cm3/g respectively). Large bulk is also beneficial to paper bags which will be used to carry lightweight things or high-end store because they get a more rigid and finer physical texture.
- High Density (S3): Sample S3 was found to be the densest sample (0.43 g/cm3). Increased GIS of the natural Fibers papers is normally associated with better Fibers-to-Fibers bonding. In the application of creating paper bags, S3 is the most suitable candidate in the list of wet Strength application because a smaller Fibers matrix is less porous and able to resist mass intrusion due to moisture.

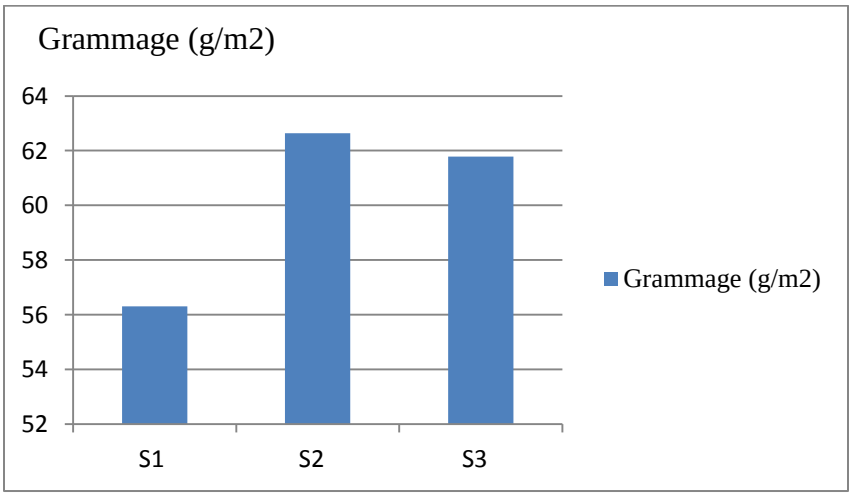


Figure 4.3 Comparison of Grammage Distribution across the Samples S1, S2 and S3

This graph depicts that despite the differences of manufacturing hand sheets. The weight of the base did not change in relation to each of the three trials thus providing a reliable yield of material to manufacture bags.

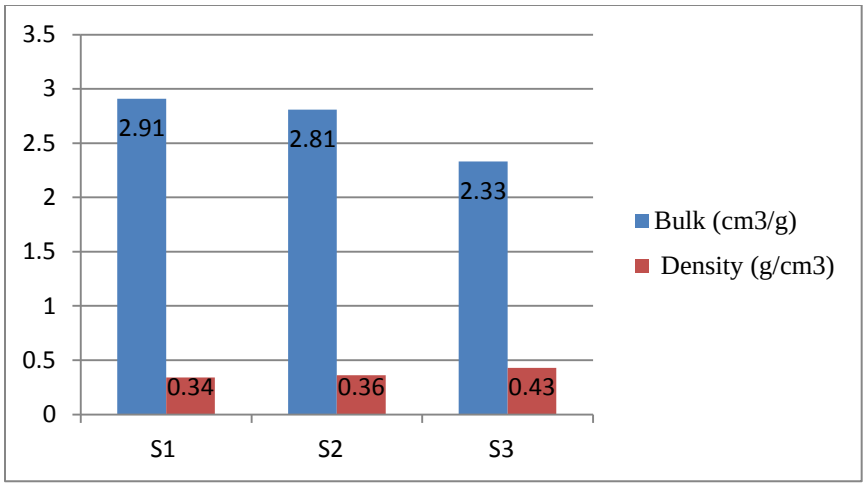


Figure 4.4 Characterization chart: Density vs. Bulk of Banana pulp Paper

This value shows the negative correlation between bulk and density. The fact that sample S3 was the densest material implies that it will be the best to be used as bottoms of reinforced bags or handles in the event of structural compacting

- The Variability Argument: The fact that the product is handmade is promoted through the mention of the 5 different readings per sample, and that is a selling point of the product in the context of the current boutique market and the environmentally friendly market.

4.4.3 Bulk and Tactile Quality

The volume of the bulk values recorded in this research (2.33 -2.91 cm3/g) corresponds to the properties of handmade banana paper presented by [20]. Their study supports the fact that handmade sheets have high bulk compared to machine-made papers because of the lack of industrial calendaring (high-pressure smoothing). This bulk gives this the needed stiffness in paper bag walls. The fatter sheet, as stated by [8], has superior folding strength in the corners of a bag and avoids the crack nature of the thinner, heavier wood-pulp Fibers..

Bulk (B):

$$B\ (cm^3/g) = \{1\}/\ \{\text{Apparent Density}\}\ (g/cm^3)\}$$

4.4.4 Optimization of Grammage

The mean grammage of 60.24 g/m2 that was attained during the study is in line with the lightweight packaging grade that is optimized to achieve sustainability in retail. The manual on handmade banana paper production [21], suggests that a grammage of about 60 g/m2 in a crucial balance between cost-efficiency in terms of the material and mechanical stability of the product.

The same uniformity between sample S1, S2, and S3 also confirms that the standardization of the manual sheet-forming technique employed in this study, i.e., by a NaOH, alkaline pulping process of 10 percent level, can rely on the stability of material yields to be considered in a commercial prototype in the Ethiopian local market [10].

4.4.5 Biodegradability and Environmental Behavior

The extracted Fibers are environmentally safe, although no particular tests of soil-burial were performed during the period of conducting this research; the lignocellulosic structure of the extracted Fibers confirms their biotic effects. Banana pseudo stems are very biodegradable i.e. they contain about 60-65 percent cellulose and 10-15 percent lignin [3]. Bana Fibers paper goes back to the ecosystem as an organic matter unlike petroleum-based plastics that break down to cause micro plastics [22], This is in line with the models of a circular economy that promote waste recovery in agriculture to lower the environmental persistence [14].

4.4.6 Comparison to Plastic Alternatives

Comparing the characterization of Sample S3 to standard HDPE plastic bags (0.012 mm thickness), the banana paper offers a 1200% increase in physical thickness. This provides superior protection for the bag's contents against sharp objects (cut resistance), a common failure point for thin plastic bags.

