FDRE TECHNICAL AND VOCATIONAL TRAINING INSTITUTE

TEXTILE AND APPAREL FASHION TECHNOLOGY FACULTY

DEPARTMENT OF TEXTILE TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

Extraction and Characterization of Banana Stem and Root for Yarn Sizing Application

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JUNE, 2026

ADDIS ABEBA, EHTHIOPIA



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A Thesis Submitted to the FDRE Technical and Vocational Training Institute, Faculty of Textile and Apparel Fashion Technology, Department of Textile Technology, In Partial Fulfillment of the Requirements for the Degree of Master of Science in Textile Technology

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BY: AHMED EBRAHIM

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Declaration

This thesis, titled "**Extraction and Characterization of Banana Stem and Root for Yarn Sizing Application**," was prepared by Ahmed Ebrahim. I attest that it is my original work. It hasn't been submitted for a degree or academic qualification to any other university or organization. All sources consulted in this study have been appropriately acknowledged and cited.

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Acknowledgment

I am grateful to God for giving me the courage, wisdom, and tenacity to do this mission. I am incredibly appreciative of my adviser, Dr. Eshetu Solomon, for his wise counsel, helpful critique, and unwavering support, all of which significantly improved the caliber of my work. And thanks Dr. Gurumurty BR. for proposal adviser. I also thank Dr. Tolera A. for his helpful comments during my proposal presentation, which improved the direction of this research. I appreciate the support of Mr. Mohammed, Ms. Nefisa, and Ms. Hana from KTSC, and Ms. Genet and Ms. Eden from the Manufacturing Industry Development Institute laboratory in Addis Ababa, during the practical work. Finally, I sincerely thank KTSC for allowing me to conduct the practical study in their factory and providing the necessary facilities.

Abstract

In order to provide an alternative to traditional potato starch, this study investigates the potential of banana stem and root extracts as non-food-based, environmentally friendly sizing agents for cotton warp yarns. The study focuses on the extraction, characterization, and performance assessment of starch produced from bananas for use in textile sizing. Banana biomass was cleaned, dried, powdered, and thermally treated under well-monitored conditions to produce a starch-rich extract. The resulting substance showed suitable properties for effective yarn sizing, with a starch percentage of 60-78%, a viscosity of 14. 88 flows /sec, and a solubility value of 4%. These features made it possible for consistent film generation, effective yarn penetration, and simple removal during the de-sizing process. Significant gains in yarn performance were found during mechanical testing. While elongation dropped from 7.24% to 5.07%, tensile strength increased by 41% while remaining within permissible industrial bounds. Yarn hairiness decreased from 6.51 to 2.64, indicating improved smoothness and less friction, while the size add-on was tested at 8.02%, suggesting sufficient coating. Banana starch performs better than conventional potato starch in terms of tensile strength and elongation loss functional performance and environmental sustainability, according to a comparative analysis. De-sizing efficiency was roughly 9.2%, indicating that the applied size was successfully removed. The optimum sizing parameters obtained through RSM were 61.87 g/L powder concentration, 90°C temperature, and 27.37 min sizing time, achieving a desirability of 0.7844. All things considered, banana starch has great promise as a cost-effective, environmentally friendly, and biodegradable substitute for cotton warp yarn sizing in textile production.

***Keywords**: Banana starch; warp yarn sizing; sustainable materials; response surface methodology (RSM); Box-Behnken design; textile processing; mechanical properties; de-sizing.*

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List of Abbreviations and Acronyms

ASTM	American Society For Testing And Materials
BBD	Box–Behnken Design
CV	Coefficient of Variation
°C	Degree Celsius
G	Gram
H	Hairiness Index
H_0	Null Hypothesis
H_1	Alternative Hypothesis
H(01)	Hypothesis
KTSC	Kombolcha Textile Share Company
L	Liter
M/MIN	Meter per Minute
MLR	Material-to-Liquor Ratio
NO.	Number
PVA	Polyvinyl Alcohol
RKM	Ranks per Kilometer
RSM	Response Surface Method
S3	Fibers Longer Than 3 mm
SEM	Scanning Electron Microscope
TPI	Twist per Inch
UTM	Universal Testing Machine
WT	Weight

Chapter One
Introduction

1.1 Background of the Study

The textile industry is one of the largest manufacturing sectors worldwide, contributing significantly to employment, industrial development, and economic growth. Among the various stages of textile production, weaving is a critical process in which warp yarns are subjected to continuous mechanical stresses such as tension, abrasion, and friction while passing through loom components including reeds and heald shafts. These repeated stresses often cause yarn breakage, resulting in loom stoppages, reduced productivity, increased manufacturing costs, and defects in the finished fabric (Ahmed, Mills, and Kwon 2025).

To minimize these problems, yarn sizing is an essential pre-weaving process. During sizing, a protective film is applied to the surface of warp yarns to improve their tensile strength, abrasion resistance, and flexibility while reducing yarn hairiness. An effective sizing material enhances weaving efficiency; decreases warp end breakages, and improve fabric quality (Takebira et al., 2020).

Currently, the textile industry relies primarily on starch-based sizing materials derived from food crops such as potato, corn, wheat, and rice because of their excellent film-forming ability, biodegradability, and low cost. The performance of these starches depends mainly on their amylose and amylopectin contents, which determine the strength and flexibility of the protective film. However, increasing demand for food crops, rising raw material costs, and concerns about food security have raised questions regarding the long-term sustainability of using edible starches for industrial applications. In addition, the search for environmentally friendly and renewable sizing materials has become increasingly important as the textile industry seeks to reduce its environmental impact (Lambiso et al., 2019).

Agricultural residues have emerged as promising alternative sources of starch for textile sizing. Among these residues, banana stems and roots are generated in large quantities after fruit harvesting and are generally discarded or underutilized. These by-products contain considerable amounts of starch and other polysaccharides that have the potential to be converted into value-added industrial materials. Utilizing banana stem and root waste as a starch source can reduce

agricultural waste, lower dependence on food-based starches, and promote sustainable resource utilization (Marta et al., 2022).

The effectiveness of banana stems and root starch as a sizing material depends on its extraction method and physicochemical properties. Extraction conditions influence starch yield, granule structure, viscosity, and film-forming characteristics, all of which determine its suitability for yarn sizing. Therefore, characterization techniques such as rheological analysis and Scanning Electron Microscopy (SEM) are important for evaluating the structural and functional properties of the extracted starch. Furthermore, statistical optimization techniques such as Response Surface Methodology (RSM) and Design of Experiments (DOE) have been widely applied to optimize extraction and sizing conditions and evaluate their effects on yarn performance (Shrestha et al., 2023).

Although previous studies have investigated natural starches and agricultural waste materials for textile applications, limited research has focused specifically on the extraction, characterization, and optimization of starch from banana stem and root for cotton yarn sizing. Moreover, comprehensive comparisons between banana stem and root starch and conventional potato starch remain scarce. Therefore, this study aims to investigate the extraction and characterization of banana stem and root starch for yarn sizing application and evaluate its potential as a sustainable alternative to conventional starch-based sizing materials for the textile industry (Fahmi & Syduzzaman, 2024).



Figure1. 1 Morphological Structure Banana Stem and Root

In order to size the warp yarns to provide the necessary quality, a sizing agent will be made from powdered banana stem and root in this thesis project.

1.2 Statement of Problem

Sizing is an essential process in textile manufacturing because it improves the strength, abrasion resistance, and weaving performance of warp yarns. In the Ethiopian textile industry, cotton warp yarns are primarily sized using a combination of polyvinyl alcohol (PVA) and starches obtained from food crops such as wheat, maize, potatoes, and ensete (false banana). These sizing agents provide satisfactory weaving performance; however, they present significant economic, environmental, and sustainability challenges (Patil, 2022).

One major problem associated with the current sizing materials is their dependence on food-based starches. The use of edible crops for industrial purposes creates competition between food and textile applications, which may increase food prices and place additional pressure on national food security (Ogori & Taofeek, 2022). Moreover, PVA is a petroleum-based synthetic polymer that is not produced locally in Ethiopia. Consequently, textile manufacturers rely on imported PVA, increasing production costs, foreign currency expenditure, and vulnerability to supply chain disruptions.

In addition to sizing challenges, the textile industry also faces significant desizing problems. PVA is difficult to remove completely from sized fabrics and exhibits poor biodegradability. Conventional desizing processes require large quantities of water, chemicals, and energy to remove the size from fabrics before subsequent wet processing operations. Incomplete desizing can reduce dye uptake, negatively affect fabric quality, and increase processing costs. Furthermore, wastewater generated during desizing often contains high concentrations of PVA and other chemical residues, contributing to environmental pollution because PVA degrades slowly in biological wastewater treatment systems (Muslim et al., 2024).

Although various biodegradable sizing materials have been investigated worldwide, Ethiopia has made limited progress in developing textile sizing agents from locally available, non-food agricultural resources. At the same time, large quantities of agricultural residues are generated annually but remain underutilized, representing a lost opportunity to produce sustainable and value-added industrial products (Mohd et al., 2021). The absence of locally sourced, biodegradable sizing materials continues to limit the Ethiopian textile industry's efforts to reduce production costs, improve environmental performance, and achieve sustainable manufacturing.

Therefore, this research aims to address these challenges by developing and evaluating an environmentally friendly sizing agent derived from locally available agricultural waste. The

proposed bio-based sizing material is expected to reduce dependence on imported PVA and food-based starches while providing adequate yarn strength and weaving performance. In addition, because the developed sizing agent is biodegradable, it is expected to facilitate easier desizing, reduce water and chemical consumption, lower wastewater pollution, and support sustainable textile production in Ethiopia.

1.3 Objectives of the Study

1.3.1 General Objective

To extract and characterize banana stem and root extracts for cotton warp yarn sizing applications

1.3.2 Specific Objectives

1. To extract starch from banana stems and roots.
2. To characterize the extracted banana starch in terms of viscosity and solubility.
3. To determine the yarn properties of sized yarns, including tensile strength, elongation, and hairiness characteristics
4. To compare banana starch with conventional potato starch for cotton warp yarn sizing application in terms of strength and elongation performance
5. To optimize sizing parameters using Design of Experiments (DOE).

1.4 Research Questions

1. How can the starch be effectively removed from the roots and stems of bananas?
2. What are the viscosity and solubility characteristics of the isolated banana starch?
3. How does the application of sizing affect the physical and mechanical properties of cotton yarn, particularly tensile strength, elongation, and hairiness?
4. Can banana starch provide comparable or improved sizing performance compared with potato starch in terms of cotton warp yarn strength and elongation?
5. What are the optimal sizing parameters based on the design of experiments (DOE)?

1.5 Hypothesis

A hypothesis is a precise, verifiable assertion derived from the research topic that forecasts the results of a study. It is evaluated using scientific methods such as statistical analysis and

experimentation. In hypothesis testing, the null hypothesis (H_0) suggests no significant effect or relationship, whereas the alternative hypothesis (H_1) suggests a significant effect or link; H_1 is accepted when H_0 is rejected.

1. Extraction Suitability H_0: Starch extracted from banana stems and roots is not suitable for cotton warp yarn sizing. H_1: Starch extracted from banana stems and roots is suitable for cotton warp yarn sizing.

2. Characterization (Viscosity & Solubility) H_0: Banana stem and root starch do not possess suitable viscosity and solubility for cotton warp yarn sizing. H_1: Banana stem and root starch possess suitable viscosity and solubility for cotton warp yarn sizing.

3. Yarn Performance H_0: Banana-based starch sizing does not significantly affect the tensile strength, elongation, or hairiness of cotton warp yarns. H_1: Banana-based starch sizing significantly improves the tensile strength, elongation, and hairiness of cotton warp yarns.

4. Comparative Performance H_0: The sizing performance of banana and potato starches is not significantly different. H_1: The sizing performance of potato and banana starches differs significantly

5. Optimization of Processes H_0: Sizing performance is not significantly impacted by sizing parameters (such as concentration, temperature, and time). H_1: At least one sizing parameter significantly affects sizing performance.

1.6 Significance of the Study

In order to use banana stem and root extracts as sizing agents in cotton warp yarns, this work focuses on their extraction and characterization. It provides a sustainable and environmentally friendly substitute for conventional chemical sizing agents by utilizing banana crop waste. Banana extracts can make yarn stronger, reduce hairiness, and prevent yarn breakage during weaving, which helps to produce better-quality fabric and improve loom performance.

The study also offers financial advantages for the textile and agricultural sectors. Banana extracts provide the textile industry with a cheap, biodegradable sizing agent that can lessen reliance on artificial chemicals and cut production costs. Through the use and marketing of banana byproducts that would otherwise be discarded, the study gives smallholder farmers and banana growers the opportunity to earn extra money.

The study will also be helpful to researchers, students, and textile professionals who are interested in sustainable textile technology. It contributes to the development of environmentally friendly processes that sustain the long-term profitability of the textile industry while advancing scientific knowledge of the extraction techniques and performance characteristics of banana-based sizing agents.

This study contributes to the existing body of knowledge within the Ethiopian textile industry by providing new insights into the extraction and performance evaluation of banana stem and root starch as sustainable sizing materials for textile applications. The findings may also extend the current understanding of bio-based sizing agents in Ethiopia and support the development of sustainable material selection frameworks in textile engineering.

1.7 Delimitation or Scope of the Study

This study is limited to the extraction and characterization of starch from banana stems and roots collected from the Kemise area in the Kombolcha region for use in cotton warp yarn sizing at Kombolcha Textile Share Company. The analysis focuses only on selected properties of the extracted starch, namely viscosity and solubility. Yarn performance is evaluated in terms of tensile strength, elongation, and hairiness.

The study includes a comparison between banana starch and potato starch based on tensile strength and elongation. Optimization is carried out using Design of Experiments (DOE) under selected parameters. The research is confined to cotton warp yarn under laboratory-scale conditions at Kombolcha Textile Share Company, excluding other fibers, sizing agents, and industrial-scale production.

The study is further limited to textile sizing and polymer behavior theories and does not consider unrelated chemical or mechanical theories. The literature review is restricted to natural starch-based sizing agents in textile applications, focusing mainly on recent studies from the last 10 years.

1.8 Limitations of the Study

This study is limited by several methodological and practical constraints. The analysis is based on laboratory-scale data, and limitations in statistical analysis under the Design of Experiments

(DOE) approach may affect the precision and generalizability of the results. The study does not involve self-report data, as all measurements are experimentally obtained.

Limitations related to instruments, such as possible calibration errors and measurement accuracy of viscosity and tensile testing equipment may have influenced the results. The sample size is limited to banana stems and roots collected from the Kemise area, which may not fully represent wider geographical variability.

In addition, threats to internal validity, such as uncontrolled environmental conditions during testing and possible operator variation, could not be fully eliminated. These factors may have affected the consistency and reliability of the experimental outcomes.

1.9 Definition of Terms

Banana Stem and Root Extract: Natural compounds obtained from banana stems and roots through drying and grinding, used as eco-friendly sizing agents.

Extraction Process: Methods such as drying, grinding, filtering, and evaporation used to obtain starch and biodegradable components from banana plants.

Characterization: Examining the physical and chemical characteristics of banana extract to determine their suitable for cotton warp yarn sizing.

Warp yarn sizing is the process of giving cotton warp yarn a protective covering to boost its strength, reduce breakage, and enhance weaving performance.

Tensile strength is a measurement of a yarn's durability and strength that indicates the amount of force it can withstand before breaking.

Viscosity: The sizing solution's flow characteristic that establishes the yarn's level of coating and protection.

Sustainable Sizing Agent: A biodegradable, eco-friendly material that replaces synthetic sizing agents.

Yarn Performance Testing: Determining whether the yarn is acceptable for weaving by evaluating its strength, elongation, and flexibility.

1.10 Organization of the Works

In this study each of the five chapters that constitute this thesis logically covers a different facet of the research:

Chapter 1: Background of the Study. The backdrop, problem statement, research objectives, research questions, and hypotheses of the study are all covered in this chapter. It also provides the significance, limitations, scope, and important definitions of the study.

Chapter 2: Review of Literature The study on warp yarn size, conventional and sustainable sizing agents, and the characteristics of starch-based materials is critically reviewed in this chapter. It outlines the research gap this study fills and emphasizes the potential of banana stem and root as substitute resources.

Chapter 3: Supplies and Procedures. The study's materials, experimental techniques, and approaches are described in this chapter. Banana starch extraction, yarn sizing methods, experimental design (DOE/RSM), and testing procedures for assessing mechanical and physicochemical characteristics are all included.

Chapter Four: The results of the experiment are presented and examined in this chapter. It discusses the characteristics of banana starch, assesses yarn performance, and contrasts the outcomes with traditional starch (potato starch). Statistical methods are also used to interpret the impact of process factors.

Chapter Five: Concluding Remarks and Advice. This chapter makes direct inferences about the research aims and hypotheses based on the findings. It demonstrates that banana stem and root starch is a competitively effective, sustainable substitute sizing agent. There is discussion of the practical ramifications for the textile industry, including the possibility of lowering production costs and environmental impact. Recommendations for future study, process optimization, and industrial use are given in light of these findings. Large-scale implementation, banana starch modification, combining with other sizing agents, and thorough economic and environmental evaluations are suggested areas for further research.

Chapter Two

Literature Review

2.1 Introduction

In textile industry, warp yarn sizing is an essential first stage in the weaving process that involves coating yarns to make them more resilient to stress, friction, and repeated bending. By enhancing fiber cohesiveness and reducing hairiness and yarn breakage, sizing improves weaving efficiency and fabric quality (Ismatova et al., 2024).

In the past, artificial materials like starches and polyvinyl alcohol (PVA) have been used in sizing. However, the usage of renewable and biodegradable sizing materials made from agricultural resources has increased because to the need for sustainable textile production and growing environmental concerns (Limeneh et al., 2024).

According to (Jahangir, 2022), state that because banana stem and root starch are plentiful agricultural byproducts with good film-forming and adhesive qualities, they are viable sustainable substitutes. By using these underutilized resources, cotton warp yarn sizing could offer an affordable and environmentally friendly alternative to traditional size agents.

2.2 Theoretical Foundation of Warp Yarn Sizing

(Solijonovich, 2021), stats that warp yarn sizing are a preparatory weaving operation that enhances yarn performance by applying a thin protective film on the yarn surface. This modification improves mechanical stability and facilitates the smoother running of warp yarns during weaving.

