FABRICATING AND TESTING PACKAGING MATERIAL MADE USING LYE AND CAUSTIC SODA TO PULP KIGANDA BANANA STEMS FROM KISII COUNTY, KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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To my late father; Dr. Kibberenge Musombi and Miss Lily Sayo, Nanjulula Musombi and my grandparents Muhenge, Nangila, the late Dishon and Takei, and Zazu.

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ABBREVIATIONS/ ACRONYMS

CD: Cross Direction

JKUAT: Jomo Kenyatta University of Agriculture and Technology

KEBS: Kenya Bureau of Standards

KBS: Kiganda Banana Stem

NRF: National Research Fund

PH: Potential of Hydrogen

MSEs: Micro and Small Enterprises

MD: Machine Direction

SPSS: Statistical Package for the Social Sciences

WVTR: Water Vapor Transmission Rate

FAO: Food and Agriculture Organization

DEFINITION OF TERMS

Alkaline pulping: A form of chemical pulping that utilizes an alkaline chemical agent as an aqueous solution (cooking liquor) for the delignification process of breaking down cellulosic fibers into a pulp.

Baseline Study: This is an analysis of the current situation to identify the starting points for a program or project. It looks at what information must be considered and analyzed to establish a starting point or the benchmark against which future progress can be assessed or comparisons made.

Biodegradable: Capable of being broken down, especially into innocuous products by the action of living things (such as microorganisms).

Caustic Soda: Is the common name given to the chemical compound sodium hydroxide (NaOH). This compound is an alkali – a type of base that can neutralize acids and is soluble in water.

Cellulose: A polysaccharide of glucose units that constitutes the chief part of the cell walls of plants.

Cellulose Content: The amount or percentage of glucose polysaccharide (~~cellulose~~) in a substance.

Chemical Characterization: Incorporates a variety of analytical techniques to identify and quantify chemical components of materials.

Chemical Composition: Corresponds to the relative amounts of the elements that constitute the substance.

Delignification: Removal of lignin from woody tissue (as by natural enzymatic or industrial chemical processes).

Mechanical Properties of Paper: These are the characteristics that a material exhibits upon the application of forces.

Moderating Variable: A variable that can strengthen, diminish, negate, or otherwise alter the association between independent and dependent variables.

Packaging: A material used to enclose or contain something.

Pulp: A material prepared by chemical or mechanical means from various materials (such as wood or rags) for use in making paper and cellulose products.

Sustainability: Relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged.

OPERATIONAL DEFINITION OF TERMS

Banana Waste:	Banana stems and banana peels.
Banana Variety:	The species or type of banana plant.
Delignification Alkalis:	Lye and Caustic Soda.
Kiganda:	The most popular banana variety prevalent in five counties in Kenya that grow the most bananas regionally. It is a cooking variety characterized by having medium-sized green bananas.
Kraft paper packaging:	The paper packaging produced from chemical wood pulp produced in the Kraft process.
Lye:	Potassium hydroxide (KOH) alkali delignification reagent made using banana peel ash.
Packaging Material:	The medium used to create different types of wrappings or enclosures specifically for packages.
Packaging Material Quality:	The level of adherence to established mechanical packaging standards.
Stems:	The plant axis of banana plants that bears the shoots, buds, and leaves and at its basal end roots.