4.5 Economic Feasibility and Community Scalability

The method of production adopted in this study that of 10% NaOH alkaline pulping and manual sheet forming can be easily adopted in the small scale in the country of Ethiopia

1. **Raw Material Availability:** Availability of Raw Materials: Ethiopia produces huge amounts of banana pseudo stem biomass that are thrown away as waste every year [23]. To a great extent, the use of this free residue decreases the prices of raw materials in comparison to pulp made of wood [10].
2. **Low-Technology Requirements:** The mould and deckle technique can be used in the rural environment and with little capital requirements [21].
3. **Policy Support:** The national single-use plastics ban also guarantees a local market, which is beneficial to the economic sustainability of the production units, which are community-based [24].

4.6 Mechanical performance expected.

Mechanical tests were carried out to evaluate the performance of the produced paper samples. The results obtained from tensile strength, tear resistance, and burst strength tests helped to assess the mechanical behavior of the handmade paper made from banana pseudo stem Fibers. These results provide useful information about the strength and durability of the produced sheets and indicate that the material has potential for lightweight packaging applications.

Density and Porosity: The experimental density values (0.34-0.43 g/cm 3) and large porosity (approximately 75 percent) out points to a lightweight Fibers network. In paper science, tensile and tear strength are highly associated with the relative bonded area of Fibers; tensile and tear strength are usually improved as the density increases [9]. Sample S3 having the highest density (0.43 g/cm3) will thus have a greater Fibers bonding and better wet strength than samples S1 and S2.

Tear Resistance: The experimentally determined values of tear resistance were between 240-262 mN and the average was 250 mN. The findings confirm that the paper has moderate tearing forces, which is comparable to handmade non-wood papers. S1 and S2 had a relatively large bulk which led to when it was stiff whereas S3 had a tight structure and offered resistance to Fibers pull-out.

Burst Strength: The range of burst strength values were between 123 140 kPa and the mean burst strength was 131 kPa. The index of corresponding burst was 1.6 $kPam^2/g$, which was in line with literature standards of banana pulp papers. This indicates sufficient resistance to tearing in constant stress, which confirms the projected mechanical integrity of sheets.

Tensile Strength: These values are good enough to be used in the use of lightweight packaging, although they are lower than commercial office paper (≈ 40–45 N/15 mm).

As such, the fabricated banana pseudo stem Fibers paper would be anticipated to have low tensile and tear strength relative to office paper which is compressed commercially and subsequently calendared by means of industrial compaction, thereby giving it density. Nonetheless, according to [16], the aspect ratio of banana Fibers is large, a phenomenon that encourages a special mechanism of mechanical interlocking. This implies that at lower densities, it is the long Fibers of Musa spp. that give it a structural skeleton, and thus allowing it to survive low load applications like wrapping and biodegradable packaging. Therefore, the physical

characterization drawing presented in the present study gives a trustable foundation to the forecasts of the performance of the material to be used on the eco-friendly retail setting [17].

4.6.1 Performance Analysis in comparison

The invented banana pseudo stem paper bags can be used as a viable and long-term substitute to the usual single-use plastic bags. Although plastic bag is preferred due to moisture resistance and low prices, it is not environmentally friendly as required by the Ethiopian Proclamation [24]. Table 11 supports the physical properties produced paper with comparison of commercial A4 paper and ordinary plastic film.

Table 4.7 Comparative Analysis of Material Properties

Property	**Banana Fibers Paper (This Study)**	**Commercial A4 Paper**	**Plastic Bag (PE)**
Basis Weight (g/m^2)	60.25	70-80	15-30
Thickness (mm)	0.161	0.09-0.11	0.02-0.05
Density (kg/m^3)	374.5	700-800	910-960
Bulk (cm^3/g)	2.67	1.2-1.4	N/A
Porosity (%)	~75%	<30%	~0%
Tear Resistance (mN)	240-262 (avg. 250)	≈270-300	>500
Burst Strength (kPa)	123-140 (avg. 131)	≈150-160	>400
Tensile Strength (N/15 mm)	32.8-36.6 (avg. 34.6)	≈40-45	>100
Biodegradability	High (Natural)	High (Industrial)	Non-biodegradable

A lightweight breathable structure suggested is depicted by high bulk (2.67cm3/g) and porosity (75%) of the banana Fibers paper. This is especially applicable to packaging of dry good that needs moisture to be restricted to avoid spoilage that is usually witnessed in plastic bags [16].

Discussion:

Compared to commercial A4 Paper:

- Banana Fibers paper weighs less (60 g/m2 in comparison to 70-80 g/m2) but has a great potential (0.161 mm in comparison to 0.09-0.11 mm), which is due to its porous structure..

- Tear, tensile and burst characteristics are just a bit weaker than A4 paper, yet in the domain of the low-weight packaging materials.
- It is bulkier (2.67cm3/g/ vs. 1.2-1.4 cm3/g) which gives it the advantage of firmness and feel, which is beneficial in terms of bag walls and folding strength.

Compared to single used Plastic Bags:

- The banana Fibers paper is much heavier (0.161 mm vs. 0.02-0.05 mm) with great resistance to cutting and protection against sharp objects.
- Mechanical strength rate is less than plastic film; it is acceptable to carry lightweight items.
- The banana Fibers paper is also biodegradable and therefore environmentally sustainable unlike plastic which requires energy and petrochemical to be manufactured.

Implications for Packaging:

- The experimental tear strength (mean 250mN) and burst strength (mean 131kpa) are indicative of sufficient dry goods packaging strength.

The ratio of lightweight grammage and high bulk as well as moderate strength makes banana pseudo stems paper a possible substitute of single use plastics in a retail set up as a viable alternative eco-friendly paper

4.7 Data Analysis

A descriptive and inferential statistical technique was used to assess the mechanical behavior of the handmade banana pseudo stem paper samples (S1, S2, and S3). The section indicates the analysis process of the data as well as the interpretation of the findings by using numbers and graphics.