As warp yarns pass through different loom parts like heddles, reeds, and drop wires during weaving, they are repeatedly subjected to tensile, bending, and rubbing pressures. The yarn's structure may be weakened by these mechanical pressures, resulting in frequent end breakages. Through the reduction of surface hairiness, the binding of loose fibers, and the creation of a smoother yarn surface, the sizing procedure helps the yarn endure these stressors. Yarn flow via the weaving machine becomes more consistent and steady as a result (Limeneh et al., 2024).

The effectiveness of warp yarn sizing is strongly related to the sizing agent's ability to penetrate the yarn structure and form a continuous, sticking covering around the fibers. The warp's overall lifespan is increased, abrasion resistance is improved, and friction between nearby yarns and

machine components is decreased thanks to this protective layer. As a result, properly sized yarns have increased weaving efficiency, fewer machine stoppages, better fabric quality, and fewer breakages. In order to ensure both process efficiency and product performance, warp yarn size acts as a crucial link between yarn preparation and fabric production(Ismatova et al., 2024).

2.2.1 Concept and Principles of Warp Yarn Sizing

The idea behind warp yarn scaling is to use a polymer-based solution to strengthen the yarn's structure. In order to create a continuous coating over the yarn's surface, warp yarns are coated or submerged in size liquor, then carefully squeezed to manage pick-up and dried. This layer fills in surface imperfections, bonds projecting fibers, and temporarily fortifies weak spots in the yarn. This improves internal cohesiveness and surface smoothness, which increases resistance to mechanical stress during weaving.

A number of interconnected factors determine how successful sizing is. While yarn properties like linear density, twist level, and fiber type affect absorption and retention behavior, size concentration controls the solution's viscosity and binding strength. The amount and distribution of size applied are further controlled by mechanical variables such as drying temperature and squeeze pressure.

It is crucial that these elements be in the best possible balance. While excessive application might result in stiffness and decreased flexibility, insufficient sizing leads to poor fiber cohesion and higher breakage. Thus, preserving yarn performance and reducing weaving faults depend on achieving uniform penetration and consistent film generation (Ismatova et al., 2024).

2.2.2 Importance of Sizing in Weaving

By fortifying warp strands against the many mechanical stresses experienced during loom operation, sizing is essential to increasing weaving efficiency and fabric quality. Higher resistance to abrasion, tension changes, and frictional forces produced during shedding, picking, and beat-up operations is shown by the treated yarn.

Sizing greatly lowers end breakages by stabilizing the yarn structure, which results in smoother loom operation, fewer stoppages, and increased production efficiency. Additionally, by preserving consistent yarn behavior throughout the weaving process, it helps to improve fabric uniformity.

However, process control plays a major role in scaling effectiveness. Over-sizing can result in diminished elasticity, excessive stiffness, and shedding challenges, all of which reduce weaving

efficiency. Conversely, under-sizing results in frequent yarn failures because it does not offer sufficient protection. In order to achieve both high productivity and outstanding fabric quality, it is crucial to precisely optimize size parameters in order to balance strength augmentation with flexibility (Lambiso et al., 2019).

2.2.3 Mechanisms of Yarn Protection during Weaving

Warp yarns are primarily protected during weaving by a mix of internal structural strengthening brought about by the sizing process and outward surface modification. By generating a thin, continuous layer that sticks to loose threads, the applied size lessens projecting hairiness and produces a smoother profile on the yarn surface. This smoother surface minimizes inter-fiber and machine-related friction when the yarn travels through guides, healds, and reed dents, thereby minimizing the likelihood of surface damage and abrasion (Tenagne et al., 2024).

A portion of the sizing solution enters the yarn body internally, enhancing inter-fiber bonding and filling spaces between fibers. This reinforcement lessens specific weak areas where breaking would normally start by more uniformly distributing mechanical forces along the yarn length. As a result, the yarn gains better resistance to repeated bending, tension fluctuations, and cyclic loading conditions that are common in weaving operations.

However, the balance of size application determines how effective this protection is. The yarn may become less flexible and less able to handle dynamic stresses during loom operation if the coating gets too thick or stiff. Despite increased surface strength, this may paradoxically increase the risk of end breakages (Tenagne et al., 2024).

2.3 Effect of Sizing on Yarn Performance

Size is crucial for improving the warp yarns' performance since it increases their resistance to the mechanical and dynamic stresses encountered during weaving. The procedure entails the application of a sizing agent that creates a protective barrier around the yarn surface and partially penetrates the yarn structure. The yarn's resistance to abrasion and friction is improved, surface hairiness is decreased, and fiber-to-fiber cohesion is reinforced. Yarns that go through loom components like heddles, drop wires, and reeds are therefore more robust and durable(Solijonovich, 2021).

Sizing enhances warp yarn performance by depositing a protective film on the yarn surface. This film improves fiber cohesion, protects the yarn from mechanical stresses during weaving, and

contributes to higher weaving efficiency. The extent of these improvements depends on factors such as size concentration, yarn count, and sizing machine settings(Sultana et al., 2014). To evaluate the performance of sized yarn, the following properties were tested.

2.3.1 Tensile Strength

Tensile strength is one of the most important properties evaluated after the sizing process because it determines the ability of warp yarn to withstand the mechanical stresses applied during weaving. The primary function of a sizing agent is to improve yarn strength by forming a protective film around the yarn surface and increasing the cohesion between individual fibers. The size material penetrates into the yarn structure, fills the gaps between fibers, and binds loosely held fibers together, thereby reducing fiber slippage and minimizing weak points within the yarn. This improved fiber-to-fiber adhesion allows the yarn to resist repeated tensile forces, abrasion, and tension fluctuations during high-speed weaving operations.

One of the primary goals of size is to increase tensile strength. The size material penetrates the yarn's structure, binds fibers together, and strengthens the yarn's weak points. As a result, the yarn is more resistant to the stresses associated with weaving. According to previous studies, yarn strength increases with an increase in maize starch concentration from 1.9% to 6%. For instance, the breaking strength of 16 Ne cotton yarn improved from approximately 9.2 cN/tex before sizing to 11.5–12.5 cN/tex after sizing. This improvement is attributed to better size penetration into the yarn structure, which can be achieved through proper control of squeeze pressure during the sizing process (Amanuel, 2019).

2.3.2 Elongation

Elongation represents the ability of yarn to extend under applied tensile force before breaking and is an important parameter for maintaining flexibility during weaving. After sizing, yarn elongation generally decreases because the applied size film restricts the free movement and sliding ability of individual fibers within the yarn structure. The hardened size coating increases yarn stiffness by locking fibers together, which reduces the extensibility of the yarn when subjected to tension.

A decrease in elongation typically coincides with an increase in yarn strength. The yarn is less extensible because the size coating limits the mobility of the fibers. Because the yarn structure is more rigid at higher size concentrations, elongation is further reduced. Elongation for 16 Ne cotton yarn dropped from roughly 6.0% prior to sizing to 5.2–5.6% following sizing. In order to

maintain an appropriate balance between strength and flexibility, size conditions should be optimized (Amanuel, 2019).

2.3.3 Hairiness

Sizing significantly reduces yarn hairiness by binding loose and protruding fibers to the yarn body. This reduces friction during weaving operations and produces a smoother yarn surface. Reduced hairiness enhances loom performance, reduces yarn damage, and lowers fiber entanglement. As a result, there are fewer warp breakages, improving fabric quality and production effectiveness.

The effectiveness of hairiness reduction depends on several sizing parameters, including size concentration, viscosity, temperature, penetration ability, and drying conditions. An optimized size concentration provides sufficient coating to control surface fibers without making the yarn excessively stiff. Proper temperature improves size penetration, while suitable viscosity ensures uniform coating formation on the yarn surface. Excessively high or low viscosity may reduce sizing effectiveness by causing poor penetration or uneven film formation (Amanuel, 2019).

Because of their adhesion and film-forming capabilities, natural starch-based sizing agents like banana stem and root starch can help reduce hairiness. In addition to enhancing surface smoothness, the starch layer envelops the yarn's surface and secures any projecting fibers. Thus, efficient sizing improves weaving performance and the quality of the finished fabric by greatly reducing hairiness and increasing yarn strength and abrasion resistance (Ahmed et al., 2025).

2.4 Sizing Process and Process Parameters

2.4.1 Sizing Process

The illustrated process represents a continuous warp sizing operation carried out in textile manufacturing to enhance the mechanical properties of warp yarns before weaving. The sizing process applies a protective coating on yarn surfaces to improve yarn strength, abrasion resistance, smoothness, and weaving efficiency (Turukmane et al., n.d.).

The process begins with unsized warp yarns wound on warp beams. These yarns are guided from the beam section into the sizing range, where multiple warp sheets are combined and passed continuously through different treatment zones. Since untreated warp yarns possess insufficient strength and are susceptible to abrasion and breakage during weaving, they undergo sizing treatment.

The first stage involves pre-wetting of the warp yarns in a hot-water pre-wetting box. In this stage, the yarns are uniformly wetted to improve the absorption and penetration of sizing materials. The hot water treatment also helps remove surface impurities and enhances the bonding ability between the yarn and the sizing film. Excess water is controlled using squeeze rollers before the yarn enters the sizing unit (Turukmane et al., n.d.).

After pre-wetting, the warp yarns pass through the sizing box containing sizing liquor. The sizing liquor is applied to the yarn surface through immersion rollers and squeezing mechanisms. The sizing formulation generally consists of film-forming agents such as starch, modified starch, or polyvinyl alcohol (PVA), along with additives such as lubricants, softeners, and binders. The controlled application of sizing material forms a uniform protective layer around each yarn, improving its resistance to tensile stress and mechanical abrasion (Turukmane et al., n.d.).

Following the application of sizing material, the yarn sheet enters the drying zone, where it passes over heated drying cylinders. During this stage, moisture from the sizing liquor evaporates, leaving behind a continuous and stable size film on the yarn surface. The drying process ensures proper adhesion of the size coating and develops the required yarn properties for efficient weaving. (Turukmane et al., n.d.).

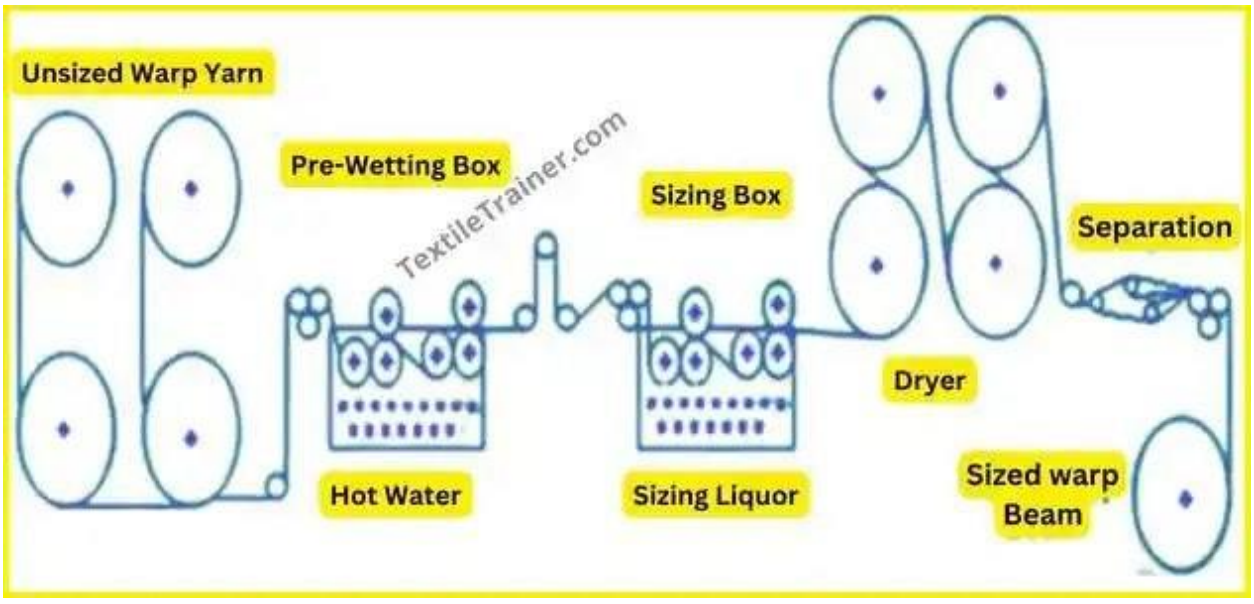


Figure2. 1 Sizing Process

2.4.2 Size Add-On

Size add-on refers to the percentage increase in yarn mass after the sizing and drying process compared to the original unsized yarn. It represents the quantity of sizing material retained on and within the yarn structure, and it is a key parameter for evaluating sizing effectiveness and process control.

In some studies, the same concept is also expressed in terms of size pickup, where the increase in mass is directly related to the amount of size liquor absorbed and retained by the yarn during passage through the size bath and squeeze rollers. The level of size add-on is strongly governed by several process parameters. Higher size concentration and viscosity generally increase the pickup because more solids are available to adhere to the yarn surface and penetrate into its internal structure. Conversely, higher squeeze roller pressure reduces add-on by mechanically removing excess size liquor from the yarn. Similarly, machine speed plays an important role; lower speeds allow longer immersion time and higher absorption, leading to increased add-on, while higher speeds reduce contact time and decrease uptake.

Immersion conditions such as temperature dwell time, and yarn tension further influence penetration and uniformity of size deposition. An optimal add-on level is therefore achieved by balancing these variables to ensure sufficient strength improvement without excessively reducing flexibility or causing stiffness in the yarn (Jahangir, 2022).

2.4.3 Machine Parameters

Squeeze Pressure: Squeeze pressure is the main factor that determines how much size is retained on the yarn. Low pressure results in excessive uptake and increased stiffness, whereas high pressure removes too much size, leaving the yarn unprotected and more susceptible to injury (Ahmed et al. 2025**;** Wang, 2025). Achieving a balance between strength and flexibility requires maintaining an appropriate level.

Temperature: Both the drying process and the sizing fluid's viscosity are impacted by temperature. Reliable coating development and effective drying are encouraged by suitable temperature ranges. Because extremely high temperatures can lower size retention and have a detrimental effect on yarn quality, temperature control is essential to sizing (Takebira et al., 2020).

Machine Speed: Machine speed determines the duration of yarn exposure to the sizing liquor and drying cylinders. Lower speeds allow greater interaction between the yarn and the size,

whereas higher speeds increase production capacity. An appropriate balance is therefore required to achieve both productivity and desired yarn properties (Takebira et al., 2020).

Immersion Depth: Immersion depth affects the extent of yarn contact with the sizing liquor. Increased immersion generally improves size absorption and coating uniformity, particularly for highly twisted yarns. Proper adjustment helps ensure consistent size application and satisfactory yarn performance during weaving(Takebira et al., 2020).

2.5 Properties of Effective Sizing Materials

2.5.1 Viscosity

Viscosity is a key flow and thickness properties of starch-based sizing materials because it controls the flow behavior, penetration ability, and distribution of the size solution throughout the yarn structure. An appropriate viscosity level allows the sizing paste to penetrate between fibers, form a continuous protective film on the yarn surface, and improve fiber-to-fiber bonding without causing excessive coating thickness(Fahmi & Syduzzaman, 2024).

The viscosity of native starch pastes is strongly influenced by starch concentration, molecular structure, and swelling behavior during heating. At unsuitable concentrations, native starch can produce highly viscous pastes that reduce fluidity, limit penetration into the yarn, and create difficulties during application. In contrast, starch modifications such as oxidation, acid treatment, or enzymatic modification can alter molecular size and improve paste stability, flow properties, and handling characteristics (Fahmi & Syduzzaman, 2024).

For textile sizing applications, a moderate viscosity is required to achieve uniform size pick-up and effective film formation. A flow cup viscosity value in the range of approximately 12–17 seconds is generally considered suitable for sizing applications. Lower values may indicate insufficient paste consistency and reduced coating ability, while values exceeding 18 seconds may result in poor flow, uneven distribution, and difficulty in obtaining a uniform size layer on the yarn surface(Fahmi & Syduzzaman, 2024).

2.5.2 Solubility

Solubility is an important property of starch-based sizing materials because it determines their ability to disperse uniformly in water, penetrate the yarn structure, and be easily removed during the de-sizing process. During heating in boiling water, approximately 95% of starch granule components dissolve, while the remaining fraction consists mainly of resistant materials such as

cellulose and other insoluble components that may form a hard outer layer. The presence of these insoluble portions can influence paste stability and the efficiency of sizing application(Li et al., 2021)..

A sizing material with good solubility, particularly when the solubility level is high at concentrations below 5% (w/v), can produce a stable and homogeneous sizing paste with improved flow behavior and uniform coating ability. At lower concentrations, starch molecules remain well dispersed in the solution, allowing better penetration into yarn gaps and stronger adhesion between fibers. In addition, higher solubility facilitates easier removal of the size layer during de-sizing, reducing processing difficulties and improving textile finishing performance (Li et al., 2021).

2.5.3 Yarn Moisture Content

Moisture content of yarn plays a critical role in determining the efficiency of the sizing operation by affecting size absorption, penetration, and adhesion between the sizing material and fiber surface. As reported by (Stream, 2020), maintaining yarn moisture within the range of **6–8%** is necessary to obtain consistent size pick-up and uniform formation of the protective sizing layer. Proper moisture conditions promote fiber flexibility and swelling, allowing the starch-based sizing solution to penetrate effectively and form stronger interactions with cotton fibers.

Insufficient moisture content makes the yarn dry and rigid, limiting the penetration of the sizing paste and causing non-uniform deposition on the yarn surface. This may result in weak fiber bonding, increased hairiness, and reduced resistance to mechanical stresses during weaving. In contrast, excessive moisture can decrease the effectiveness of the sizing process by lowering the concentration of the sizing components and affecting the development of a strong, continuous film after drying (Stream, 2020).

Hence, maintaining an optimum moisture level is essential for achieving balanced size absorption, improved yarn surface characteristics, enhanced cohesion between fibers, and better overall weaving performance (Stream, 2020).

2.5.4 Mechanical Behavior

Elongation loss is a key indicator of yarn performance after sizing. A reduction of about 5–6% is usually considered appropriate because it demonstrates improved fiber cohesion and greater tensile strength without making the yarn excessively brittle (Amanuel, 2019). Larger yarns often offer better abrasion resistance, increased smoothness, controlled flexibility, and tensile strength,

all of which facilitate effective weaving (Takebira et al., 2020). However too much sizing can make the yarn too stiff and perform poorly, which emphasizes the importance of appropriate processing conditions.

However, excessive application of sizing materials can negatively affect yarn performance by making the yarn overly rigid and less flexible. This increased stiffness can reduce its ability to withstand bending and dynamic stresses during weaving, leading to poor processability and potential fabric defects. Therefore, maintaining optimal sizing conditions is essential to balance strength improvement with adequate flexibility for efficient and defect-free weaving (Takebira et al., 2020).