ABSTRACT

Packaging has both functional and aesthetic purposes. In 2017, various Kenyan industries including the fashion industry were affected by the ban of single-use plastic bags in Kenya. This created a need for more biodegradable packaging options. Banana stems and peels are part of the waste produced in Kenyan farms, suggested for the construction of biodegradable paper packaging material. The objectives of this study were: to extract banana stem fibers using a decorticating machine, to pulp banana stem fibers using; a)Lye a) Caustic Soda, to construct samples of paper packaging material from; a) pulp treated with Lyeb) pulp treated with Caustic Soda, to test selected physical and mechanical properties of the constructed paper packaging materials made from; a) pulp treated with Lye b) pulp treated with Caustic Soda, to compare the properties of the paper packaging material made from the pulp treated with Lye to those made from pulp treated with Caustic Soda and finally to compare the properties of the paper packaging material made from pulp treated with Lye to established standard Kraft paper packaging properties of the Kenya Bureau of Standards (KEBS).The literature revealed that banana waste is an underutilized resource for creating packaging material and limited studies document banana stem paper properties. The research design for this study was an experimental design in which the following variables were measured; independent variables; banana variety and cellulose content, moderating variables: Lye and Caustic Soda, and the dependent variable was paper packaging quality measured through selected physical and mechanical properties which are color, water absorbency, bursting strength, tearing strength and tensile strength. The control was standard Kraft paper packaging from KEBS. A baseline study was done to establish the area of the study where the banana stems would be collected. Five counties known to be banana-growing counties were selected for the baseline. These were Embu, Kakamega, Kirinyaga, Kisii and Muranga. Kisii County was selected having the popular variety (Kiganda) with the highest cellulose content. 40 stems of one-meter length were collected, the outer sheath layers were included because they have fibers that are stronger and have a higher cellulose content. The 40 stems yielded 4200g of fiber which was pulped and converted to 80 paper sheets, 40 from the Lye and 40 from the Caustic Soda processes. Testing of the paper packaging material was done in the KEBS laboratory under set conditions of 65% ± 2% humidity and a temperature of 20^0C ± 2^0 C. The Research instruments were; a Pantone color chart, Cobb testing machine, Frank bursting strength tester, TexTest-FX 3750 Elmendorf tester, and Tinius Olsen tensile testing machine. The data was analyzed using one sample and two sample independent T-Test and on Excel 2013 software. Findings reveal that decorticating one-meter stem takes 10 minutes yielding 105g of dry fiber. The yield from the pulped banana fiber was 68% and 56% for Lye and Caustic Soda respectively. The making of 80 A4 papers took 16 hours to prepare and each paper takes 8 hours to air dry. The color of the papers was determined to be sand brown. The other property tests showed that for water absorptiveness, bursting strength, and tearing strength there was no significant difference between with Lye and that made with Caustic Soda. However, the tensile strength of the Caustic Soda sample was significantly higher than that of Lye. It also revealed that the Lye paper packaging material surpassed the minimum KEBS requirement for bursting strength and tearing strength however it had undesirable tensile strength and water absorbency and thus further research to improve these properties was recommended.

CHAPTER ONE: INTRODUCTION

1.0 Introduction

This chapter introduces the study. Each segment builds up on the study and sheds light on the foundational elements of the study. It gives the background to which the study is stemmed, the problem statement that highlights the problem, the purpose for carrying out the study and the objectives set to address the problem. It also outlines the hypothesis of the study, the significance of the study, the scope and the limitations of the study as well as the theoretical and conceptual frameworks for the study.

1.1 Background to the Study

Packaging in the fashion industry is significant, being considered a great tool for marketing a brand in terms of product presentation and brand differentiation (BayWater Packaging, 2023). The Kenyan textile industry is still developing and different studies exploring various fiber sources for various applications are being done to add value to underutilized and eco-friendly natural fiber sources (Mbugua, 2014).

Globally, plastic bags which are the most dominant type of plastic packaging, have contributed to a large share of pollution due to their short life span (Vidal, 2020). Given that they are non-biodegradable, plastic bags end up in landfills or are washed into oceans. Solutions to the plastic bag menace have mainly encouraged the manufacture and use of biodegradable paper bags. However, according to Poole (2021), the increase in demand for biodegradable packaging has fueled the rate of deforestation given that these paper bags are made mainly from wood pulp. To remedy this, different non-wood fibers have been used as an alternative to create biodegradable paper packaging. These include jute, flax, bagasse, corn straw, bamboo, reed, grass, sisal, and banana stems which have a high cellulose content thus making them great raw materials for paper packaging (Liu et al., 2018; Subagyo & Chafidz, 2018).