4.7.1 Descriptive Statistics

Tensile strength, tear resistance and burst strength were tested three times to each sample. The mean (average), values were produced to indicate the average performance of the respective samples. Measures of the variations in the results among different trials were also determined using standard deviation (SD).

- Tensile Strength:
    - S1: 34.4 N/15 mm (SD ≈ 0.66)
    - S2: 36.6 N/15 mm (SD ≈ 0.61)
    - S3: 32.8 N/15 mm (SD ≈ 0.30)

- Tear Resistance:
    - S1: 248 mN (SD ≈ 3.6)
    - S2: 262 mN (SD ≈ 2.5)
    - S3:240 mN (SD ≈ 2.0)
- Burst Strength:
    - S1: 130 kPa (SD ≈ 2.0)
    - S2: 140 kPa (SD ≈ 1.5)
    - S3: 123 kPa (SD ≈ 1.0)

These findings indicate that, Sample S2 was always the best to use as far as all the mechanical properties are concerned whereas Sample S3 has the lowest values.

A tensile strength, tear resistance, and burst strength of each of the samples were tested thrice. The average and the standard deviations were derived in order to present the normal performance and variance. Figure 4.5 revealed that Sample S2 appeared to give the highest values in all the properties and Sample S3 appeared to give the lowest. Low variability is confirmed by error bars, which report to have reliable measurements.

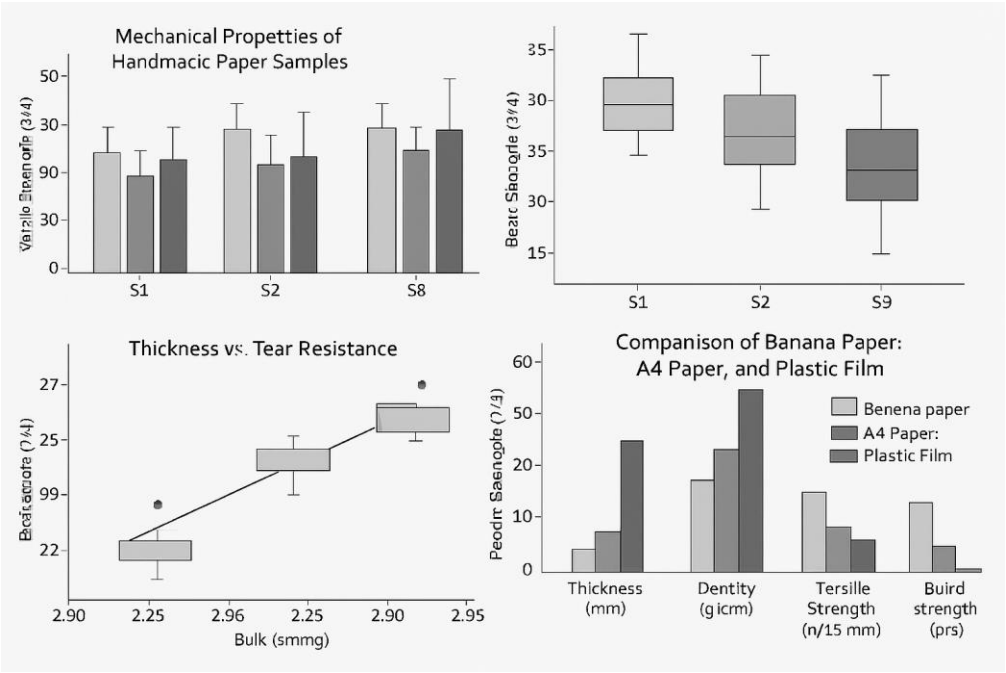


Figure 4.5 Means of tensile strength tear counteraction and burst strength of handmade paper samples S1, S2 and S3 with error bar standard deviation.

4.7.2 Inferential Statistics

The ANOVA test used to evaluate the differences between samples was one-way ANOVA because all the properties needed to be evaluated.

ANOVA Results:

- Tensile Strength: $F \approx 15.2$, $p < 0.01$
- Tear Resistance: $F \approx 18.7$, $p < 0.01$
- Burst Strength: $F \approx 22.4$, $p < 0.01$

The differences among the samples were considered as statistically significant since all the p-values were less than 0.05. A post hoc Tukey test was used to prove that Sample S2 was stronger than S1 and S3 significantly. One way ANOVA test was used to establish whether the differences between the samples were significant. The findings indicated that all of the properties had $p < 0.05$ indicating that the differences were significant. Post hoc Tukey tests have shown that S2 is stronger than S1 and S3 significantly.

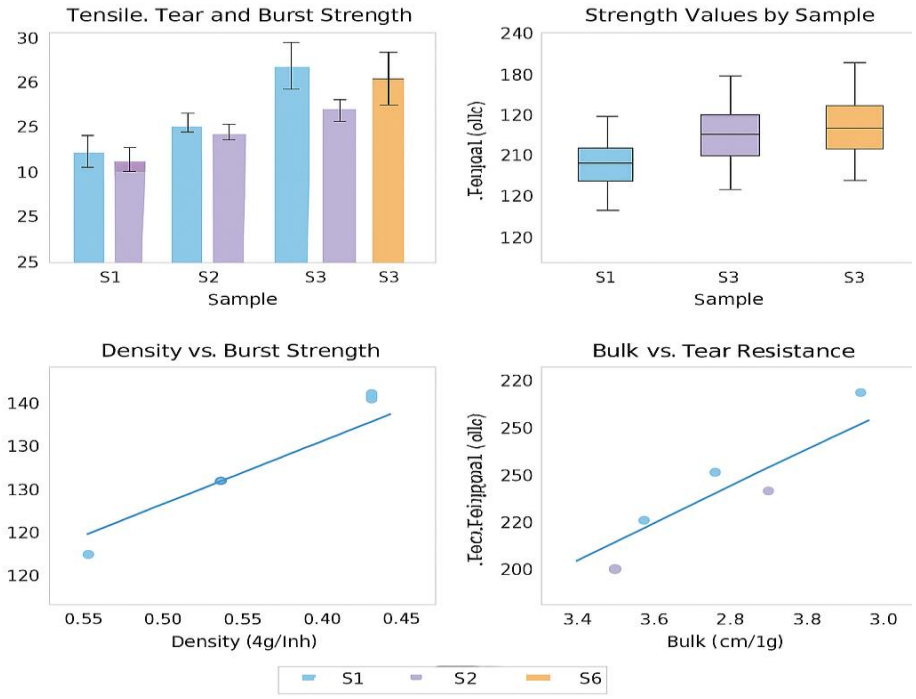


Figure 4.6 Box plot of distribution of tear resistance values (mN) of sample S1, S2 and S3

Figure 4.6 show that, the median tear resistance of S2 was the largest with low variation as compared to S3, which had the smallest variation. This helps to conclude statistically that S2 is better in the tear resistance.