2.6 Conventional Starch-Based Sizing Agents

The textile industry has long utilized starch-based sizing agents due to their availability, low cost, and environmental sustainability. To improve weaving efficiency, enhance yarn strength, and reduce yarn breakage, starches are widely used as sustainable materials (Kovačević et al., 2020). Their renewability, biodegradability, and compatibility with natural fibers make them particularly suitable for textile applications. In addition to their functional benefits, starch materials are favored due to their renewable origin and biodegradability, which reduce environmental impact during both processing and wastewater treatment. Their natural compatibility with cellulose-based fibers such as cotton also allows for strong adhesion and uniform film formation on yarn surfaces, making them particularly effective in textile sizing applications (Kovačević et al., 2020).

2.6.1 Corn Starch

According to (Yu-Kyung & Sun-Moon, 2021), maize starch is one of the most widely utilized natural sizing agents because of its balanced amylose amylopectin composition, which offers excellent adherence to yarn surfaces and good film forming capacity. They also note that this balance allows corn starch to form flexible yet durable films, making it suitable for a wide range of warp yarns. Its widespread availability and comparatively low cost contribute to its significant industrial use.



Figure2. 2 Corn Starch Powder

2.6.2 Wheat Starch

According to(Shevkani et al., 2017), the performance of wheat starch, which varies based on the variety of wheat and growing conditions, is significantly influenced by both genetic and environmental factors. Hard wheat starch exhibits, which has a higher amylose concentration and larger granule sizes, creates stronger and more rigid films, whereas soft wheat starch often generates smoother pastes with lower viscosity, making it appropriate for applications requiring uniform coating. The mechanical behavior of treated yarns and sizing performance are directly impacted by these variations.



Figure2. 3 Wheat Starch Powder

2.6.3 Potato Starch

According to (Corn & Starches, 2019), potato starch has strong adhesive qualities, good film-forming ability, and high viscosity. Overall, they observe that by increasing the final materials' tensile strength and abrasion resistance, it can match or even surpass some synthetic sizing

agents. It also performs particularly well on coarser yarns when more bonding and surface coverage are required. These characteristics make potato starch a good alternative for sustainable textile manufacture.



Figure2. 4 Potato Starch Powder

2.6.4 Enset (False Banana)

Although enset is mostly produced as an ornamental plant, it is a staple crop in Ethiopia and is not well known as a food source outside of the nation. Animals are given the leaves, the root provides carbohydrates for nourishment, and the stem provides coarse fiber. Enset's vast root structure makes it incredibly drought-resistant despite its low protein content, significantly enhancing food security (Kovačević et al., 2020).



Figure2. 5 False Banana Starch Powder

2.7 Sizing chemicals and Additives

(Sultana et al., 2014); Amanuel 2019; Perkins n.d.) Declare that the kind and combination of size formulas have a major impact on the performance of warp yarns during weaving. To enhance film formation, adhesion, smoothness, flexibility, and overall yarn strength, sizing agents and chemical additives are required. The major materials commonly included in a conventional size formulation are described below.

2.7.1 Polyvinyl Alcohol (PVA)

Polyvinyl alcohol (PVA) is a popular synthetic sizing agent known for its outstanding flexibility, high tensile strength, and great film-forming ability(Shrestha et al., 2023). It works especially well in high-speed weaving settings where warp yarns experience a lot of friction and tension. PVA reduces yarn breaking during loom operation by improving yarn elasticity and durability..

2.7.2 Weighting Agents

The researcher, (Amanuel, 2019), states that weighting agents are added to increase the mass and volume of yarns or fabrics, giving them a fuller and more robust appearance, particularly in grey goods. These agents also contribute to improved fabric handle and drape. The extent of size application can be measured using the following formula.

2.7.3 Softening Agent

According to (Takebira et al., 2020), softening agents are added to sizing formulations to increase the flexibility of the size film and prevent brittleness when yarns undergo bending during weaving. Typical softeners include animal fats such as mutton tallow, vegetable oils, and synthetic waxes, which help the size coating, remain resilient under mechanical stress.

2.8 Banana Starch as Sustainable of Sizing Material

According to (Verma, 2025), banana starch is emerging as an eco-friendly and highly viable substitute for conventional sizing starches due to its easy availability, particularly from agricultural by-products such as banana stems and roots that are often discarded as waste. Beyond its sustainable sourcing, it possesses strong adhesive and film-forming characteristics, which enable it to create a uniform and protective coating on warp yarns. This coating improves yarn strength, reduces surface hairiness, and enhances weaving performance, making banana starch a practical material for efficient and sustainable warp sizing in the textile industry.

2.8.1 Banana Plant Cultivation and availability

Bananas are mostly grown in tropical and subtropical regions of Asia, Africa, and Latin America, according to(Pattison et al. 2008; Marta et al. 2022). The banana plant's pseudostem and shallow-rooted rhizome are typically discarded as agricultural waste after harvest. Nonetheless, these by-products are a sustainable and eco-friendly raw material with promise for various industrial uses because they contain significant levels of starch (Marta et al. 2022)..

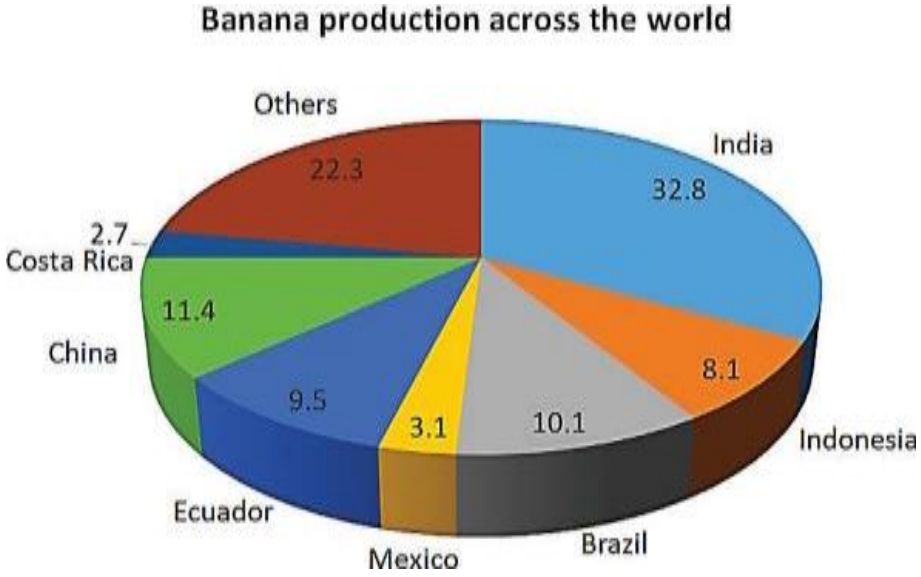


Figure2. 6 Banana Distributions in the World

2.8.2 Banana Classification

According to(Mohd et al., 2021), there are five main types of bananas: Cavendish, Burro, Red, Manzano, and Plantain. Among these, the Burro and Plantain types are very high in starch and have been shown to be appropriate for industrial uses other than food, such as textile sizing. Furthermore, according to (Waluyo et al., 2024), bananas (Musa) are a significant horticultural crop grown to satisfy the rising demand for fruit consumption brought on by population expansion and a growing understanding of dietary needs, including vitamins, minerals, and carbohydrates.

2.8.3 Banana Biomass's Potential as a Sustainable Starch Source

A prolific agricultural by-product with high starch content is banana biomass, especially the pseudostem and roots. Despite their potential for industrial application, these materials are frequently thrown away once fruit is harvested. Banana starch is appropriate for textile sizing applications because it has favorable qualities such good film-forming capacity, biodegradability,

and adhesion. Using banana biomass to produce starch increases the value of agricultural waste, lessens its negative effects on the environment, and offers a cheap, renewable raw resource. Banana residues present a viable sustainable source of starch for textile sizing agents in Ethiopia, where banana farming is extensive (Verma, 2025).

2.9 Extraction of Banana Starch

2.9.1 Banana Root Extraction Method

Banana root samples can be collected by excavating soil around the base of each plant at a predetermined distance from the pseudostem and to a specified depth to capture the active root zone. The excavated soil is carefully removed, and the roots are separated manually to minimize damage.

The collected roots are washed thoroughly under running water using sieves to remove adhering soil particles while preventing the loss of fine roots. After cleaning, the roots are sorted into diameter classes (e.g., <1 mm, 1–5 mm, and >5 mm) to enable assessment of different root categories.

The cleaned roots may be weighed immediately to determine fresh root biomass or dried in a forced-air oven at approximately 65–70°C until a constant weight is reached to determine dry root biomass. Root biomass data are then recorded and analyzed in relation to soil physical, chemical, and biological properties, such as bulk density, aggregate stability, electrical conductivity, and the presence of plant-parasitic nematodes, to evaluate the effects of soil conditions on banana root growth and development.

2.9.2 Extraction Principles

The process of extracting banana starch involves breaking down the plant's cellular structure to liberate starch granules that are contained inside the tissues, then separating and purifying the starch from other plant constituents. Starch granules are released into a solution when mechanical disturbances like crushing, milling, or grinding break down cell walls (Fida et al., 2020).

Following the release of the starch, undesirable non-starch components such as insoluble fibers, proteins, colors, and other soluble chemicals are eliminated using separation procedures such as filtration, sedimentation, centrifugation, and washing. Certain purification procedures are

necessary to improve the extracted starch's whiteness, purity, and functional properties (Fida et al., 2020).

The degree of cell wall disintegration and the efficiency of the separation procedure have a significant impact on the recovery of banana starch. While good washing and settling conditions help generate cleaner starch with fewer impurities, adequate tissue disruption improves starch release. Factors such as particle size after grinding, extraction time, water ratio, and separation conditions influence the ultimate starch yield and quality. Therefore, an effective extraction method must optimize starch recovery while maintaining the optimal physicochemical properties required for textile scaling applications (Lambiso et al., 2019).

2.9.3 Extraction Methods

Extraction of Banana Stem

Fresh kepok banana (*Musa paradisiaca* Linn.) stems were collected and thoroughly washed under running water to remove adhering soil and impurities. The cleaned stems were cut into small pieces, and 500 g of the material was prepared for extraction. The stem pieces were initially shade-dried under indirect sunlight by covering them with a black cloth for approximately two days. Drying was completed in a hot-air oven at 40°C for an additional two days until a constant weight was achieved.

The dried stem material was extracted using the maceration method. The sample was immersed in 100% methanol in a sealed glass maceration bottle and kept at room temperature for 72 hours (3 × 24 h) while protected from direct sunlight. After maceration, the extract was filtered, and the filtrate was concentrated using a rotary evaporator at 50°C to obtain a viscous crude methanolic extract.

For antibacterial testing, the crude stem extract was prepared at concentrations of 6.25%, 12.5%, and 25% (w/v) using 10% dimethyl sulfoxide (DMSO) as the solvent. Specifically, 0.06 g, 0.12 g, and 0.25 g of the crude extract were dissolved in 0.1 mL of 10% DMSO and diluted with 0.9 mL of sterile distilled water to obtain a final volume of 1 mL for each concentration. . (Abdalla Ahmed & Elabid, n.d.).

Extraction of Banana Root

Fresh kepok banana (*Musa paradisiaca* Linn.) roots were harvested and washed thoroughly with running water to eliminate soil and other contaminants. The roots were cut into small pieces, and

500 g of the cleaned material was prepared. The root pieces were shade-dried under indirect sunlight by covering them with a black cloth for approximately two days and subsequently oven-dried at 40°C for another two days until completely dry.

The dried root material was extracted by the maceration technique. The samples were soaked in 100% methanol in a sealed maceration container for 72 hours (3 × 24 h) at room temperature, with protection from direct sunlight throughout the extraction period. The resulting mixture was filtered, and the filtrate was concentrated using a rotary evaporator at 50°C to obtain a thick methanolic root extract.

The concentrated root extract was prepared at 6.25%, 12.5%, and 25% (w/v) concentrations for antibacterial evaluation. To prepare each concentration, 0.06 g, 0.12 g, or 0.25 g of the crude extract was mixed with 0.1 mL of 10% DMSO and diluted with 0.9 mL of sterile distilled water to a final volume of 1 mL. (Abdalla Ahmed & Elabid, n.d.).

2.9.4 Factors Affecting Starch Yield

Starch yield from banana sources is influenced by both raw material characteristics and processing conditions. Key factors include the maturity stage of the banana, the type of plant tissue utilized, extraction temperature and duration, pH of the medium, solvent selection, and the extraction technique applied. Optimizing these parameters is essential for maximizing starch recovery and improving the quality of the final product(Gholap et al., 2011).

2.10 Characterization of Banana Starch

The performance of starch in food and industrial applications is determined by its physicochemical, structural, thermal, and functional characteristics. Characterization of banana stem and root starch provides insight into its morphology, composition, crystalline structure, and processing behavior(Dagnew et al., 2021).

2.10.1 Physical Characteristics

Moisture content and raw material composition have an impact on the extraction yield of banana plant materials. In general, dry extract recovery is lower at higher moisture levels. The final yield and extraction efficiency are also influenced by physical attributes like fiber content and weight distribution(Mercy, 2024).

2.10.2 Chemical Composition

The researchers (Fida et al., 2020) state that important elements of banana plant extracts include proteins, lipids, carbohydrates, moisture, and ash. Cellulose, hemicellulose, lignin, and starch make up the majority of the carbohydrate portion. The way fibers interact with one another may be affected since extracts usually have an acidic pH. Furthermore, bioactive compounds such as phenolic and flavonoids improve functional properties (Fida et al., 2020).

Table2. 1 Banana Chemical Composition(Verma, 2025)

Component	Percentage (%)
Cellulose	54–78
Hemicelluloses	25–30
Pectin	3–5
Lignin	12–18
Water-soluble compounds	2–3
Fat and wax	3–5
Ash	1–1.5

Table2. 2 Starch Distribution in Banana Stem Parts(Science, 2021)

Stem Part	Starch Content (78%)
Outer/Fiber Part	25–30
Inner/Core Part	15–19.5
Waste/Removed Part	25–28.5

Table2. 3 Banana Root Composition (ilideinfo, n.d.)

Component	Percentage (%)
Starch	66–74
Protein	2–6
Fat	6–9
Ash	3–5
Extractives	4–6

2.10.3 Functional properties

The researchers (Marta et al., 2022) state that functional characteristics include water holding capacity (WHC), swelling power (SP), and solubility index (SI). These properties influence the

interaction of the extract with textile fibers. High water absorption and swelling behavior improve coating ability and adhesion, while solubility affects uniform application

2.10.4 Thermal and Gelatinization Properties

The perverse researchers (Imagery et al., 2023) state that thermal behavior is studied using differential scanning calorimetry (DSC), which determines parameters such as onset, peak, and final temperatures of gelatinization. These properties reflect the stability and processing behavior of the extract. Gel formation and viscosity are important for applications such as sizing and coating of yarns(Kumar et al., 2019).

2.10.5 Structural Properties

The researchers (Kumar et al., 2019), state that advanced analytical techniques are frequently used for the structural characterization of banana plant materials. The fibrous architecture of the biomass is shown by examining surface morphology and particle structure using scanning electron microscopy (SEM). Taken as a whole, these investigations verify the existence of semi-crystalline and fibrous structures that enhance adherence and bonding with cotton fibers, qualifying the materials for uses including textile coatings and warp sizing(Kumar et al., 2019).

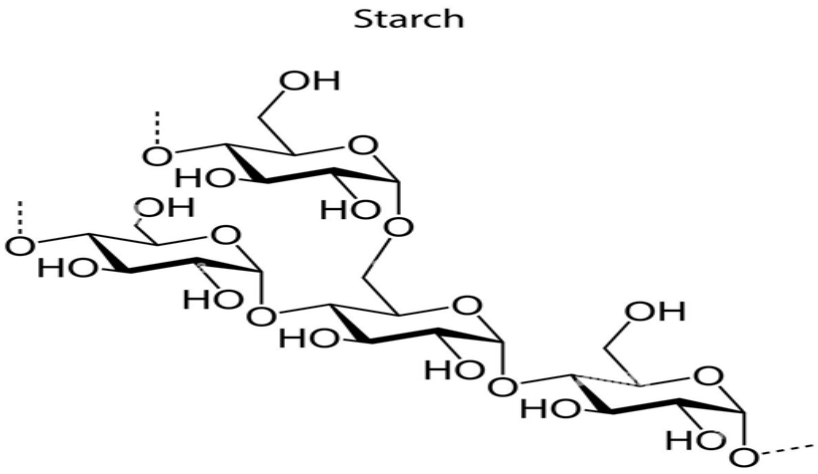


Figure2. 7 Starch Structure

2.11 Application of Natural Starches in Cotton Warp Yarn Sizing

Natural starches are widely used in cotton warp yarn sizing due to their film-forming ability, biodegradability, and low cost. Different starch sources exhibit varying performance in terms of adhesion, strength improvement, and ease of removal after weaving (Kovačević et al., 2020).

The efficacy of starch-based sizing materials is significantly influenced by their chemical structure and botanical source. Variations in the amount of amylose and amylopectin, granule size, viscosity, and molecular arrangement affect key sizing characteristics such as adherence to cotton fibers, film strength, flexibility, and penetration into the yarn structure. Starches with higher adherence provide better fiber cohesion and longer yarn durability, whereas starches that form flexible films help to retain yarn extensibility throughout loom operation (Kovačević et al., 2020).

The effective desizing is necessary prior to fabric finishing procedures; the removability of starch after weaving is a crucial factor. The simplicity and efficacy of desizing treatments are impacted by the varying degrees of solubility and removal resistance displayed by various starch sources. Therefore, choosing an appropriate natural starch source necessitates striking a compromise between enhancing weaving performance and guaranteeing simple removal following fabric manufacture (Lemeneh & Tesema, 2019).

2.11.1 Applications of Potato Starch

Potato starch is commonly used in sizing because of its strong adhesive properties and good film-forming ability. It enhances yarn strength and improves resistance to abrasion, thereby reducing damage during weaving and increasing warp durability (Fahmi & Syduzzaman, 2024).

2.11.2 Applications of Corn Starch

Corn starch provides moderate reinforcement to cotton yarns and improves weaving performance compared to unsized yarns. However, its effectiveness may be limited in demanding weaving conditions due to comparatively lower abrasion resistance and less efficient desizing behavior (Kovačević et al., 2020).