In 2017, Kenya introduced a nationwide ban on single-use plastic bags thus increasing the demand for additional sustainable packaging options especially of the biodegradable kind (*Kenya Law - Kenya Gazette*, 2017). This ban affected all industries including the fashion industry. This means that the exploitation of underutilized eco-friendly packaging raw materials such as banana waste (banana stems and peels) is vital. Furthermore, Ngonou (2019) outlines that the Kenyan government is pushing the packaging manufacturing market to be more inclined to the production of biodegradable options by offering them additional tax incentives to help enforce the plastic ban.

Banana plants that belong to the family *Musaceae* and genus *Musa* have been determined to have stems with cellulose content ranging from about 60% to 69% (Goswami et al., 2008; Oyewo et al., 2023). These banana stems are often considered waste and are mainly left to decompose on farms or given to cattle to supplement their feed (Acevedo et al., 2021). Kenya alone produces over 1 million tons of bananas annually (*FAOSTAT*, 2019a). The by-products of banana farming mainly include; banana stems, banana leaves, and banana peels (Acevedo et al., 2021). The banana stems produced are an underutilized source of fiber for paper, given that they are often left to rot after the banana fruits are harvested (Acevedo et al., 2021). The banana stems that are put to use post-harvest are commonly used for making manure, livestock feed, craft items such as mats and bags (Dubey, 2021). Various studies have established its potential as a fiber source for making paper and paper products given their high cellulose content (Goswami et al., 2008; Liu et al., 2018; Priyadarshana, Kaliyadasa, Ranawana, & Senarathna, 2022; Subagyo & Chafidz, 2018). On the other hand, according to research from Waithaka and Muriuki (2019), banana peels have been used in Lye form to create an alkali suitable to replace soap-making alkalis such as Caustic Soda. Given its alkaline nature, this Lye would be valuable in the pulping process of making paper from cellulosic fibers such as banana stem fibers. Despite this, banana peels remain majorly underutilized and undervalued in Kenya as they are still being disposed of as waste.

In light of this background, the study aimed to create a biodegradable paper packaging material from banana waste and assess its quality.

1.2 Problem Statement

In 2017, Kenya established a ban on single-use plastic thus increasing the demand for additional eco-friendly packaging options with those of the biodegradable variety being preferred. This ban gravely affected various industries including the fashion industry leaving them with limited sustainable packaging options.

As an attempt to increase sustainable packaging options, non-woven propylene bags were introduced as a favored option to replace plastic bags due to their durability and reusability. However the high demand for these non-woven bags had consequently led to the production of low-quality bags and as a result, a cessation of the importation, manufacture, supply, or utility of the low-quality bags was instituted by the National Environment Management Authority (NEMA) on the 31st of March 2019 (Irungu, n.d.).This is because these bags encouraged poor disposal practices by consumers, posing a potential recurrent threat to the environment (Magudha, 2019). To impel this challenge further, limited biodegradable packaging alternatives were available to meet the need created as a result of this ban (*Kenya Law - Kenya Gazette*, 2017).In contrast, It has been established that despite its potential for the production of paper packaging, banana waste specifically; banana stems and peels have been underutilized as they are mostly discarded post-harvest (Dubey, 2021). The limited biodegradable packaging options coupled up with the underutilization of banana waste, presented an opportunity for creating a biodegradable packaging material that would utilize the banana waste to mitigate the packaging challenge in the Kenyan fashion industry. This study aimed to fabricate a paper packaging material from banana waste and establish its quality by testing some of its physical and mechanical properties in order to come up with a packaging material that would offer a solution to the packaging challenges faced by the fashion industry and others alike.