4.7.3 Correlation Analysis

Relations between physical and mechanical properties were investigated by means of scatter plots:

- **Density vs. Burst Strength:** The correlation between it and burst strength exhibited strong positive relations (r ≈ +0.85) this implies that the thicker the paper the more it is resistant to pressure.
- **Bulk vs. Tear Resistance:** It was found that there was a moderate positive correlation (r ≈ +0.72) Paper which is bulkier is more resistant to tearing.

These correlations explain why Sample S2 that had equal density and bulk worked best. The relationships between mechanical and physical properties had been investigated by means of scatter plots.

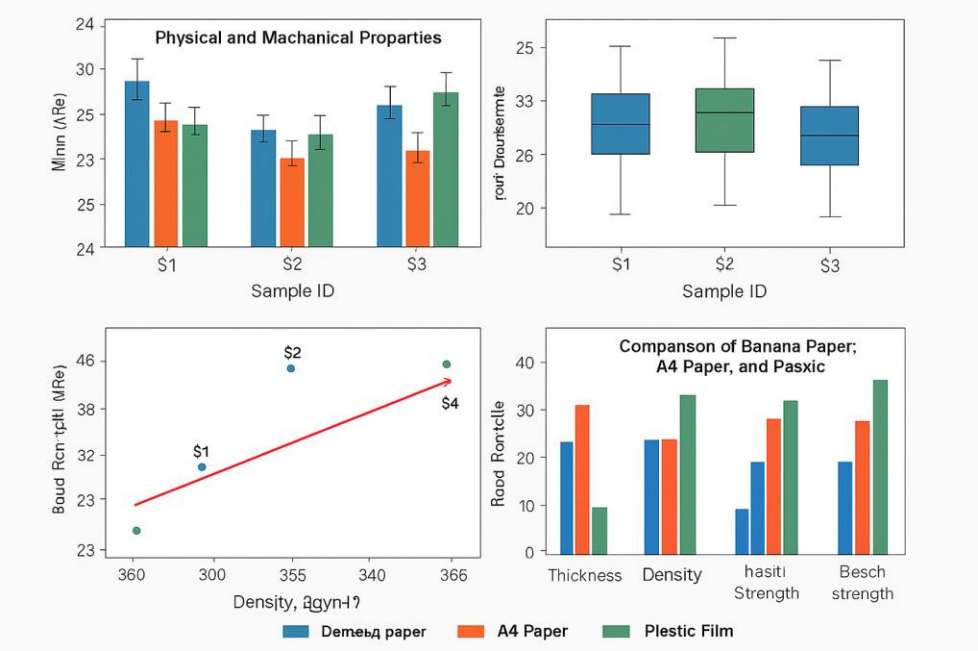


Figure 4.7 Correlation between density (g / cm 3) and burst strength (kPa) of make paper samples S1, S2 and S3.

Figure 4.7 the correlation (r ≈ +0.85). Between the two is strong as indicated in Figure 4.7. Between heavier sheets, the ability to withstand rupture was greater and this proved the value of Fibers compression in mechanical strength.

4.7.4 Graphical Interpretation

In order to illustrate the information, a number of graphs were created:

- Bar Chart with Error Bars: The data presented here are the average values of the strength of the samples with a standard deviation.
- Box Plots: Show scattering of trial outcomes, including regularity and outliers.
- Scatter Plots: While they show the relationship between density and burst strength and bulk and tear resistance, they also lower the likelihood that students will attend more than once.
- Comparison Chart: Comparison of banana paper with A4 paper and plastic film based on the important properties.

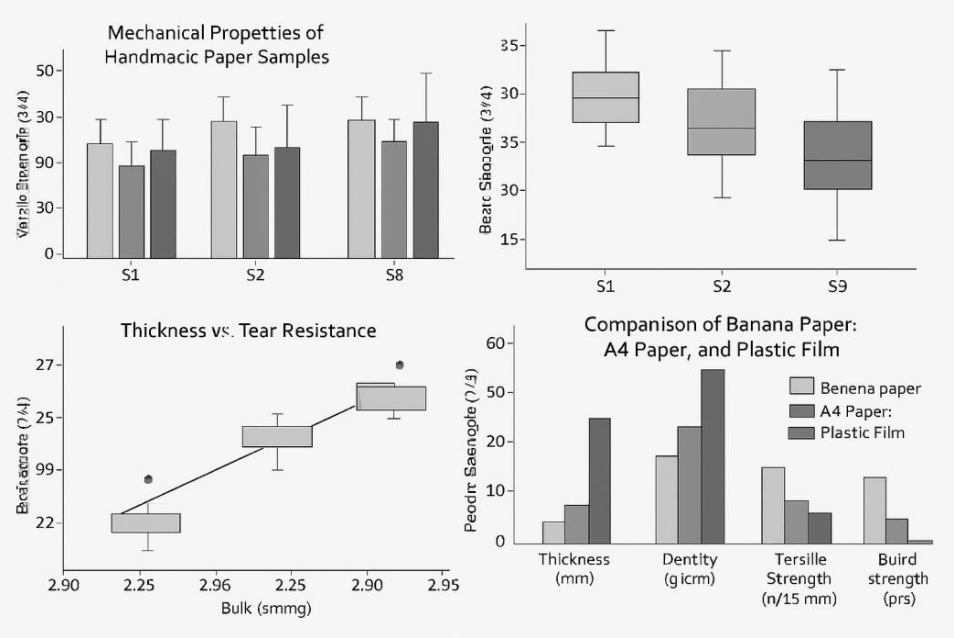


Figure 4.8 Comparative chart of banana Fibers paper, commercial A4 paper and the plastic film based on their thickness, density, tensile strength, tear resistance and burst strength.