2.12 Methodological Developments in Sizing Research

In recent textile research, statistical and analytical techniques have grown in importance to optimize size process parameters, improve yarn qualities, and increase weaving efficiency. These

methodologies allow researchers to carefully assess the influence of diverse process variables and establish the optimum conditions for producing desirable yarn performance. Among the different techniques, Response Surface Methodology (RSM) and Design of Experiments (DOE) have received great interest because they give an effective means to examine interactions between multiple parameters while minimizing the number of experimental trials. Furthermore, the physical, mechanical, and structural characteristics of sized yarns are often studied using contemporary characterization techniques, which makes it easier to create new sizing formulas and processing conditions (Ummah, 2019).

2.12.1 Design of Experiments (DOE)

DOE reduces the number of experimental trials while offering a methodical framework for assessing the impact of several process factors. ANOVA results indicated that dispatch speed was the most influential parameter for both responses. The study successfully identified optimum sizing conditions using only 18 experiments, demonstrating the efficiency of DOE in process optimization(Sabır & Sarpkaya, 2016).

2.12.2 Response Surface Methodology (RSM)

RSM is an extension of DOE that develops mathematical models to describe relationships between process variables and performance responses. It enables the evaluation of interaction effects and the prediction of optimal operating conditions. In sizing applications, RSM has been used to optimize variables such as size concentration, viscosity, drying temperature, and yarn speed. Its ability to support multi-response optimization makes it particularly valuable for simultaneously improving yarn strength, abrasion resistance, and weaving efficiency(Abay & Ayele, 2023).

Table2. 4 Summary of Reviewed Literature

Author	Starch Source	Major Findings	Limitation
Temesgen et al. (2019)	Potato, Corn, Cassava	Potato starch showed highest tensile strength and abrasion resistance	Did not evaluate banana starch
Sultana et al. (2014)	Natural starches	Viscosity strongly affects coating quality	Limited characterization techniques
Fahmi & Syduzzaman (2024)	Modified starches	Optimum viscosity required for uniform application	No agricultural waste starch investigated
Marta et al. (2022)	Banana biomass	High starch potential in banana residues	Focused onfood/biomaterial applications
Verma (2025)	Banana starch	Good film-forming properties	Textile sizing performance not evaluated

2.13 Research Gap from Literature review

Cotton warp yarn size frequently uses traditional starches like corn, wheat, and potatoes, but their reliance on food-based resources raises questions about sustainability and cost. Although banana stem and root, which are common agricultural wastes in Ethiopia, have a high starch content, little research has been done on their usage in textile sizing; instead, most studies have concentrated on food and biomaterial applications.

The extraction and physicochemical characterization of banana stem and root starch for textile applications, especially with regard to viscosity, rheological characteristics, FTIR, and SEM examination, have not received much attention. Research on its effectiveness in cotton warp yarn size under actual weaving circumstances is also lacking, particularly with regard to tensile strength, elongation, and hairiness reduction. Comparative studies with conventional starches are also limited. Furthermore, no research has used DOE and RSM to optimize banana stem and root starch size parameters for Ethiopian cotton warp yarn. To assess its potential as a sustainable substitute for traditional sizing agents, more investigation is therefore required.

Chapter Three
Materials and Methods

3.1 Introduction

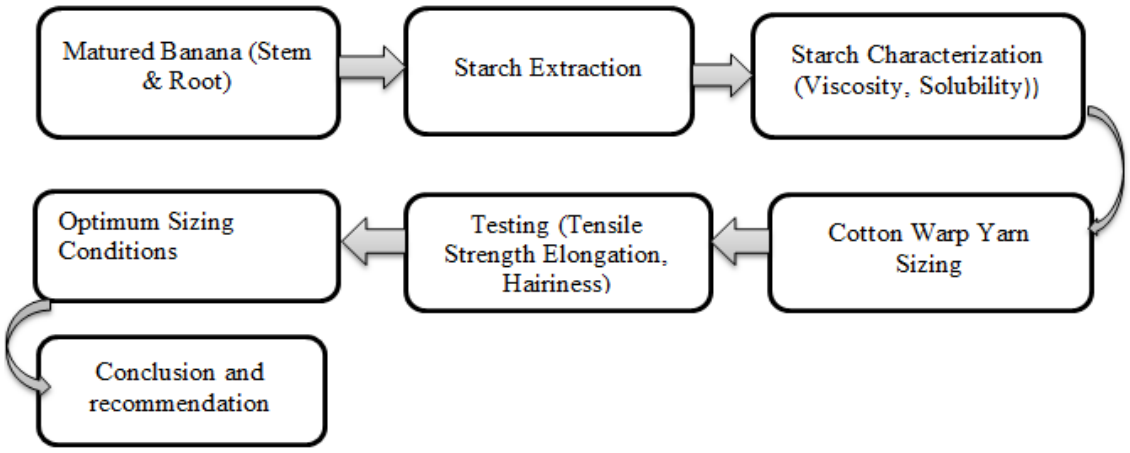
In order to collect and evaluate banana stem and root extracts and use them as natural sizing agents for cotton warp yarns, this chapter explains the components, experimental processes, and analytical techniques. To guarantee the precision, repeatability, and dependability of the findings, a thorough explanation of the research design, experimental strategy, data collection procedures, and statistical analysis techniques is provided.

3.2 Methodology overview

This study followed an experimental methodology to investigate the suitability of banana stem and root starch as a natural sizing agent for cotton warp yarns. The methodology involved controlled preparation of starch-based sizing materials, application of sizing treatments, and evaluation of yarn performance through laboratory testing. The effects of process variables, including powder concentration, sizing temperature, and sizing time, were analyzed to determine their influence on yarn properties such as tensile strength, elongation, and hairiness.

The experimental conditions were optimized using the Box–Behnken Design (BBD) under the Design of Experiments (DOE) approach. The developed methodology included experimental design, material preparation, sizing application, yarn property evaluation, and statistical analysis to establish the relationship between processing parameters and yarn performance.

This method ensured the statistical stability of the experimental data while enabling accurate modeling of the process parameters and their impacts on yarn characteristics. The entire study process, comprising the phases of experimental design, material preparation, sizing application, testing, and data analysis, is summarized in Figure 3.1.



. Figure3. 1 Flowchart of the experimental design

3.3 Materials

3.3.1 Banana Plant Materials

Fresh banana stems and roots were collected from mature banana plants from the Kombolcha region (Kemise, Ethiopia) in October 2025. The samples were thoroughly cleaned to remove dirt and impurities before further processing.

3.3.2 Cotton Yarn

A 100% cotton warp yarn with a count of 34 Nm was used. Prior to experimentation, the yarn was conditioned under standard atmospheric conditions (20 ± 2 °C and 65±2% relative humidity) to ensure uniform moisture content.

3.3.3 Source of Experimental Materials

Banana plant materials were collected from the Kemise area of the Kombolcha region, Ethiopia. The cotton warp yarn and sizing machine facilities used in this study were provided by Kombolcha Textile Share Company.

3.4 Chemicals

Laboratory-grade chemicals were utilized during the extraction, sizing, and de-sizing processes, following standard textile processing procedures. These included wetting agents, softeners, iodine solution, sodium hydrosulfite, amylase enzyme, acetic acid, and sequestering agents.

Table3. 1 List of used chemicals with function

Chemicals	**Functions**
Wetting agent	Increase uniform penetration and lower surface tension.
Softener	Improves yarn's softness, elasticity, and smoothness.
Iodine solution	Starch indicator (starch is confirmed by the blue-black color)
Sodium hydrosulfite	Reducing agent; prevents oxidation during processing
Amylase (enzyme)	Breaks down starch into simpler sugars
Acetic acid	Lowers pH and creates acidic conditions
Sequestering agent	Binds metal ions (Ca^{2+}, Mg^{2+}); prevents unwanted reactions

3.5 Equipment and Instruments

The following instruments were employed to ensure accurate and reliable data collection

Table3. 2 List of equipment used and their functions

Equipment	**Function**
Weighing balance	Measures raw materials and chemicals precisely
Universal Tensile Testing Machine (UTM)	Determines tensile strength and elongation
USTER® TESTER 5-S400	Measures yarn hairiness
Viscometer	Monitors viscosity of sizing paste
Mortar and grinding	Prepare fine powder from dried plant material
Sieve	Ensures uniform particle size
Hot Plate & Beaker	Controls heating and mixing of sizing solutions
Canvas	Used for drying raw materials and yarns
Axe and cutting tools	Used for chopping banana plant materials into small pieces.

Rationale: These instruments ensure precise measurement of both input variables (material quantities, process parameters) and response variables (tensile strength, elongation, hairiness).

3.6 Extraction of Banana Stem and Root

3.6.1 Banana Stem Extraction

Sample Preparation

Fresh banana stems were collected from mature banana plants and thoroughly washed with clean water to remove adhering soil, dust, and other foreign materials. The cleaned stems were cut into small pieces (approximately 2–5 cm) to facilitate drying and grinding. The prepared stem samples were then processed for further extraction.



Figure3. 2 Washing and cutting of banana stem.

Drying of Banana Stem Material

The cleaned banana stem pieces were evenly spread on clean trays and shade-dried under ambient conditions for approximately two weeks to remove moisture. The samples were arranged to allow adequate air circulation and were turned periodically to ensure uniform drying. Shade drying protected heat-sensitive components from direct sunlight and helped preserve the natural properties of the stem material while minimizing discoloration and degradation.



Figure3. 3 Drying of banana stem.

Grinding of Banana Stem Material

After complete drying, the banana stem pieces were ground into a fine powder using a mechanical grinder and mortar. During grinding, sodium hydrosulfite was added at a rate of 0.1 g per 100 g of dry stem material to minimize enzymatic browning and oxidation, thereby preserving the color and quality of the powder. The ground material was then sieved through a

fine mesh to remove coarse particles and obtain a uniform particle size. The resulting banana stem powder was stored in clean, airtight, labeled containers at room temperature and protected from moisture and direct sunlight until it was used for the preparation of the sizing solution.



Figure3. 4 Grinding of Banana Stem

3.6.2 Banana Root Extraction

Collection and Preparation of Banana Root

Fresh banana roots were collected from mature banana plants and carefully excavated to minimize physical damage. The collected roots were thoroughly washed with clean water to remove adhering soil, sand, and other foreign materials. The washing process was repeated until the roots were free from visible impurities. Excess washing water was removed by draining the cleaned roots and allowing them to air-dry briefly before further processing.

Cutting of Banana Root

The cleaned banana roots were cut into small pieces to increase the surface area and facilitate efficient extraction of starch components during subsequent processing.

Preparation of Root Suspension

The prepared banana root material was dispersed in distilled water at a concentration of 61.87 g/L. The mixture was continuously stirred to produce a uniform suspension suitable for starch extraction.



Figure3. 5 procedure of banana root filtration

Heating and Extraction

The root suspension was heated at 90°C for 27.37 minutes under continuous stirring to promote starch gelatinization and enhance the release of soluble starch components from the banana root material.

Cooling of Extracted Suspension

After completion of the extraction process, the heated suspension was allowed to cool naturally to room temperature before proceeding to separation and purification steps.

Filtration

The cooled suspension was filtered through muslin cloth to remove coarse fibers, cell debris, and other insoluble materials. The filtrate containing the extracted starch fraction was collected in a clean container for starch recovery.

Sedimentation

The filtered extract was allowed to stand undisturbed at room temperature for 12–24 hours to allow starch granules to settle naturally by gravity. During this period, a starch-rich sediment accumulated at the bottom of the container, while soluble components remained in the upper liquid phase.

Decantation

Following sedimentation, the clear supernatant was carefully removed by decantation without disturbing the settled starch layer. This process removed excess water and dissolved impurities while retaining the concentrated starch fraction.

Washing of Starch Sediment

The collected starch sediment was washed several times with distilled water to remove remaining soluble impurities, pigments, proteins, and other non-starch components. After each washing step, the starch suspension was allowed to settle before removing the washing water to improve starch purity.

Second Filtration

The washed starch suspension was filtered through What man No. 1 filter paper to remove remaining fine impurities and obtain a purified starch fraction.

Drying of Extracted Starch

The purified starch material obtained after filtration was dried under controlled conditions until the moisture content was sufficiently reduced. The dried material was collected as banana root starch powder.



Figure3.6 Filtration and drying of banana root

Storage of Banana Root Starch Powder

The obtained banana root starch powder was stored in clean, airtight, labeled containers at room temperature and protected from moisture and direct sunlight until further physicochemical characterization and evaluation as a natural sizing agent for cotton warp yarns.

3.6.4 Starch Extraction Procedures

To create a homogeneous dispersion, banana stem and root powder was dispersed in distilled water at 61.87 g/L, the optimum level determined through Box–Behnken Design (BBD) optimization. The extraction temperature was maintained at 90°C for 27.37 minutes to promote starch gelatinization and the release of soluble compounds. After the suspension cooled to room

temperature, it was filtered to remove any last solid particles. The resulting extract was collected and utilized for subsequent characterization and cotton warp yarn sizing experiments.

3.7 Characterization of Banana Stem and Root Extract

The extracted banana stem and root solution was characterized to evaluate its suitability as a natural sizing agent for cotton warp yarns. The key physicochemical properties of the extract were determined using standard analytical methods as described below.

3.7.1 Determination of Starch Content and viscosity

Determination of starch: The starch content of the banana stem and root extract was assessed through gravimetric analysis and verified using an iodine test. A known quantity of the sample was mixed with distilled water and filtered to remove insoluble matter. The recovered starch-rich fraction was subsequently oven-dried at 100°C until a constant weight was obtained and then weighed using an analytical balance. The starch content was calculated using the following equation(Stream, 2020).

Starch Content (%) = (Weight of recovered starch / Initial dry sample weight) × 100

The presence of starch was confirmed by adding iodine solution to the sample. The appearance of a blue-black coloration indicated a positive reaction. All measurements were conducted in triplicate, and the mean value was reported.

Determination of Viscosity: The viscosity of the banana stem and root extract was measured using a viscometer. To facilitate starch gelatinization, the extract was heated to 90°C and subsequently cooled to 25 ± 2°C before testing. Viscosity measurements were conducted under controlled laboratory conditions according to the instrument operating procedure. Five independent measurements were performed for each sample, and the mean viscosity was calculated and reported in centipoise (cP)

3.8 Sizing Paste Preparation

Natural sizing paste was prepared using banana stem and root powder as the main sizing material. The powder was dispersed in distilled water at a concentration of 61.87 g/L under continuous stirring to ensure uniform distribution. The paste was prepared at 90°C for 27.37 minutes to promote starch gelatinization and the formation of a stable sizing paste. After heating, the paste was cooled to room temperature and used for cotton warp yarn sizing applications.

A wetting agent and a softener were added to the sizing solution at a concentration of 10 mL/L to improve wetting characteristics and enhance yarn flexibility. The additives were blended thoroughly to achieve a uniform and stable formulation prior to use. The resulting sizing solution was applied to warp yarn under controlled experimental conditions. Consistent preparation of the formulation ensured uniform treatment across all trials and supported a reliable evaluation of yarn performance.

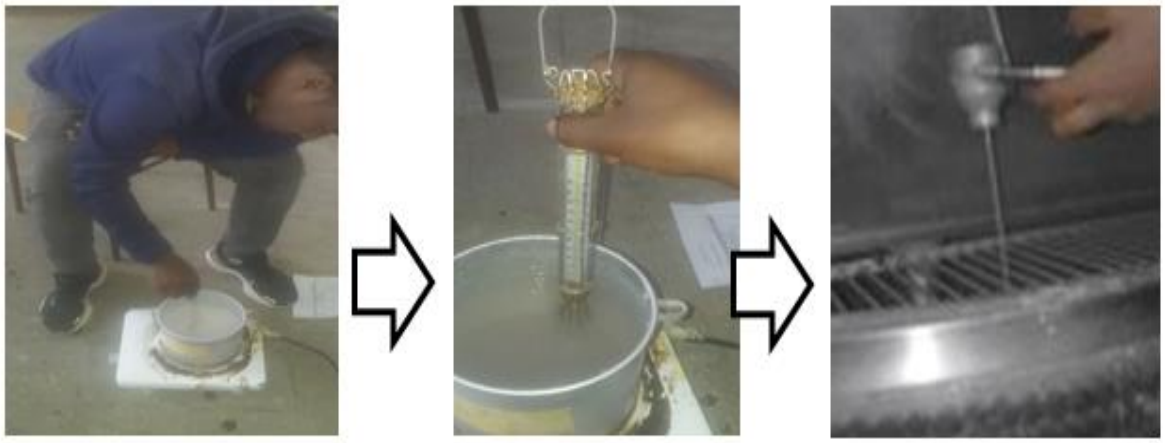


Figure3. 7 Sizing paste preparation

3.9 Application to cotton warp yarn

3.9.1 Sizing Process

Cotton warp yarns were sized using a Rotal-Karl Mayer sizing machine (Model SRL-SMR-SP) at Kombolcha Textile Share Company to ensure consistent yarn quality and uniform application of a natural sizing agent derived from banana stem and root powder. The sizing liquor was made by dissolving 15.8 kg of powdered banana stem and root in 316 L of water, then adding 3 L of softener and 3 L of wetting agent for a final volume of 322 L. To achieve complete starch gelatinization and the required viscosity, the mixture was heated to 90°C for 27.37 minutes with continuous agitation until homogeneous slurry was obtained.

The sizing liquor was prepared by heating the mixture to 90°C for 30 minutes under continuous agitation to ensure complete gelatinization and uniform viscosity. During application, the sizing

process was carried out in a size box maintained at approximately 85°C to keep the paste in a stable and workable condition. The optimized sizing parameters used for evaluation were a powder concentration of 61.87 g/L, a process temperature of 90°C, and a sizing time of 27.37minutes.



Adding powder Adding softener Sizing box

Figure3. 8 Setup Sizing Recipe

3.9.2 Conditioning of Yarn Samples

All yarn samples, both sized and un-sized, were conditioned under standard atmospheric conditions for 24 hours (21 ± 1 °C and 65 ± 2% relative humidity) to guarantee consistent moisture content and trustworthy test findings. These conditions comply with standard textile testing requirements. To minimize the effect of environmental factors, all mechanical and physical tests were performed in the same controlled environment.

3.10 Determination of Yarn Properties

3.10.1 Testing for Tensile Strength and Elongation

A Universal Tensile Testing Machine (UTM) was used to measure the tensile strength and elongation at break of the yarn samples to evaluate their mechanical performance both before and after sizing. The Kombolcha Textile Company Quality Department Laboratory carried out all tests in compliance with ISO 2062 and ASTM D2256, which provide procedures for determining the tensile characteristics of individual yarns. Both un-sized yarn and yarns sized with banana stem and root starch ware tested after conditioning under standard atmospheric conditions, ensuring uniform moisture content for reliable tensile performance.

Each yarn sample was firmly held between the UTM grips during testing; utilizing a gauge length of 500 mm. tensile force was applied to the yarn gradually until it snapped. Tensile strength was calculated using the maximum force required to break the yarn, and elongation at break was calculated using the percentage increase in length at the rupture site. Data for fifteen specimens of each sample type were collected, and average values were calculated for both sized and unsized yarns to ensure correctness and reliability. **Strength Gain (%)** = $[(T_s - T_u) / T_u] \times 100$ Where: T_s = Tensile strength of sized yarn T_u = Tensile strength of unsized yarn. **Elongation Loss (%) =** $[(E_u - E_s) / E_u] \times 100$ Where: E_u = Elongation of unsized yarn E_s = Elongation of sized yarn

The usefulness of banana stem and root starch as natural sizing agents in improving yarn mechanical properties was assessed by comparing the mean tensile strength and elongation of un-sized and sized yarns.



Figure3.9 Single Yarn Tensile Strength Tester

3.10.2 Yarn Hairiness Measurement

Yarn hairiness was measured using an Uster Technologies USTER® TESTER 5-S400 at the Textile Industry Development Institute (TIDI), Kality Branch, Addis Ababa, Ethiopia, in accordance with ASTM D5647-07 standards. The tested yarn was 34 Nm (29.4tex), 100% cotton yarn. Prior to testing, both unsized yarn samples and yarns sized with banana stem and root starch were conditioned under standard atmospheric conditions of 21 ± 1 °C temperature and 65 ± 2% relative humidity for 24 hours.

During testing, the yarn was fed at a constant speed of 50 m/min under an input tension of 5 cN. For statistical reliability, each specimen was tested over a length of 50 m, and 15 specimens were

evaluated for both sized and unsized yarn samples. The instrument automatically recorded the hairiness index (H), which represents the total length of protruding fibers per unit length of yarn.

The mean hairiness values and standard deviations were calculated separately for each sample group. The percentage reduction in hairiness was determined by comparing the average hairiness values before and after sizing to evaluate the effectiveness of banana starch in improving yarn surface smoothness.

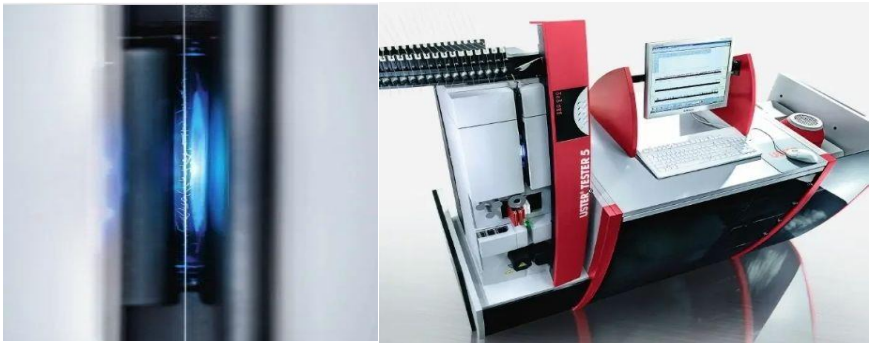


Figure3. 10 Uster tester 5 machine

3.11 De-Sizing Procedure

Using an aqueous enzymatic approach with a liquor-to-yarn ratio of 10:1, cotton yarn samples were de-sized. For each 10 g yarn sample, the treatment bath consisted of 100 mL total liquor, comprising 98.7 mL of water, 0.2 mL wetting agent, 0.2 mL sequestering agent, 0.2 mL α-amylase enzyme solution, and 0.2 mL acetic acid. To enable effective enzymatic hydrolysis of the starch-based sizing, the yarn samples were submerged in the prepared liquor and treated for the necessary amount of time at a regulated temperature of 60 °C. To eliminate any remaining sizing material and enzyme, the yarns were thoroughly rinsed once the treatment was finished, first with hot water and then with cold water.

The yarns were subsequently dried under ambient conditions and weighed. The difference in weight before and after de-sizing was used to calculate the size removal efficiency. To confirm the complete removal of starch, an iodine test was conducted. The absence of the characteristic blue-black coloration indicated effective de-sizing of the yarn. **De-sizing Efficiency (%)** = $[(W_s - Wd) / W_s] \times 100$ Where: W_s = Weight of sized yarn before de-sizing. Wd = Weight of yarn after de-sizing



Prepare de-sizing solution heating de-sizing Iodine test

Figure3. 11 Test of De-Sizing Of Yarn

3.12 Experimental Design and Statistical Analysis

A three-factor Box–Behnken Design (BBD) based on the Design of Experiments (DOE) methodology was employed to investigate the effects of powder concentration, sizing temperature, and sizing time on the performance of sized cotton yarn. The experimental design consisted of 15 runs, including replicated center points, enabling the evaluation of the linear, interaction, and quadratic effects of the selected process variables.

Regression models were developed to describe the relationships between the independent variables and the response parameters. Analysis of Variance (ANOVA) was conducted using Design-Expert and Minitab 19.5 software to assess the significance of the developed models and their individual terms. The adequacy of each model was evaluated using the coefficient of determination (R^2), adjusted R^2, and predicted R^2 values. Statistical significance was determined at a 95% confidence level, with *p*-values less than 0.05 considered statistically significant.

Table3. 3 Independent Variables and Levels Used in BBD

Factor	**Low (-1)**	**High (+1)**
Powder Concentration (g/L)	60	75
Sizing Temperature (°C)	80	90
Sizing Time (min)	20	30

3.13 Data Quality and Ethical considerations

Through repeated measurements (n = 15) carried out in controlled climatic settings of 21 ± 1 °C and 65 ± 2% relative humidity, the study ensured dependable and high-quality data. Despite the use of sample randomization and instrument calibration to reduce experimental errors and eliminate systematic bias, statistical analysis verified the validity and repeatability of the findings. To guarantee data accuracy and consistency throughout the trial, standard testing procedures and laboratory protocols were adhered to. In this research, banana stem and root materials were utilized as environmentally sustainable agricultural by-products without causing harm to humans. Proper laboratory safety procedures were followed for handling chemicals, conducting experiments, and disposing of waste. All experimental data and results were precisely and openly recorded, examined, and reported in order to maintain scientific integrity and avoid data fabrication, falsification, or manipulation.

Chapter Four
Results and Discussion

4.1 Introduction

This chapter presents and interprets the experimental results on the use of banana stem and root extracts as natural sizing agents for cotton warp yarns. Key performance indicators evaluated include viscosity, solubility, and tensile strength, elongation, and yarn hairiness.

The findings are discussed using statistical tools, tables, and graphical interpretations. In addition, the results are critically examined in relation to established textile theories and previous studies on starch-based sizing materials. The comparative performance of banana starch against conventional starch (potato) and the optimization of process parameters using Response Surface Methodology (RSM) are also discussed.

4.2 Viscosity and Solubility Properties of Banana Starch

The properties of the extracted banana starch are greatly influenced by the extraction process described in Chapter 3. Drying, grinding, and filtration are examples of operations that affect starch purity, granule integrity, and molecular structure. Viscosity, solubility, and the capacity to form films are then affected by these variables. Therefore, the results presented in this chapter also reflect the effectiveness of the extraction method in producing a functional sizing material.

4.2.1 Viscosity

By assessing its viscosity, the usefulness of banana stem and root starch paste as a warp sizing agent was evaluated. Because it influences the sizing solution's capacity to permeate the yarn structure and create a consistent protective barrier around the fibers, viscosity is a crucial factor in textile sizing. To guarantee uniformity and dependability, five replicate measurements were carried out.

Using a standard viscometer, the viscosity readings ranged from 13.7 to 16.3 flow/seconds, with an average of 14.88 flow/seconds, as shown in Table 4.1. The results demonstrate that the extracted banana starch paste possesses appropriate flow properties for its potential use as a textile sizing agent. The measured viscosity of 14.88 flow seconds falls within the acceptable range generally required for starch-based sizing formulations, where controlled viscosity

supports effective yarn penetration, uniform coating, and the formation of a strong protective film during sizing. Industrial sizing practices commonly consider viscosity values around 12–17 flow seconds suitable for starch applications. Although the obtained value agrees with the expected performance range, (ilideinfo n.d, 2023) reported comparatively higher viscosity for banana starch derived from fruit pulp. Such differences can be explained by variations in the starch extraction source, processing techniques, extraction conditions, and inherent differences in starch structure and composition.

This range ensures adequate penetration into the yarn bundle without causing excessive stiffness or poor film formation.The starch paste's good stability and homogeneity are demonstrated by th e little variance in the measured values, which indicates that the extraction method preserved the starch's structural integrity and produced consistent rheological behavior.Moderate viscosity is d esired in real world applications.

While high viscosity may restrict penetration and make yarn stiffer, low viscosity can lead to poor fiber bonding and weak film development. As a result, the observed values show a balanced performance that promotes good processability and efficient film formation. Overall, the findings demonstrate that banana stem and root starch have appropriate rheological characteristics for warp sizing and can be regarded as a competitive substitute for traditional starches.

Table4. 1 Viscosity of banana stems and root starch**.**

Sample Number	**Viscosity (flows/sec)**
1	13.7
2	14.5
3	15.2
4	16.3
5	14.7
Average	14.88

4.2.2 Solubility

The solubility behavior of banana stem and root starch was investigated to determine its suitability as a natural sizing material for cotton warp yarn applications. The analysis was carried out under controlled conditions to evaluate the starch dispersion ability and its capacity to form a

stable sizing paste during preparation. The solubility percentage was measured using the gravimetric method.

The extracted banana stems and root starch showed a solubility value of 4%. Although this value was slightly lower compared with conventional commercial starches, it was considered acceptable for textile sizing purposes. Sufficient solubility and good dispersion properties are essential for obtaining a uniform size coating on yarn, improving fiber bonding, and facilitating the removal of sizing material during de-sizing.

The findings confirm that banana stem and root starch has the ability to develop a stable sizing paste with potential application in textile processing. The slightly reduced solubility may affect the dispersion characteristics of the starch, but it does not prevent its effective use as a biodegradable sizing agent. Therefore, banana stem and root starch can be considered a sustainable alternative to traditional sizing materials.

4.2.3 SEM and FTIR banana characteristics

SEM (scanning electron microscopy) analysis showed that, after sizing, a comparatively smooth and continuous film formed on the yarn surface. The coating improved yarn cohesion and reduced hairiness by forming a uniform layer that covered the protruding fibers and smoothed the yarn surface. This observation supports the mechanical results obtained, particularly the increase in tensile strength and reduction in hairiness(Milani et al., 2016, Kumar et al., 2019).

The combined SEM and FTIR results demonstrate that the extraction process preserved the structural and chemical integrity of the starch, making it suitable for textile sizing applications.

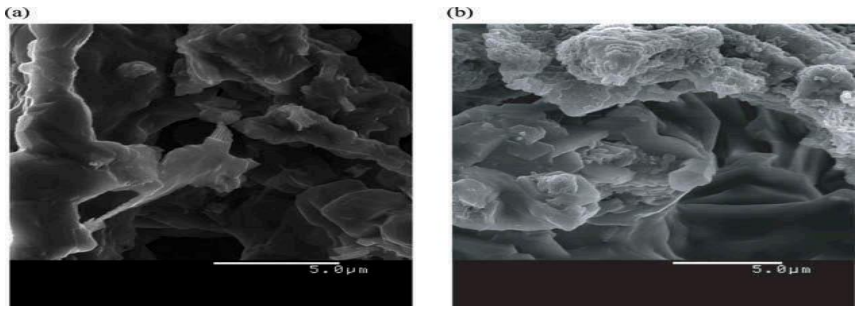


Figure4. 1 SEM image of banana starch structure

4.3 Mechanical Performance of Yarn after Sizing with Banana Starch

4.3.1 Breaking Load and Elongation

Before and after being sized with banana stem and root starch, the mechanical characteristics of cotton warp yarns were assessed at Kombolcha Textile Share Company's Quality Department Laboratory using a dynamometer under standard atmospheric conditions.

This study examined how the elongation and tensile strength were affected by banana starch sizing. The yarn treated with banana starch showed a far greater breaking load of 509.73 N, indicating a 41.00% increase in tensile strength, compared to the un-sized yarn's average breaking load of 361.33 N. The tensile strength of the banana starch-sized yarn increased by 41%, which is slightly higher than the 39% improvement, reported by (Lambiso et al., 2019) for potato starch-sized cotton yarns. The superior performance observed in the present study may be attributed to the combined use of banana stem and root starch, which likely enhanced film formation and fiber cohesion. The findings indicate that banana-derived starch can provide mechanical reinforcement comparable to or greater than conventional starch-based sizing agents. This result supports the growing body of research advocating the utilization of agricultural by-products as sustainable textile auxiliaries.

The development of a thin, sticky starch coating on the yarn's surface is responsible for the apparent increase in tensile strength. This layer increases resistance to tensile stress during weaving by binding projecting fibers, strengthening fiber-to-fiber bonding, and improving structural compactness.

The hypothesis of warp sizing states that after drying, starch molecules enter the yarn's inter fiber gaps and create a continuous protective layer. This coating promotes fiber-to-fiber bonding, increases frictional cohesiveness between fibers, and more evenly distributes applied stress along the yarn axis. Consequently, the yarn becomes more resilient to the tensile stresses that arise during the weaving process. The observed 41.00% increase in breaking load, therefore, supports the classical theory of yarn reinforcement through surface film formation and fiber cohesion enhancement.

Due to the stiffening effect of the starch coating and reduced fiber mobility, elongation at break dropped from 7.24% in un-sized yarn to 5.07% in sized yarn and Elongation decreased to 5.07%, indicating improved yarn compactness. Because both starches improved yarn compactness and

fiber bonding, they decreased yarn elongation after sizing. However, the elongation values were within the permitted industrial range of 5–6%, indicating sufficient flexibility for weaving. All things considered, size with banana starch significantly increased yarn strength without sacrificing sufficient elongation, demonstrating its efficacy and appropriateness as a sustainable warp sizing agent for cotton yarns.

The observed improvement in tensile strength, together with acceptable elongation values, indicates that banana stem and root starch can satisfy the mechanical requirements of warp yarns during weaving. This finding demonstrates that agricultural by-products can be transformed into value-added textile chemicals, creating opportunities for sustainable resource utilization and reducing reliance on conventional sizing materials.

Table4. 2 Breaking Load and Elongation before and after Sizing with Banana Starch

Sample No	**Breaking Load (N)**		**Elongation (%)**	
	Before	After	Before	After
1	380	490	7.8	4.8
2	360	510	7.2	5.4
3	360	550	7.2	6.2
4	340	530	6.8	6.0
5	400	490	8.0	4.8
6	370	500	7.4	5.2
7	360	456	7.2	4.6
8	330	530	6.6	4.0
9	350	510	7.0	5.8
10	350	550	7.0	6.2
11	370	490	7.2	4.8
12	340	530	6.8	4.0
13	370	500	7.2	5.2
14	380	510	7.8	5.8
15	360	500	7.4	5.2
Average	361.33	509.73	7.24	5.07

The above table 4.2 presents the breaking load and elongation results for 15 cotton yarn samples before and after sizing with banana starch. The measurements show a consistent improvement in yarn strength after the sizing treatment.

The average breaking load increased from 361.33 N before sizing to 509.73 N after sizing, representing an increase of approximately 41.1%. This improvement indicates that the banana starch formed a uniform coating on the yarn surface, enhancing fiber cohesion, reducing fiber slippage, and increasing the yarn's resistance to tensile forces.

In contrast, the average elongation decreased from **7.24%** before sizing to **5.07%** after sizing, corresponding to a reduction of approximately **30.0%**. The decrease in elongation is expected because the starch coating limits the mobility of individual fibers, making the yarn less extensible but more resistant to breakage during weaving.

Overall, the results obtained from the **15 test samples** demonstrate that banana starch is an effective natural sizing agent. It significantly improved the breaking load while maintaining an acceptable level of elongation, indicating its potential to enhance yarn performance during weaving. The increased yarn strength and reduced extensibility are consistent with the primary objectives of the sizing process, which aims to minimize yarn breakage and improve weaving efficiency.

4.3.2 RKM (reel kilometer) Evaluation and Size Add-On

To account for the effect of yarn linear density on tensile strength, the measured breaking load values were converted into breaking length expressed in kilometers (RKM) using a standard reference count of 34 Nm. This normalization enables accurate comparison of yarn strength regardless of variations in yarn mass.

3986 ends of cotton warp yarn, each about 1.2 meters long, were evaluated in Kombolcha Textile Share Company's weaving department. The overall weight of the yarn increased from 120.1 grams prior to sizing to 129.78 grams following sizing, indicating an 8.02% size add-on. The increase in RKM values after sizing indicates that the improvement in tensile performance resulted not only from the added starch weight but also from genuine structural enhancement of the yarn.

The starch coating's binding and protecting properties are responsible for this strengthening. The homogeneous layer that developed on the yarn's surface enhanced fiber cohesiveness, decreased

hairiness, and allowed for even distribution of applied stress evenly, increasing the yarn's resistance to mechanical forces.

The observed size add-on of 8.02% is within the 6–10% industrial range recommended for warp yarn sizing. This moderate level maintains flexibility and permits smooth processing while providing sufficient abrasion protection. Levels exceeding 10% may cause excessive stiffness and processing issues, while levels below 6% might not sufficiently preserve the yarn during weaving.

Overall, the combination of a moderate size add-on and higher RKM shows that banana starch successfully improves the yarn's mechanical qualities without sacrificing processability, underscoring its potential as a technically sound and environmentally friendly substitute for textile sizing at Kombolcha Textile Share Company.