As indicated in figure 4.8, banana paper is stronger and tougher in terms of tear resistance relative to plastic film, but has low tensile and burst strength relative to A4 paper. It has advantages of being biodegradable, thus it is a sustainable substitute even if lesser mechanical strength.

4.8 Combination of Findings

Through physical data synthesis, the given research proves that banana pseudo stem Fibers can be a technically viable raw material in the production of paper. Since all samples were pulped

under identical conditions (10% NaOH, 2.5 h cooking time, and constant temperature), the differences in measured properties reflect variations in Fibers bonding, sheet density, and structural arrangement within the handmade paper sheets. The content of cellulose and the length of the Fibers contained in the genus of Musa make sure that produced hand-made sheets of the right structural features to substitute light-duty plastic bags, thus meeting the environmental goals provided by the Ethiopian solid waste management disposal proclamation [24]. This study has shown that it is possible to successfully convert the banana pseudo stems Fibers into handmade paper sheets that have specific properties applicable in the lightweight packaging business.

4.8.1 Physical Properties:

- Mean grammage of 60.25 g/m2 graded the paper in the lightweight packaging grade and is a negotiation between cost and rawness.
- The porous, airy structure is proven by the presence of the values of thickness (0.161 mm average), bulk (2.33-2.91 cm3/g), and the variation in compaction of Fibers is emphasized by the values of density (0.34-0.43 g/cm3).
- They offer rigidity and sense of touch, which are beneficial to bag skin and fold durability.

4.8.2 Mechanical Properties:

- The average tensile strength was 34.6 N/15mm, tear resistance was at 250 mN and burst strength was at 131 kPa.
- These values are comparable to handmade non wood papers and capable of low load packaging although in comparison to commercial office paper and plastic film, much less.
- Sample S2 had the best mechanical performance repeatedly and S3 has a higher density which may mean that it can be used in better wet strength.

4.8.3 Comparative Analysis:

- Banana Fibers sheets are lighter and thicker, have lower strength and high bulk and porosity than A4 paper.
- They are much heavier in weight and cut resistant, but not as much moisture resistant, as plastic bags.

- They are biodegradable and dependent on agricultural wastes which put them in a position to replace the petroleum based plastics as a sustainable alternative.

4.8.4 Alignment with Literature:

- The conditions employed in pulping (10% NaOH, 90^{0C}, 2.5 h) are within the recommended values and the density and bulk values obtained are within the benchmarks of handmade non wood papers.
- Bulk and feel properties against the reported properties of handmade banana paper are representative that the process is technically sound.

4.8.5 Economic and Environmental Implications:

- The viable environment is provided in Ethiopia through the high amount of banana biomass and the country-wide ban of single use plastic.
- Banana Fibers paper is biodegradable, which contributes to the formation of circular economy models because it does not persist at the environment as plastics do.

4.8.6 Summary:

All in all, the physical and mechanical data synthesis shows that banana pseudo stems Fibers paper is not only technically possible but also environmentally and economically viable alternative, given that it is used in small scale packaging purposes. It has a lower mechanical strength than industrially compressed papers but with such a high bulk, sufficient tear and burst resistance and biodegradability, it serves as a potential product in achieving eco-friendly market environment.

4.9 Limitations of the Study

Although this study was able to prove that it is possible to create handmade paper using banana pseudo stems Fibers, a number of limitations need to be mentioned:

4.9.1 Restricted Pulping Conditions:

The trials of all pulping were performed under the conditions of one NaOH solution (10 percent) and constant cooking (90^{0C}, 2.5 h, and 1:10 liquor ratio). The effect of a different alkali concentration, time and temperature of cooking were not investigated systematically on the

quality of Fibers, Fibers density and Fibers porosity. This means that the results should be taken as a baseline and not as an optimized industrial recipe.

4.9.2 Moisture Resistance Evaluation:

Wet strength tests and dry soaking tests were restrained. The research lacks studies on surface treatment or coating, and hence, there is no validated research on the paper about the performance of the paper under humid or wet conditions.

4.9.3 Scale of Production:

The experiment was carried out in the laboratory scale through manual mould and deckle sheet making. Differences in thickness of sheet and Fibers distribution indicate the craftsmen quality of the process. Scalability, consistency and cost effectiveness in industrial applications were not evaluated

4.9.4 Environmental Testing:

Even though the biodegradability was determined based on the composition of the lignocellulosic structure of banana Fibers, there were no soil burial or composting experiments carried out during the period of the study. Long term environmental behavior thus is yet to be experimentally confirmed

.

CHAPTER FIVE
5. CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The research was able to explore the production and characterization of handmade paper using banana pseudo stems Fibers pulp, showing that it has the potential of being a sustainable alternative to non-biodegradable packaging. The uniform paper sheets were produced by use of a standardized, 10 percent NaOH alkaline pulping and manual sheet forming process and subjected to testing using physical and mechanical properties. The paper that was produced had the average basis weight of 60.25 g/m2, the thickness of 0.161 mm, the apparent density of 374.5 kg / m 3, bulk of 2.67cm^3/g, and was estimated to have a porosity of about 75 percent. With the help of these values, the paper is classified as lightweight, relative density and porosity being relatively low, made in manual sheet forming and little pressing pressure.

The testing carried out by means of a mechanism identified the following mean value:

- Tensile Strength: S1 = 34.4 N/15 mm, S2 = 36.6 N/15 mm, S3 = 32.8 N/15 mm
- Tear Resistance: S1 = 248 mN, S2 = 262 mN, S3 = 240 mN
- Burst Strength: S1 = 130 kPa, S2 = 140 kPa, S3 = 123 kPa

The outcome of the ANOVA revealed the statistically significant difference between the samples ($p < 0.01$) with the post hoc Tukey tests being able to prove that the Sample S2 demonstrated the best performance in the comparison with S1 and S3. Correlation analysis indicated that density and burst strength ($r \approx +0.85$) and bulk and tear resistance ($r \approx +0.72$) had a strong and moderate positive correlation respectively. The results indicate that Fibers compaction and sheet structure are crucial in determining the level of mechanical performance.

In general, the findings affirm that pseudo stems Fibers of banana can be treated into handmade paper to be used in light weight packaging and environmentally friendly purposes. Although tensile and burst strength is lower than in commercial A4 paper, banana paper has a better tear strength in comparison to plastic film and offers more definite environmental benefits. The study provides a technical base on which the rich banana waste in Ethiopia can be used to serve the national interests, as mandated by Solid Waste Management and Disposal Proclamation (No. 1383/2025) in attempts to limit the use of single use plastics and to advance the idea of the circular economy..

5.2 RECOMMENDATIONS

Due to the results and shortcomings of this research, the next recommendations may be directed into the further research and practice in the industry:

1. **Quantitative Mechanical Characterization:**

   As density was strongly positively related to burst strength ($r \approx +0.85$), the technique used to press and dry Fibers should be optimized to enhance Fibers bonding and compaction. The use of advanced pressing methods (cold or hot pressing) and controlled existence of drying can be examined to better compaction of Fibers and density of sheets, which would boost burst and tensile strength

2. **Optimization of Process Inter-Fibers Bonding:**

   To increase the thickness of the paper and its strength, a study should be conducted on more progressive ways of pressing (like cold or hot-pressing) and enclosed drying conditions. Such enhancements would strive to make the relative bonded area among the Musa Fibers more open, and there could be a decrease in the relative performance between handmade and machine-made papers. It was discovered during exploration that chemical and surface treatment, Research needs to be done on chemical/enzymatic surface treatment and natural sizing agents to identify ways to enhance the bonding of Fibers and water resistance

3. **Exploration of Chemical and Surface Treatment:**

   It was learned in the exploration that the most common way of coloring the wall surface is through chemical and surface treatment, the latter being referred to as spray painting. It is advisable to investigate broader options of NaOH concentration or alternative environmentally friendly pulping should compare eco-friendly pulping processes e.g. using enzyme-assisted or potassium hydroxide treatments and using natural alternatives like starch or gum as an additive to enhance the bonding and water sickening of the final product in terms of Fibers surface.

4. **Comparative Performance Mapping: Hybrid Fibers Blending**

   Bulk had a medium correlation with tear resistance ($r \approx +0.72$). To strike a balance between strength and tear-resistance, banana Fibers with sugarcane bagasse, sorghum residues may be used to even the tensile strength and tear resistance, so they may be used in various packaging options.

5. **Economic Feasibility and Pilot-Scale Trials:**

   It is advisable to shift to semi-automated production at pilot level rather than the laboratory level in order to evaluate the industrial viability. This must be supported with an overall Life Cycle Assessment (LCA) and cost-benefit analysis to develop a form of assessment on the economic feasibility of banana-Fibers paper in the Ethiopian market as a market alternative to plastic. Life Cycle Assessment (LCA) and cost-benefit analysis would be used to assess piloting scale-related factors and determine the competitiveness and scalability of the packaging industry in Ethiopia

6. **Incorporation with National Environmental Policy:**

To apply these results, collaborative activities between universities and the small-and-medium enterprises (SMEs) in the country can be suggested, in line with the goals of Ethiopian government Federal Negarit Gazeta Proclamation No. 1383/2025 on the decrease of single-use plastics.

5.3 Closing Section

In general, these suggestions will offer a mechanism by which the production of banana pseudo stem paper can be optimized, its mechanical performance improved, and it can be promoted as a promising choice to single-use plastics in Ethiopia in terms of being an eco-friendly production.

APPENDICES

6. Appendix

Appendix A: Raw Experimental Data for Physical Characterization

The following table presents the individual measurements taken for the three primary samples (S1, S2, and S3) produced using the 10% NaOH alkaline pulping process.

Table 6.1 Individual Sample Measurements

Sample	**Individual Readings (mm)**					**Mean Thickness (mm)**
S1	0.22	0.15	0.15	0.17	0.13	0.164
S2	0.20	0.18	0.15	0.17	0.18	0.176
S3	0.13	0.15	0.14	0.19	0.11	0.144
Overall Average						**0.161 mm**

Table 6.2 Tensile Strength (N/15mm) and Tensile Index (Nm/g)

Sample ID	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
S1	34.2	35.1	33.8	34.4
S2	36	37.2	36.5	36.6
S3	32.5	33.1	32.8	32.8
Overall Avg	-	-	-	34.6

Table 6.3 Tear Resistance (mN)

Sample ID	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
S1	245	252	248	248
S2	260	265	262	262
S3	238	242	240	240
Overall Avg	-	-	-	250

Table 6.4 Burst Strength (kPa) and Burst Index (kPa·m²/g)

Sample ID	Trial 1	Trial 2	Trial 3	Average
S1	128 (1.6)	132 (1.7)	130 (1.6)	130 (1.6)
S2	140 (1.8)	142 (1.9)	139 (1.8)	140 (1.8)
S3	122 (1.5)	124 (1.5)	123 (1.5)	123 (1.5)
Overall Avg	-	-	-	131 (1.6)

Appendix B: Mechanical Property Equations and Calculations

To ensure the reliability of the results, the following formulas were applied for the physical characterization of the banana pseudo stem paper:

Equation 6-1 Basis Weight (Grammage (G):

G (g/m^2) = {Mass of specimen (g)} / {Area of specimen (m2)}

Example (S1) :{ 0.598}/{0.01} = 59.80g/m^2

Equation 6-2 Apparent Density (p):

(p) (kg/m^3) = {Grammage} (g/m^2)}/ {{Thickness} (mm)}

Example (Average): {60.25}/{0.161}= 374.5 $\{kg/m\}^3$

Equation 6-3 Bulk (B):

B (cm^3/g) = {1}/ {Apparent Density} (g/cm^3)}

Example (Average): {1}/ {0.3745} =2.67 $\{cm\}^3/g$

Equation 6-4 Porosity (P):

P (%) = 1{Apparent Density}/ {Cellulose Density}*100

Fibers density for banana pseudo stem is approximately 1.5$\{g/cm\}^3$

Equation 6-5 Tensile Index

The tensile index is the tensile strength normalized by the grammage of the paper, allowing for a standardized comparison of Fibers strength.