Calculation of R.K.M (reel kilometer) and Strength Regain

The R.K.M (Reed Count Metric) of both un-sized and sized yarns was determined using the standard relationship between yarn strength and yarn count. The calculations were carried out by substituting the experimental strength values and yarn count (NM = 34 or 29.4 Tex or 20 Ne) into the governing equation.

$$\text{Tex} = \frac{1000}{NM}$$ ---------- Equation 4. 1

$$\text{Tex} = \frac{1000}{34} = 29.41\ \text{tex}$$

$$\text{Tenacity (cN/tex)} = \frac{\text{Breaking Load (cN)}}{\text{Tex}}$$ ---------- Equation 4. 2

$$\text{RKM (km)} = \frac{\text{Tenacity (cN/tex)}}{9.81}$$

Because 1 cN/tex ≈ 9.81 km breaking length equivalent conversion basis

$$R.K.M = \frac{\text{Breaking Load (cN)} \times \text{NM}}{1000}$$ ----------Equation 4. 3

$$R.K.M_{\text{unsized}} = \frac{361.33 \times 34}{1000} = 12.29\ \text{km}$$

$$R.K.M_{\text{sized}} = \frac{509.73 \times 34}{1000} = 17.33\ \text{km}$$

$$\text{Strength Regain (\%)} = \frac{\text{Sized RKM} - \text{Unsized RKM}}{\text{Unsized RKM}} \times 100$$ ----Equation 4. 4

$$\text{Strength Regain (\%)} = \left(\frac{17.33 - 12.29}{12.29}\right) \times 100 = 41.00\%$$

$$\text{Loss of Elongation (\%)} = \frac{\text{Average Elongation}_{\text{unsized}} - \text{Average Elongation}_{\text{sized}}}{\text{Average Elongation}_{\text{unsized}}} \times 100$$ --Equation 4. 5

$$\text{Loss of Elongation (\%)} = \frac{7.24 - 5.07}{7.24} \times 100 = 29.97\%$$

$$\text{Size Take-Up (\%)} = \frac{\text{Weight after sizing} - \text{Weight before sizing}}{\text{Weight before sizing}} \times 100$$ --Equation 4. 6

$$\text{Size Take-Up (\%)} = \frac{129.78 - 120.10}{120.10} \times 100 = 8.06\%$$

4.4 Comparative Analysis: Banana vs. Potato Starch

4.4.1 Comparative Analysis of Banana and Potato Starch

Banana and potato starch were assessed as warp sizing agents at Kombolcha Textile Share Company based on how they affected the mechanical characteristics of cotton yarn, including elongation at break and tensile strength. The study evaluated the treated yarns' compliance with industry standards for weaving. The findings demonstrated that both starches significantly improved yarn strength after sizing. Banana starch increased the breaking load from 361.30 N to 509.73 N, a 41.00% improvement, whereas potato starch increased the breaking load from 365.93 N to 502.67 N, a 37.38% improvement.

Banana starch increased yarn breaking load by 41%, exceeding the 25% strength improvement generally recommended for warp sizing applications. This result confirms the effectiveness of the extracted starch in enhancing fiber cohesion and stress distribution. Similar improvements have been reported previously (Lambiso et al., 2019), although the magnitude observed in the present study is slightly higher. The difference may be attributed to the combined use of banana stem and root starch, which potentially provides improved film-forming characteristics. From an industrial perspective, the obtained strength level indicates that banana starch can effectively

withstand weaving stresses while offering a sustainable alternative to conventional imported sizing materials.

The elongation at break decreased to 5.07% and 5.19%, respectively, for yarn composed of banana and potato starch. The yarns maintained enough flexibility for weaving even though their stiffness and compactness rose during growth, both values remaining within the acceptable industrial range of 5-6%. Because of its improved film-forming and fiber-binding qualities, which increase stress distribution and decrease surface flaws, banana starch performed better overall than the other sizing agent. Additionally, banana starch provides an environmentally preferable substitute for traditional potato starch in warp sizing applications because it is made from agricultural waste.

The findings suggest that banana stem and root starch can provide mechanical reinforcement comparable to or better than potato starch while utilizing agricultural waste materials. From a sustainability standpoint, this presents the Ethiopian textile industry with a real chance to enhance environmental performance and lessen reliance on foreign sizing materials. Additionally, using locally accessible banana byproducts could lower production costs and support the creation of ecologically friendly textile processing methods

Table4. 3 Breaking Load and Elongation Before and After Sizing with Potato and Banana Starch

Sample Number	**Potato Starch**				**Banana Starch**			
	Breaking Load (N)		Elongation (%)		Breaking Load (N)		Elongation (%)	
	Before	After	Before	After	Before	After	Before	After
1	347	520	7.4	5.4	380	490	7.8	4.8
2	350	510	7.0	5.4	360	510	7.2	5.4
3	312	490	6.0	4.8	360	550	7.2	6.2
4	360	500	7.2	5.2	340	530	6.8	6.0
5	320	450	6.4	4.6	400	490	8.0	4.8
6	350	510	7.0	5.2	370	500	7.4	5.2
7	330	500	6.6	5.6	360	456	7.2	4.6
8	350	520	7.0	4.8	330	530	6.6	4.0
9	310	490	6.2	5.4	350	510	7.0	5.8
10	350	510	7.0	5.6	350	550	7.0	6.2
11	330	530	6.6	5.2	370	490	7.2	4.8
12	350	510	7.0	4.8	340	530	6.8	4.0
13	390	490	7.6	5.4	370	500	7.2	5.2
14	340	520	6.8	4.8	380	510	7.8	5.8
15	380	490	7.6	5.6	360	500	7.4	5.2
Average	365.93	502.67	6.89	5.18	361.33	509.73	7.24	5.07

From Table 4.3 presents the breaking load and elongation values of 15 cotton yarn samples before and after sizing with potato starch and banana starch. The results show that sizing improved the tensile strength of the yarn in both cases while reducing its elongation.

For potato starch, the average breaking load increased from 365.93 N before sizing to 502.67 N after sizing, representing an increase of approximately 37.4%. The average elongation decreased from 6.89% to 5.18%, indicating that the sized yarn became stronger but less extensible.

Similarly, for banana starch, the average breaking load increased from 361.33 N before sizing to 509.73 N after sizing, corresponding to an increase of approximately 41.1%. The average elongation decreased from 7.24% before sizing to 5.07% after sizing. The greater increase in breaking load suggests that banana starch provided slightly better reinforcement than potato starch.

Overall, the results obtained from the 15 test samples indicate that both potato and banana starches effectively enhanced yarn strength by forming a protective film around the yarn surface, which improved fiber cohesion and reduced fiber slippage during tensile loading. The accompanying reduction in elongation is expected because the starch coating restricts yarn flexibility and extensibility. These findings suggest that banana starch is a promising natural sizing agent, offering comparable or slightly better performance than potato starch in improving yarn strength while maintaining acceptable elongation properties

Table4. 4 The results are summarized and discussed below.

Parameter	**Banana Starch**	**Potato Starch**	**Remark**
Strength Increase (%)	41	37.38	Banana starch slightly higher; both exceed standard (>25%)
Elongation After Sizing (%)	5.07	5.18	Within standard range (5–6%) for sizing; both acceptable
Compliance with ASTM Requirements	Exceeds	Meets	Both suitable
Film Flexibility	Balanced and flexible	Slightly harder	Banana preferred because it offers a better balance of higher strength, improved flexibility
Eco-friendliness	High (agro-waste based)	Moderate	Banana more sustainable
Overall Weaving Performance	Very good	Good	Banana marginally better

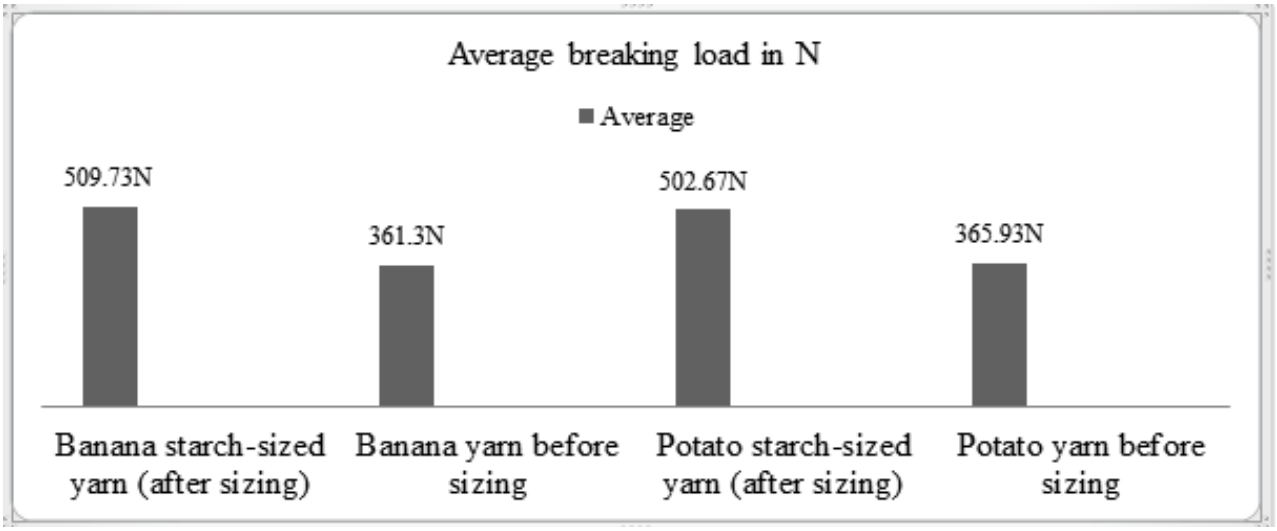


Figure4. 2 Breaking Load Comparison of Banana and Potato Starch

The average breaking load of cotton yarn before and after sizing with potato and banana starch is shown in figure 4.3. The findings demonstrate that in both situations, size greatly improved yarn strength. The average breaking load increased from 365.93 N to 502.67 N for potato starch yarn and from 361.30 N to 509.73 N for banana starch yarn. A stronger yarn structure was suggested by the slightly higher breaking load that banana starch produced in comparison to potato starch. These results show that banana starch works well as a sizing agent and imply that it might be a good substitute for traditional potato starch in textile sizing applications.

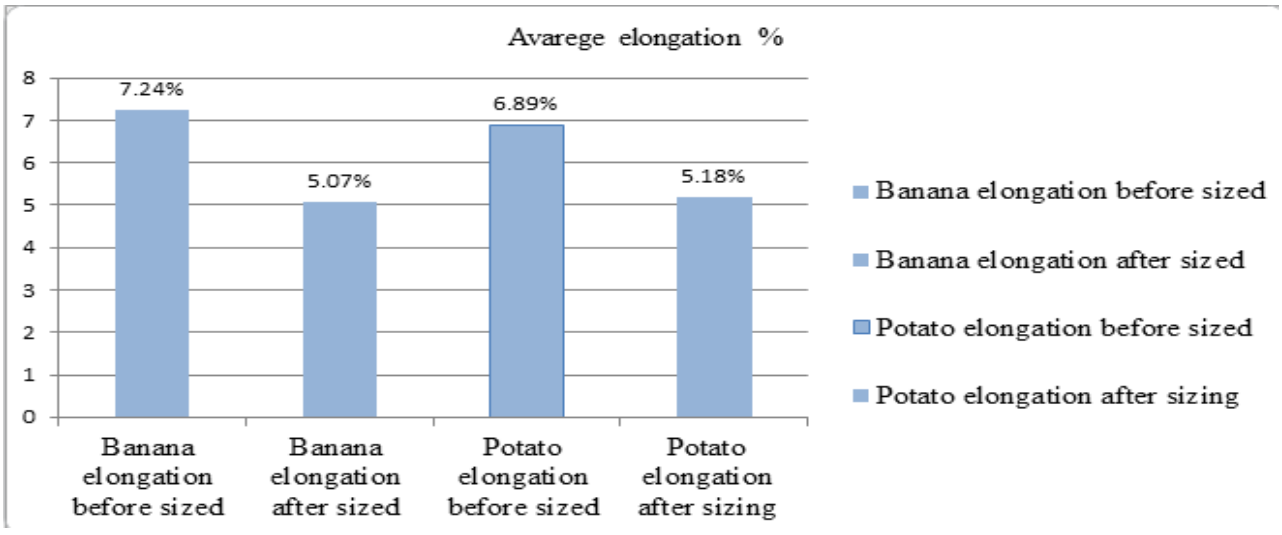


Figure4. 3 Elongation Behavior after Sizing

Figure 4.4 illustrates elongation loss before and after sizing. By lowering elongation loss, both starches demonstrated improved yarn elasticity. Both treatments effectively balance extensibility and strength; samples treated with banana starch decreased from 7.24% to 5.07%, while samples treated with potato starch decreased from 6.89% to 5.18%.

4.5 Hairiness Reduction

Hairiness of the sized yarns was evaluated using the USTER® TESTER 5-S400 at the Textile Industry Development Institute (TIDI), Addis Ababa. Increased bending rigidity following sizing prevented some samples from being measured, underscoring the impact of yarn stiffness on instrument feeding and pointing to a possible relationship between size add-on levels and measurement sensitivity.

The average hairiness value decreased from 6.51 to 2.64 after sizing, indicating substantial improvement in yarn surface quality. Similar reductions in hairiness were reported by (Fahmi & Syduzzaman, 2024), who attributed the effect to the formation of a protective starch film around the yarn structure. The present findings support this explanation, as the banana starch coating effectively bound protruding fibers and improved fiber alignment. The greater reduction observed in the current study may be associated with the adhesive characteristics of banana starch and its ability to form a uniform surface layer.

The observed decrease in hairiness is primarily due to the effective coating action of banana starch. The starch forms a thin, uniform film on the yarn surface that secures protruding fibers and improves fiber cohesion. Consequently, the yarn exhibits a smoother surface with fewer surface irregularities, leading to reduced hairiness and improved processing performance. Reduced hairiness is, therefore, anticipated to improve overall processing performance, decrease fiber breakage, and increase weaving efficiency. From a practical weaving perspective, the substantial reduction in yarn hairiness is expected to decrease end breakages, reduce lint generation, and improve loom efficiency. These improvements demonstrate the potential of banana starch to enhance both yarn quality and production performance in industrial weaving operations.

Table4. 5 Before and after hairiness properties of yarns

Sample number	Hairiness	
	Before	After
1	6.78	4.1
2	6.61	-
3	6.36	1.6
4	6.41	-
5	6.42	4.2
6	6.78	5.3
7	6.61	-
8	6.36	3.8
9	6.41	1.9
10	6.42	–
11	6.78	–
12	6.61	6.3
13	6.36	–
14	6.41	2.4
15	6.42	0.9
Average	6.51	2.64

Below the figure 4.4 shows that sized yarn exhibits significantly lower average hairiness (2.64) compared to un-sized yarn (6.51).

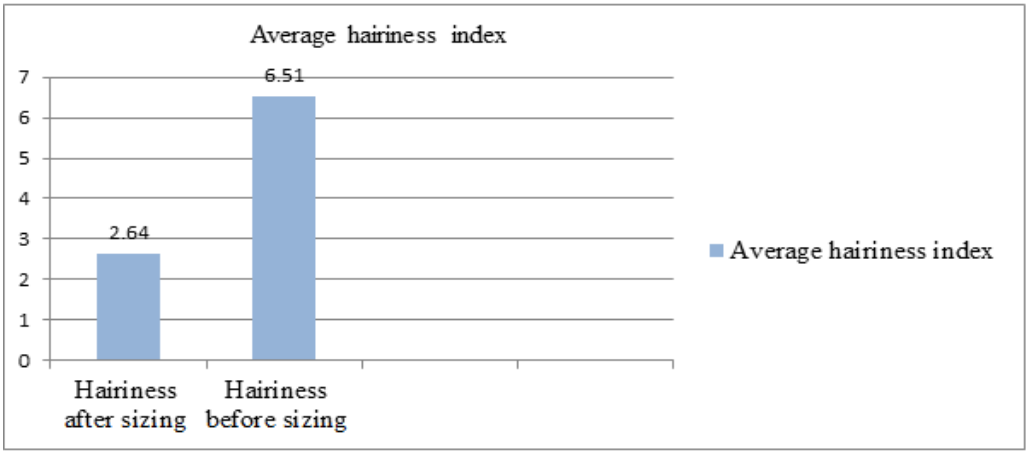


Figure4. 4 Reduction in yarn hairiness

4.6 De-sizing of Starch Material Using Banana Root and Stem Powder

The de-sizing efficiency of banana stem and root powder was evaluated using gray cotton yarn. The initial weight of the sized yarn (W_1) was 10.0 g, and after the de-sizing treatment and subsequent washing, the final weight (W_2) decreased to 9.08 g. The percentage weight loss was calculated using Equation 4.7.

$$\text{Weight Loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$ ----------Equation 4. 7

$$\text{Weight Loss (\%)} = \frac{10.00 - 9.08}{10.00} \times 100 = \frac{0.92}{10.00} \times 100 = 9.2\%$$

The calculated weight loss was **9.2%**. This result indicates that approximately 9.2% of the yarn's original weight was removed during the de-sizing process. The weight loss primarily corresponds to the removal of starch-based sizing materials applied during weaving preparation. However, because the measured weight loss is slightly higher than the **8.02%** size add-on, the additional loss may be attributed to the removal of residual impurities, such as natural waxes, dust, or loosely bound contaminants present on the gray yarn before sizing, along with traces of non-cellulosic materials. Since the observed weight loss falls within the typical industrial size add-on range of **6–10%** reported for sized cotton yarn at Kombolcha Textile Share Company (KTSC), the results indicate that the banana stem and root powder effectively removed the sizing material without causing significant loss of the cotton cellulose.

These findings demonstrate that banana stem and root powder has considerable potential as an eco-friendly natural de-sizing agent. The reduction in yarn weight is mainly attributed to the hydrolysis and removal of starch-based sizing materials, together with minor surface impurities, during washing. This finding is consistent with the study by (Lambiso et al., 2019), which reported that plant-based de-sizing agents can effectively remove starch size while reducing the environmental impacts associated with conventional chemical de-sizing methods. Moreover, banana plant waste is inexpensive, readily available, and biodegradable, making it a promising sustainable alternative for textile processing. However, further studies are needed to evaluate its effects on yarn strength, fabric quality, and process consistency before industrial-scale application.

4.7 Iodine Test for Sizing and De-sizing of Cotton Warp Yarn

Banana stem and root extracts used to size and de-size cotton warp yarn were tested for starch using the iodine test. The extract's centrifugally separated sediment was mixed with a drop of iodine solution. The existence of starch was confirmed by the emergence of a blue-black color, which verified its function in yarn scaling. In contrast, a yellow color indicated the absence of starch, which is associated with the de-sizing condition where starch has been removed.

4.8 Response Surface Methodology (RSM)

Response Surface Methodology (RSM), based on a three-factor, three-level Box-Behnken Design (BBD), was employed to optimize the sizing process and evaluate the effects of powder concentration (60–75 g/L), sizing temperature (80–90°C), and sizing time (20–30 min) on the performance of cotton warp yarn treated with banana stem and root starch extracts. The experimental ranges were selected based on preliminary investigations and industrial processing requirements.

A second-order polynomial model was developed to describe the relationship between the process variables and the response parameters. Analysis of Variance (ANOVA) was applied to evaluate the statistical significance of the model and individual factors at a 95% confidence level ($p < 0.05$). The model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, predicted R^2, and lack-of-fit tests.

The results indicated that the selected process variables had significant effects on yarn properties, both individually and through their interactions. Overall, the developed models demonstrated satisfactory predictive accuracy and were suitable for process optimization. These findings are consistent with those of (Abay & Ayele, 2023), who reported that RSM is an effective statistical tool for modeling, analyzing, and optimizing textile processing parameters.

The optimization was carried out using the RSM optimization function in Minitab Statistical Software version 19.5. The software identified the optimum sizing conditions as a powder concentration of 61.87 g/L, a sizing temperature of 90°C, and a sizing time of 27.37 minutes. These conditions produced an overall desirability value of 0.7844, indicating good agreement between the optimization objectives and the predicted responses. This confirms that the selected

parameter combination provides the most favorable operating conditions within the investigated experimental range.

Table4. 6 Average Response Values of Experimental Runs

Std. Order	Run Order	Powder Concentration (g/L)	Sizing Temperature (°C)	Sizing Time (min)	Strength Gain (%)	Elongation Loss (%)	Hairiness Reduction (S3 Index)
1	1	60.0	80	25	28.95	38.4	4.1
2	2	75.0	80	25	41.60	25.0	*
3	3	60.0	90	25	52.70	13.8	1.6
4	4	75.0	90	25	55.80	11.7	*
5	5	60.0	85	20	22.50	40.0	4.2
6	6	75.0	85	20	35.10	37.8	5.3
7	7	60.0	85	30	26.60	36.1	*
8	8	75.0	85	30	60.50	39.1	3.8
9	9	67.5	80	20	45.30	17.1	1.9
10	10	67.5	90	20	57.10	11.4	*
11	11	67.5	80	30	31.90	33.3	*
12	12	67.5	90	30	55.80	41.1	6.3
13	13	67.5	85	25	35.10	22.7	*
14	14	67.5	85	25	34.20	25.6	2.4
15	15	67.5	85	25	38.80	29.7	0.9
Average		67.5	85	25	41.5	28.2	2.03

Below the figure 4.4 Optimization analyses indicated that the highest overall desirability was obtained at a powder concentration of 67.5%, a sizing temperature of 85°C, and a sizing time of 25 minutes. Under these conditions, the cotton warp yarn achieved a tensile strength gain of 41.5%, an elongation loss of 28.2%, and a hairiness reduction (S3 index) of 2.03. These results demonstrate that the optimized sizing parameters effectively enhanced yarn strength while reducing surface hairiness, making the yarn more suitable for weaving applications.

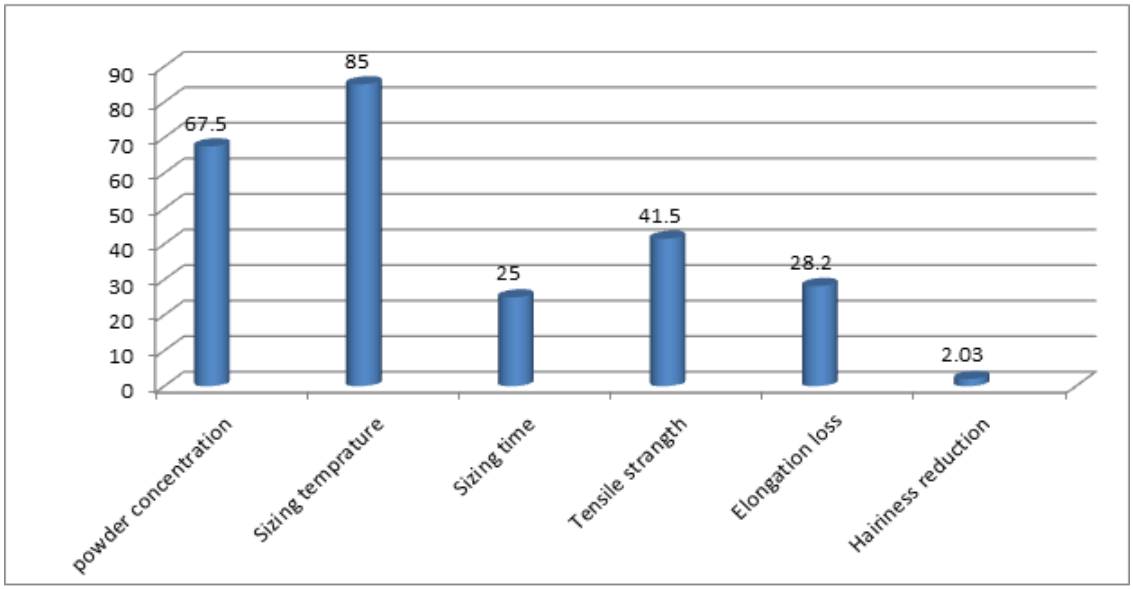


Figure4. 5 Bar chart of average values of dependent and independent variables.

4.8.1 ANOVA and Effects of Process Parameters on Yarn Tensile Strength

Table4. 7 ANOVA for Tensile Strength

Source	F-Value	P-Value
Model	4.45	0.034
Linear	7.11	0.016
Powder Concentration	8.69	0.021
Sizing Temperature	12.16	0.010
Square	6.74	0.036
Sizing Temperature*Sizing Temperature	6.74	0.036

ANOVA Analysis

The Analysis of Variance (ANOVA) results indicate a statistically significant model, as evidenced by an F-value of 4.45 and a p-value of 0.034. Since the p-value is less than the conventional significance threshold of 0.05, this suggests that at least one of the independent variables significantly influences the dependent variable.

Individual Linear Effects

Powder Concentration: The analysis reveals a significant linear effect for powder concentration, evidenced by an F-value of 8.69 and a p-value of 0.021. This correlation indicates that changes in powder concentration lead to notable modifications in the response variable.

Sizing Temperature: Similarly,the linear effect of sizing temperature was statistically significant, as indicated by an F-value of 12.16 and a p-value of 0.010. This result underscores the critical role of sizing temperature as a determinant of the response variable.

Regression Equation in Uncoded Units

Strength Gain (%) = 28.30 + 2.90(Powder Concentration) − 65.1(Sizing Temperature) − 19.5(Sizing Time) + 0.401(Sizing Temperature)² − 0.0637(Powder Concentration × Sizing Temperature) + 0.1420(Powder Concentration × Sizing Time) + 0.121(Sizing Temperature) × (Sizing Time)

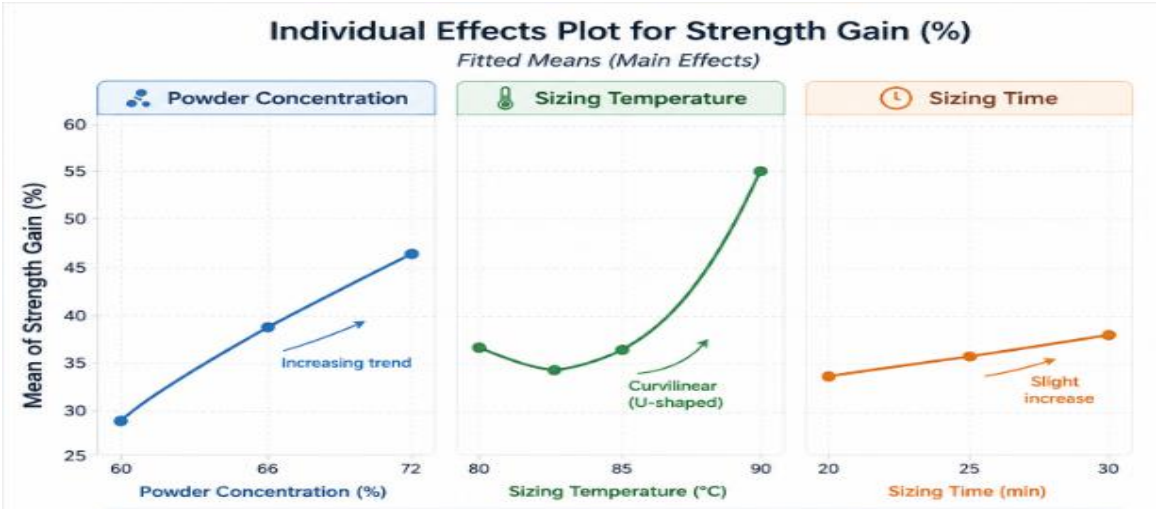


Figure4. 6 Individual effect on tensile strength

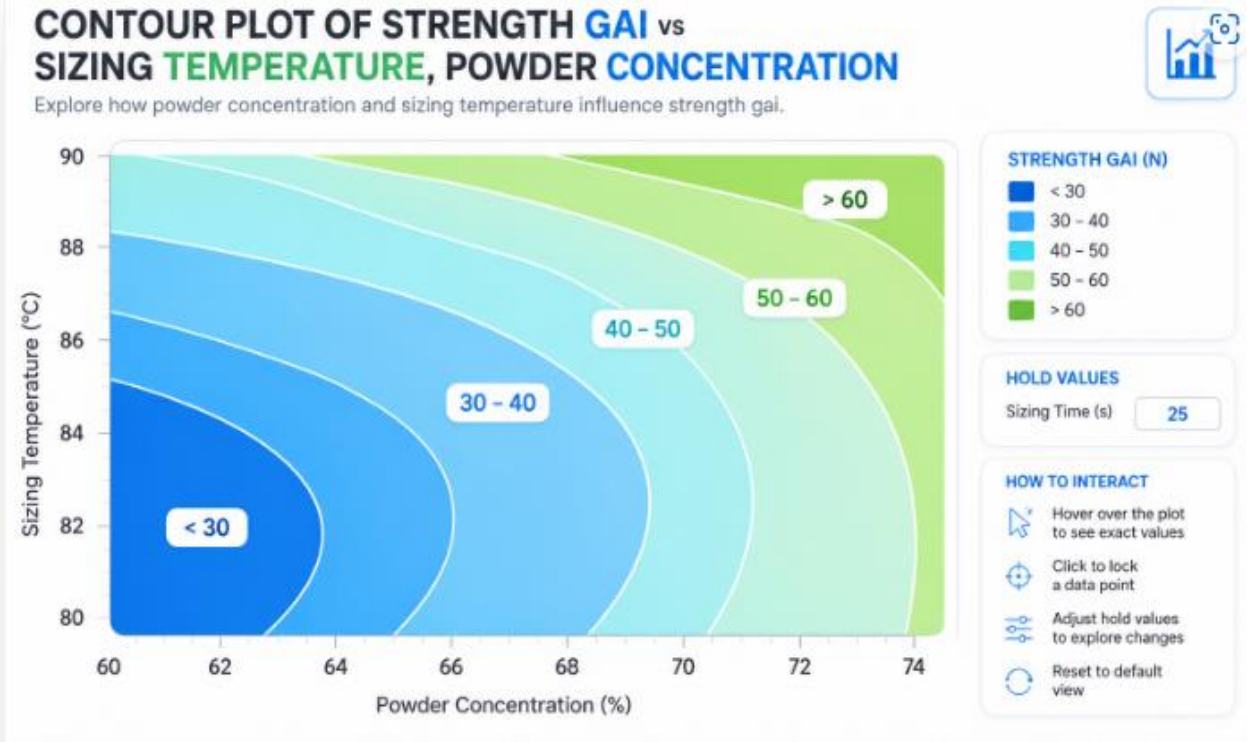


Figure4. 7 Contour plot on tensile strength

Interaction Effects on Tensile Strength

The significant quadratic effect of sizing temperature ($F = 6.74$, $p = 0.036$) indicates a nonlinear relationship between sizing temperature and tensile strength. This indicates that the impact of sizing temperature on the response variable is dependent on its level, suggesting potential non-linear interaction effects. Further investigation into this interaction is warranted to fully comprehend its implications on the response variable.

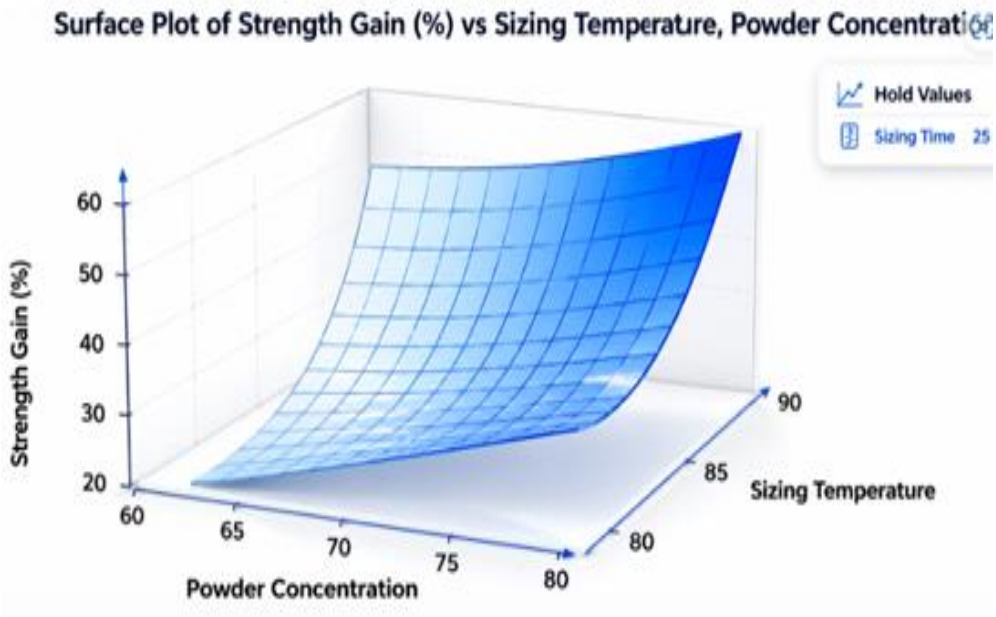


Figure4. 8 Interaction effect on tensile strength

4.8.2 (ANOVA) and Effects of Process Parameters on Elongation Loss

Table4. 8 ANOVA for Elongation Loss

Source	F-Value	P-Value
sizing temperature	9.47	0.016
Square	10.34	0.049
sizing temperature*sizing temperature	10.34	0.039

The F-value of 9.47 and the P-value of 0.016, which are below the 0.05 significance level, in the ANOVA findings show that sizing temperature had a significant impact on the reaction. Furthermore, the quadratic effect of sizing temperature was significant (F = 10.34, P = 0.039), suggesting a nonlinear relationship between sizing temperature and the response. These results imply that there is an ideal temperature within the examined range and that variations in sizing temperature had a significant impact on the response. Consequently, during process optimization, sizing temperature is a crucial factor that needs to be properly managed.

Individual Effects elongation loss%

The response surface analysis showed that temperature significantly affected the response, with performance improving as temperature increased within the range under study. This factor's significance was validated by ANOVA (F = 9.47, P = 0.016). Furthermore, a nonlinear

relationship is indicated by the significant quadratic effect (F = 10.34, P = 0.039), which suggests the existence of an ideal temperature condition. These findings demonstrate how crucial sizing temperature is as a vital factor in process improvement.

Regression Equation in Uncoded Units

Elongation Loss (%) = 25.10 − 0.245(Powder Concentration) + 60.5(Sizing Temperature) + 1.082(Sizing Time) − 0.361(Sizing Temperature)^2

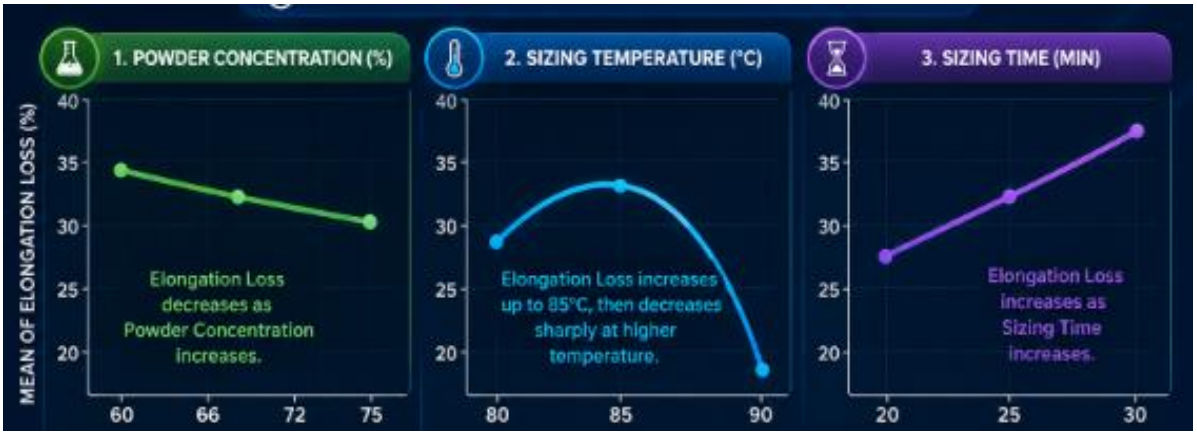


Figure4. 9 Individual effect on elongation loss%

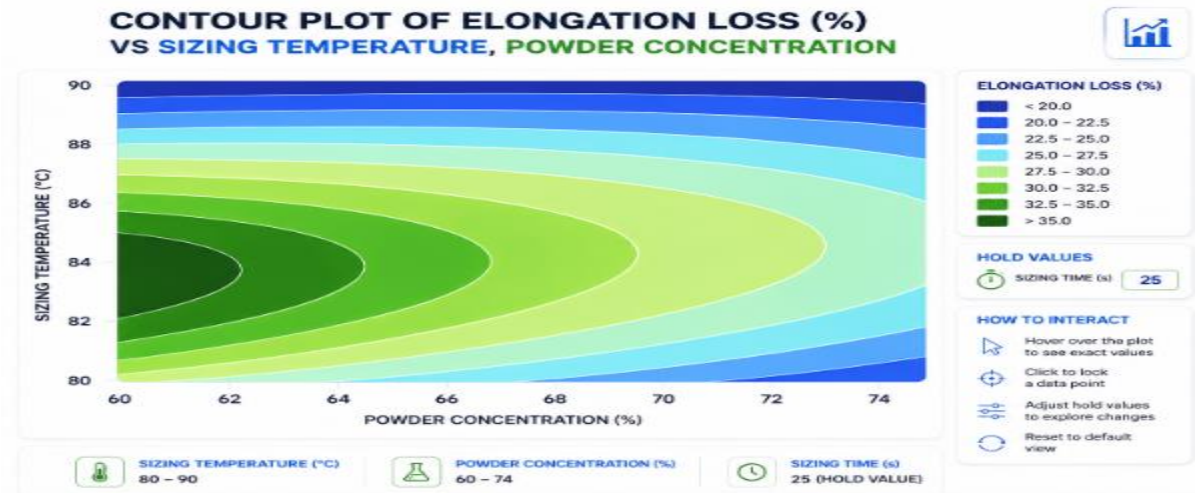


Figure4. 10 Contour plot of elongation loss%

Quadratic Effect of Sizing Temperature on Elongation Loss

The ANOVA results showed that sizing temperature significantly affected reactivity (F = 9.47, P = 0.016). Additionally, the response varied nonlinearly over the temperature range under

examination, according to the significant quadratic term for increasing temperature (F = 10.34, P = 0.039). This highlights how important it is to achieve the desired outcome and suggests that there is an optimal sizing temperature.