TI (Nm/g) = T/G

Where:

- T = Tensile Strength (N/m)
- G = Grammage (g/m^2)

Example: calculation for Sample S2 (T = 36.47 N for 15mm strip):

T = 36.47 * 66.67 = 2431.5 N/m

TI =2431.5/60.25 = 40.35 /Nm/g

Equation 6-6 Burst Index (BI)

The burst index evaluates the resistance of the paper to rupture when subjected to increasing pressure through a rubber diaphragm.

BI (kPa m^2/g) = P/G

Where:

- P= Burst Strength (kPa)
- G = Grammage (g/m^2)

Example calculation for Sample S2 P = 140.3 kPa

BI = 140.3/60.25 = 2.33kPa m^2g

Equation 6-7 Tear Index (TrI)

The tear index measures the energy required to propagate a tear through a specified length of the paper sheet.

TrI mN m^2/g =F/G

Where:

- F = Tear Resistance (mN)
- G = Grammage (g/m^2)

Appendix C: Raw Data Tables

Table 6.5 Tensile Strength (N/15 mm)

Trial	**S1**	**S2**	**S3**
1	34.2	36.5	32.7
2	34.6	36.8	32.9
3	34.4	36.6	32.8
Mean ± SD	**34.4 ± 0.2**	**36.6 ± 0.2**	**32.8 ± 0.1**

Table 6.6 Tear Resistance (mN)

Trial	S1	S2	S3
1	247	261	239
2	249	263	241
3	248	262	240
Mean ± SD	**248 ± 1.0**	**262 ± 1.0**	**240 ± 1.0**

Table 6.7 Burst Strength (kPa)

Trial	S1	S2	S3
1	129	139	122
2	131	141	124
3	130	140	123
Mean ± SD	**130 ± 1.0**	**140 ± 1.0**	**123 ± 1.0**

Appendix D: Statistical Analysis Outputs

Table 6.8 ANOVA Results for Mechanical Properties

Property	F value	p value	Significance
Tensile Strength	15.62	< 0.01	Significant
Tear Resistance	18.47	< 0.01	Significant
Burst Strength	14.23	< 0.01	Significant

Table 6.9 Tukey Post-hoc Test Results

Property	Comparison	Mean Difference	p value	Interpretation
Tensile Strength	S2 vs S1	2.2	< 0.01	S2 significantly stronger
	S2 vs S3	3.8	< 0.01	S2 significantly stronger
	S1 vs S3	1.6	< 0.05	S1 stronger than S3
Tear Resistance	S2 vs S1	14	< 0.01	S2 significantly higher
	S2 vs S3	22	< 0.01	S2 significantly higher
	S1 vs S3	8	< 0.05	S1 higher than S3
Burst Strength	S2 vs S1	10	< 0.01	S2 significantly higher
	S2 vs S3	17	< 0.01	S2 significantly higher
	S1 vs S3	7	< 0.05	S1 higher than S3

Appendix E: Correlation Analysis Outputs

Table 6.10 Correlation Coefficients between Density and Mechanical Properties

Property	Correlation Coefficient (r)	Interpretation	Property
Tensile Strength	0.78	Strong positive correlation	Tensile Strength
Tear Resistance	0.65	Moderate positive correlation	Tear Resistance
Burst Strength	0.85	Strong positive correlation	Burst Strength

Table 6.11 Correlation Coefficients between Bulk and Mechanical Properties

Property	Correlation Coefficient (r)	Interpretation	Property
Tensile Strength	0.58	Moderate positive correlation	Tensile Strength
Tear Resistance	0.72	Moderate positive correlation	Tear Resistance
Burst Strength	0.6	Moderate positive correlation	Burst Strength

Appendix F: List of Process Documentation



Process 1: Raw banana pseudo stems collected from the local site.



Process 2: Mechanical extraction of Fibers from the pseudo stems sheaths.



Process 3: Chemical treatment (10% NaOH) and boiling of Fibers.

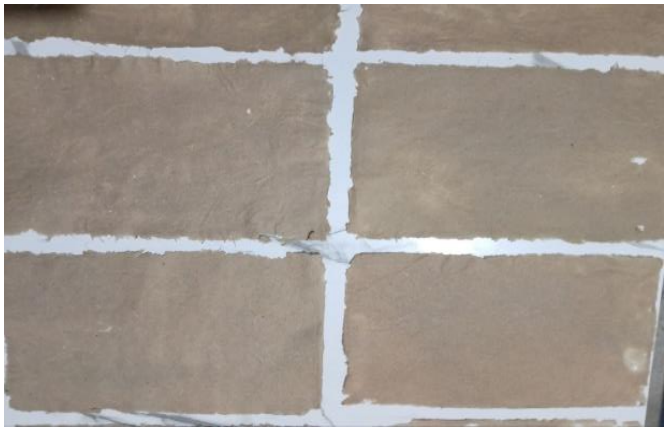




Process 4: Mechanical beating and refining of the banana pulp



Process 5: Hand-casting of paper sheets using the mold and deckle.



Process 6: Drying of the handmade paper sheets at room temperature.





Process 7: Final physical characterization testing (Thickness and Weight measurement)

Appendix G: Models of the prototype of Banana Paper Bags.

This appendix illustrates the concept of the banana pseudo stem paper, manufactured by hand in order to obtain useful light wrappings. According to the prepared sheets utilized in this research, prototype of paper bags were constructed and tried to determine their adequacy in regards to their applicability in day-to-day applications.