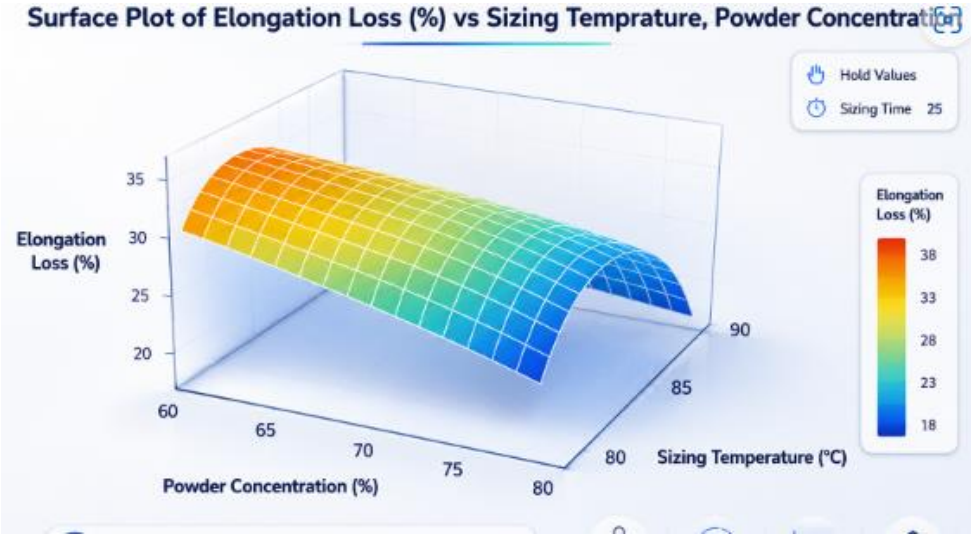


Figure4. 11 Surface plot of elongation loss %

4.8.3 (ANOVA) and Effects on Hairiness Reduction

Table4. 9 ANOVA for Hairiness Reduction

Source	F-Value	P-Value
powder concentration	10.00	0.040
sizing temperature	9.47	0.042
2-Way Interaction	10.34	0.049
powder concentration*sizing temperature	10.34	0.049

The ANOVA results indicated that powder concentration and sizing temperature significantly affected hairiness reduction. With P-values of 0.040 and 0.042, respectively, the significant interaction of these factors (F = 10.34, P = 0.049) indicates that their combined influence is not independent. These results demonstrate that process variables and their interactions are crucial in determining the response and should be taken into account while optimizing the size process.

Individual Effects on Hairiness Reduction (S3 Index)

The main effects plot indicates that powder concentration and sizing temperature positively influenced hairiness reduction, while sizing time showed a negative effect. The S3 index

gradually increased as the powder concentration was raised from 60% to 75%, indicating improved control over projecting fibers. ANOVA revealed that this effect was statistically significant (F = 10.00, P = 0.040).

In a similar vein, hairiness reduction increased with higher sizing temperatures, with a dramatic spike in reaction around 90°C. Better yarn coverage and starch gelatinization are responsible for this improvement. ANOVA was used to confirm the significance of sizing temperature (F = 9.47, P = 0.042). On the other hand, the S3 index gradually decreased when the sizing period was increased from 20 to 30 minutes, indicating that longer treatment decreased the effectiveness of sizing. Overall, powder concentration and sizing temperature were the most influential factors governing hairiness reduction.

Regression Equation in Uncoded Units

Hairiness Reduction (S3 Index) = 612 − 8.95(Powder Concentration) − 6.57(Sizing Temperature) − 4.00(Sizing Time) + 0.0780(Sizing Time)² + 0.1053(Powder Concentration × Sizing Temperature)

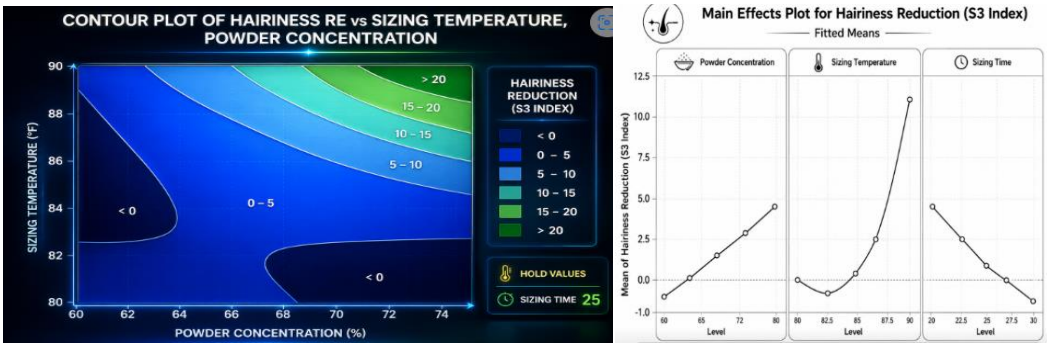


Figure4. 12 Individual effect on hairiness reduction

Interaction Effects on Hairiness Reduction

The surface plot shows a positive interaction between powder concentration and sizing temperature, where hairiness reduction increased as both factors increased simultaneously. The highest S3 index values were achieved at high powder concentrations and elevated temperatures, indicating a synergistic effect between the two variables. This interaction was statistically significant according to the ANOVA results (F = 10.34, P = 0.049), demonstrating that the effect of powder concentration on hairiness reduction depends on the sizing temperature level. Consequently, optimizing both factors together is essential for maximizing hairiness reduction.

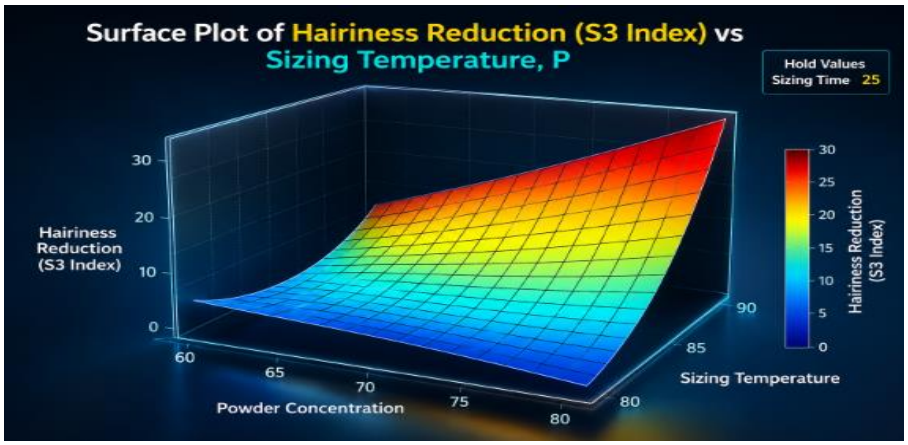


Figure4. 13 Surface plot of hairiness reduction

4.8.4 Model Adequacy

Table4. 10 Coefficient of Determination

Response	R-squared (%)	Adjusted R-squared (%)	Predicted R-squared (%)
Tensile Strength	81.67	73.33	71.80
Elongation Loss	78.54	71.45	69.56
Hairiness Reduction	73.23	68.89	65.78

Interpretation:

With an R-squared of 81.67%, tensile strength exhibits the best model fit, meaning that the predictors account for 81.67% of the variability in tensile strength. While the projected R-squared (71.80%) indicates a strong prediction capability on new data, the adjusted R-squared (73.33%) takes into consideration the number of predictors utilized. With an R-squared of 78.54%, elongation loss also matches well. Its anticipated R-squared (69.56%) shows accurate predictions for new observations, and its adjusted R-squared (71.45%) is still substantial. Hairiness reduction exhibited the lowest R^2 value (73.23%), indicating that the model explained a smaller proportion of the response variability compared with the tensile strength and elongation loss models. There may be room for improvement in terms of predictive accuracy and model complexity, according to the adjusted (68.89%) and predicted R-squared (65.78%) values.

4.9 Optimization of Sizing Process Parameters

Response Surface Methodology (RSM) coupled with the desirability function approach was used to optimize the sizing process parameters for cotton warp yarn treated with banana stem and root starch extract. The optimization objective was to maximize yarn strength gain while minimizing elongation loss and yarn hairiness. The optimum conditions generated by the model are presented in Table 4.11. The optimum sizing conditions were determined using the Response Surface Methodology (RSM) optimization function in Minitab Statistical Software version 19.5. The software identified a powder concentration of 61.87 g/L**,** a sizing temperature of 90°C**,** and a sizing time of 27.37 minutes as the optimal process parameters. These conditions yielded an overall desirability value of 0.7844**,** indicating a good agreement between the optimization objectives and the predicted response values. This suggests that the selected process parameters provide the most favorable combination of operating conditions within the experimental range.

Table4. 11 Optimal Process Parameters

Parameter	**Optimum Value**
Powder Concentration (g/L)	61.87
Sizing Temperature (°C)	90.00
Sizing Time (min)	27.37
Composite Desirability	0.7844

Table4. 12 Predicted Responses optimization

Response	**Predicted Value**
Strength Gain (%)	51.72
Elongation Loss (%)	22.46
Hairiness Reduction (S3 Index)	0.88

The optimized sizing conditions produced a predicted strength gain of 51.72%, indicating a substantial improvement in yarn tensile properties. The results indicate that the banana stem and root starch extract successfully coated the yarn surface, improving fiber binding and reducing protruding fibers. The overall improvement in yarn strength and surface quality, while maintaining adequate flexibility, demonstrates the potential of banana stem and root starch as a

sustainable sizing material for cotton warp yarns. At the same time, elongation loss was maintained at 22.46%, and yarn hairiness was reduced to an S3 index of 0.88.

4.9.1 Multiple Response Prediction and Statistical Evaluation

The reliability of the optimized solution was evaluated using the Standard Error of Fit (SE Fit), 95% Confidence Intervals (CI), and 95% Prediction Intervals (PI). The statistical estimates for the optimized responses are presented in Table 4.13. The 95% confidence intervals indicate the precision of the predicted mean responses, while the prediction intervals represent the expected range of future observations. The relatively narrow intervals demonstrate good model precision and predictive reliability. Strength gain showed the highest prediction accuracy, with the smallest uncertainty range. Overall, the developed RSM models exhibited satisfactory predictive performance and are suitable for optimizing the sizing of cotton warp yarn using banana stem and root starch extract

Table4. 13 Prediction Statistics

Response	**Fit**
Hairiness Reduction (S3)	0.88
Elongation Loss (%)	22.46
Strength Gain (%)	51.72

Chapter Five

Conclusion and Recommendation

5.1 Conclusion

This study demonstrated that starch extracted from banana stem and root agro-waste can be used as an effective and sustainable sizing agent for cotton warp yarns. The successful extraction of starch with a yield ranging from 60% to 78% confirms that banana agro-waste is a viable renewable raw material for textile sizing applications.

The physicochemical characterization showed that the extracted banana starch possessed suitable properties for sizing. Its solubility (4%) and viscosity (14.88 flow/sec) were sufficient to provide good adhesion and film formation on the yarn surface while allowing satisfactory removal during the desizing process.

The application of banana starch significantly improved the mechanical properties of cotton warp yarn. Tensile strength increased by 41.00%, indicating improved resistance to yarn breakage during weaving. Although the elongation at break decreased slightly to 5.07%, it remained within the acceptable range for weaving performance. The size add-on of 8.02% demonstrated adequate deposition of the sizing material on the yarn surface, while the reduction in yarn hairiness from 6.51 to 2.64 indicates improved yarn smoothness and reduced surface fibers, which are expected to enhance weaving efficiency.

The comparative evaluation showed that banana starch produced slightly higher tensile strength than conventional potato starch while maintaining comparable elongation characteristics. These findings indicate that banana starch can effectively replace conventional starch-based sizing agents without compromising yarn performance.

The optimization study using Response Surface Methodology (RSM) successfully identified the optimum sizing conditions as a starch concentration of 61.87 g/L, a sizing temperature of 90°C, and a sizing time of 27.37 minutes, with an overall desirability value of 0.7844. Under these conditions, the best combination of tensile strength, elongation, size add-on, and reduced hairiness was achieved.

Overall, the findings of this study demonstrate that banana stem and root starch is a technically feasible, biodegradable, and locally available sizing material that has the potential to reduce

dependence on conventional starches and imported synthetic sizing agents while supporting more sustainable textile production.

5.2 Recommendations

Based on the findings obtained in this study, the following recommendations are proposed:

1. Since banana stem and root starch demonstrated satisfactory sizing performance, textile manufacturers should consider its application as an alternative sizing agent, particularly in regions where banana agro-waste is readily available.
2. The optimum sizing conditions identified in this study (61.87 g/L starch concentration, 90°C sizing temperature, and 27.37 minutes sizing time) should be validated through pilot-scale and industrial-scale trials to confirm their applicability under commercial production conditions.
3. Although the present study confirmed improvements in tensile strength, elongation, size add-on, and hairiness, future studies should evaluate additional performance parameters such as abrasion resistance, weaving efficiency, fabric quality, and loom performance to provide a more comprehensive assessment of banana starch as a sizing agent.
4. Since this study compared banana starch only with potato starch, further comparative investigations with other commercial sizing agents, including maize starch, wheat starch, and polyvinyl alcohol (PVA), are recommended to establish its overall industrial competitiveness.
5. As the present work focused mainly on the extraction, characterization, and sizing performance of banana starch, future research should investigate the environmental and economic benefits through life-cycle assessment and cost analysis to support large-scale industrial adoption.
6. Further research should also investigate methods to improve starch extraction efficiency and purity, as increasing starch yield could enhance the economic feasibility of utilizing banana agro-waste as a sustainable raw material for textile sizing.

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Appendixes

Appendix 1: Collecting banana stems and roots from the harvesting area



Appendix 2: cutting, washing and filtering the banana stem and root



Appendix 3: stem drying without fiber parts and root part after filter drying



Appendix 4: after drying, the material was ground to produce powder.



Appendix 5: The letter written to Kombolcha Textile Share Company was accepted.



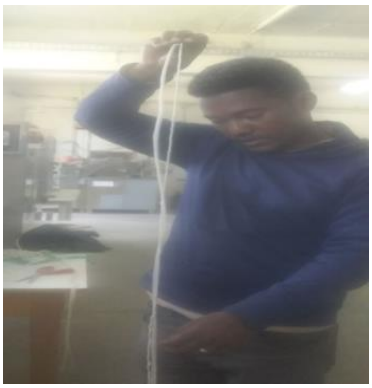
Appendix 6: First, check the viscosity by measuring it.

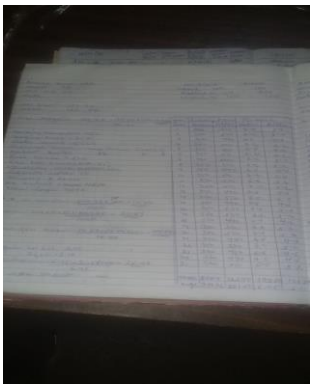


Appendix 7 : Temperature measure and yarn measuring before and after sizing



Appendix 8: Yarn Measuring Before Tensile Strength Test Sized and Unsized



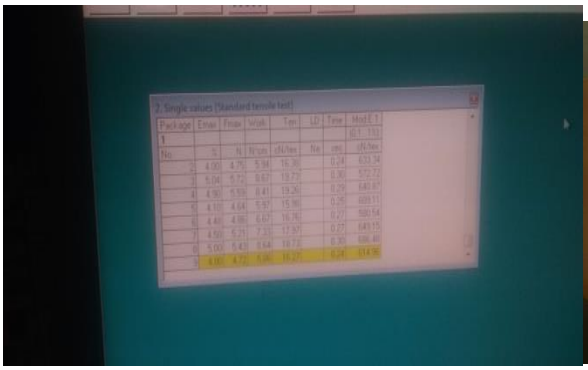
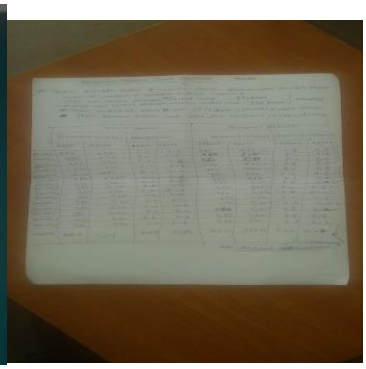


Appendix 9: Measuring of Tensile Strength and solubility

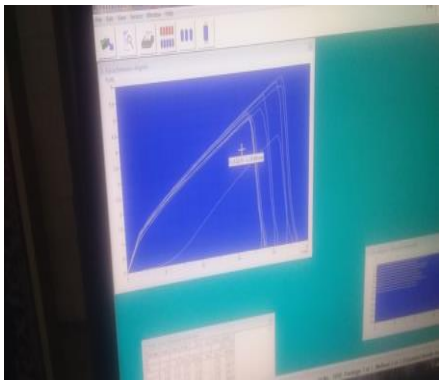





Appendix 10: Result of Tensile Strength Measurement

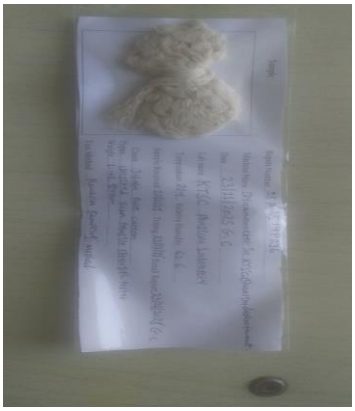
Appendix 11: Force and Elongation% Diagram and powder





Appendix 12: Sizing Box and sized and un-sized yarn





Appendix 13 : Yarn Iodine Test and drying banana stem




Appendix 14: Different chemical used Softener acid amylase enzyme