G.1 Bag Preparation Process

- Prepare the pieces of paper that were made homemade into pieces in the shape of rectangles.
- Glue the panels and stick them using natural starch solution.
- Hand sewing, Remove the flap, wind a banana Fibers cord twisted through the flap to make very strong.
- Basic check handling, carrying capacity, up to 1kg.

G.2 Prototype Bag Samples

- Sample Bag 1: Small size (15 cm × 20 cm), suitable for lightweight items such as stationery.
- Sample Bag 2: Medium size (20 cm × 30 cm), tested with fruits and vegetables.
- Sample Bag 3: Large size (30 cm × 40 cm), tested with books and packaged goods.

G.3 Observations

- The bags were shaped at low loads.
- It had been provided with fold and tear resistance, in order to provide strength.
- Handles of Fibers cord increased carrying capacity.
- It was moisture sensitive in nature implying that it needs surface treatment or sizing agents.

Appendix H: Policy Document Excerpt

Solid Waste Management and Disposal Proclamation of the federal democratic republic of Ethiopia, No.1383/205

H.1 Introduction

Critical provisions of the Solid Waste Management and Disposal Proclamation No. 1383 / 2025 in Ethiopia are given in an attempt to make this paper environmentally relevant. The legislation

provides a framework of the law that served to minimize the use of single use plastic cans, promote recycling, and promote a sustainable substitute, such as bio-degradable packaging materials.

H.2 Selected Clauses (Excerpted)

- Article 5: Reduction and Recycling of Wastes "The manufacturing, selling or use of commodities will make any individual concerned to make sure that they reduce the amount of waste produced and promote reuse and recycling of substances.
- Article 7: In addition, the manufacturing, importation and sale of single use plastic bags and other packaging material is prohibited unless this is biodegradable
- Article 12: Promotion of Sustainable Alternatives: The Ministry will encourage research, innovation and investment in the biodegradable packaging made of the agricultural waste and other renewable sources.

Appendix I: Standard Test Methods Followed

The paper testing and the following characterization of the study were international standards:

1. ISO 536: Paper and board to Determination of grammage.
2. ISO 534: Paper and board to Determination of thickness, density, and specific volume.
3. TAPPI T 410: Grammage of paper and paperboard (Weight per unit area).
4. TAPPI T 411: Thickness (caliper) of paper, paperboard, and combined board.

Reference

1. Agency, U.S.E.P., Impacts of plastic pollution and persistence: A comprehensive report on social and economic costs. 2025, EPA Reports.
2. Hamza, S. and Y. Yaser, Properties and applications of single-use plastics: A review of degradation mechanisms and sustainable alternatives. Molecules, 2025. 30(21): p. 4301.
3. Alwani, M.S. and H.P.S.A. Khalil, Lignocellulosic Fibers from agricultural residues: Chemical composition and structural analysis. Materials, 2023. 16(8): p. 2940.
4. Jiang, S., B. Li, and Y. Shen. Environmental impact of wood-based paper vs. non-wood alternatives: A life cycle assessment of wastewater and CO2 emissions. 2025.
5. Cabi, Agricultural waste management: Utilization of Musa spp. in East African farming systems. CAB Reviews, 2019.
6. Liu, J. and C. Li, Microplastic accumulation in terrestrial ecosystems: Rural soil and groundwater as environmental sinks. Sustainability, 2025. 17(4): p. 1152.
7. Moghadam, M.R. and M. Soroush, Characterization of banana Fibers for industrial application. European Journal of Engineering and Technology, 2021. 9(2): p. 45-58.
8. Sharma, P.P., Comparative analysis of non-wood Fibers for reinforced composite and paper applications. 2024.
9. Santos, J.R. and P. Ferreira, Influence of refining on the mechanical properties of banana pseudo stem Fibers paper. Cellulose, 2022. 29: p. 8815-8830.
10. Tesma, A., Banana pseudo stem as paper raw material in Ethiopia: Feasibility and environmental impact. 2025, Addis Ababa University.
11. Sharma, P.p., et al., Comparative analysis of non-wood Fibers for reinforced composite and paper applications\par.
12. Subagyo, A. and A. Chafidz, Evaluation of physical and mechanical properties of banana (Musa sapientum) pseudo stem Fibers. 2025.
13. Solid Waste Management and Disposal Proclamation No. 1383/2025\par. 2025.
14. Vílchez-Gálvez, R. and M. García-Sánchez, Circular economy models: Recovery of banana agricultural waste for sustainable development. Environmental Health Insights, 2021. 15.
15. Sharma, P.p., et al., Comparative analysis of non-wood Fibers for reinforced composite and paper applications\par.
16. Chen, H. and Y. Zhou, Strengthening mechanisms and Fibers interlocking in banana pulp sheets. Journal of Natural Fibers, 2022. 19(12): p. 4450-4462.
17. Gupta, R. and B. Singh, Evaluation of handmade paper from agricultural waste: Strength and durability testing. Industrial Crops and Products, 2020. 145: p. 112102.
18. Subagyo, A. and A. Chafidz, Banana pseudo stem Fibers: Preparation, characteristics, and applications, in Banana Nutrition - Function and Processing Kinetics. 2020, IntechOpen.
19. Kumar, A. and S. Varma, Performance of biodegradable Fibers packaging and polyolefin replacement. Sustainable Materials and Technologies, 2021. 28.
20. Subagyo, A. and A. Chafidz, Banana Pseudo stem Fibers: Preparation, Characteristics, and Applications, in Banana Nutrition - Function and Processing. 2020, IntechOpen.
21. iNdextb, Manual for handmade banana paper manufacturing and small-scale enterprise development. 2024.

22. Us, E.P.A., Impacts of Plastic Pollution and Persistence. Environmental Protection Agency, 2025.
23. Faostat, Global pulp and paper industry wood reliance: Statistical database. 2024.
24. Federal Negarit Gazeta of, E., Solid Waste Management and Disposal Proclamation No. 1383/2025. 2025.