1.3 Purpose of the Study

The purpose of this study was to fabricate and test packaging material made using Lye and Caustic Soda to pulp Kiganda banana stems from Kisii County, Kenya.

1.4 Research Objectives

This study sought to:

1. Extract banana stem fibers using a decorticating machine.
2. Pulp banana stem fibers using; a) Lye. b) Caustic Soda.
3. Construct samples of paper packaging material from; a) Pulp treated with Lye. b) Pulp treated with Caustic Soda.

4. Test selected physical and mechanical properties of the constructed paper packaging materials made from a) Pulp treated with Lye. b) Pulp treated with Caustic Soda.

5. Compare the properties of the paper packaging material made from pulp treated with Lye to those made from pulp treated with Caustic Soda.

6. Compare the properties of the paper packaging material made from pulp treated with Lye to established standard Kraft paper packaging properties of the Kenya Bureau of Standards (KEBS).

1.5 Research Hypotheses

The following hypotheses were tested:

H_{01} –There is no significant difference in paper packaging material quality made from pulping with Lye and that made from pulping with Caustic Soda.

H_{02} – There is no significant difference in paper packaging material quality made from pulping with Lye and the KEBS standard packaging material.

1.6 Significance of the Study

This study provides information that may be useful for the textile industry as it elaborates on the viability of banana fiber as a raw material for paper packaging material.

The findings of this research will be useful to various stakeholders in the following manner;

Farmers: It offers information on the value addition of banana waste which will enable them to alleviate their current challenge of banana stem accumulation on the farms.

Commercial packaging industry: It will drive interest in producing sustainable biodegradable packaging alternative.

Micro and Small Enterprises (MSEs): It will offer an alternative to creating cost effective eco-packaging products thus fostering local entrepreneurship from the farm level.

Policy: It will inform policy making on promoting green growth for industries utilizing agricultural waste such as banana stems.

Climate change activists: It will form a basis for them for advocating for continuous efforts in the innovation of sustainable products for environmental preservation.

Academia and research: It will present data that will open an avenue for exploration of bio-based materials, aiding the shift towards renewable energy.

1.7 Scope of the Study

This study focused on constructing paper packaging material using banana stems of Kiganda variety from Kisii by alkaline pulping. Lye was used for delignification as well as Caustic Soda. Selected physical and mechanical properties of the paper packaging materials which are color, water absorbency, bursting strength, tearing strength, and tensile strength were tested against KEBS standards to evaluate its quality. The control was standard Kraft paper packaging from KEBS.

1.8 Limitations of the Study

Only Kiganda variety banana stems from Kisii County were used for this study since they were found to have the highest cellulose content (Appendix A). The paper was constructed manually via the alkaline pulping method. The alkalis used were Lye for one set of papers and Caustic Soda for the other set of papers.

1.9 Theoretical Framework

The study was anchored on the systems theory by Von Bertalanffy and the circular economy theory elaborated by Walter Stahel. The systems theory is a theory of production where emphasis is put on the completeness of a system rather than individual elements of a system and changing one element of the system affects the other elements (Bertalanffy, 1972). The systems theory elemental process in production is structured as input, process, and output. On the other hand, the circular economy theory by Walter Stahel is a systematic approach to economic development that is based on a regenerative design principle focused on waste elimination, extension of product life cycle, and total efficiency in production systems (Stahel, 2016). Fogarassy (2019), details how the circular economy theory contrasts with theories such as the systems theory whose processes are linear and are denoted as resource extraction, production, distribution, consumption, and waste or simply; input, process, and output.

As a reflection of these two theories production of quality banana paper packaging material will ensure optimization of each stage of production (in this case input, process, and output) while factoring waste elimination during and post-production. This means that the output stage is subjected to a regenerative design where it can be used as an input to generate either the same product or a different product thus filling the sustainability gap in the systems theory. Figure 1.1 shows an illustration of an improved systems theory, edified by the circular economy theory concept of waste elimination.

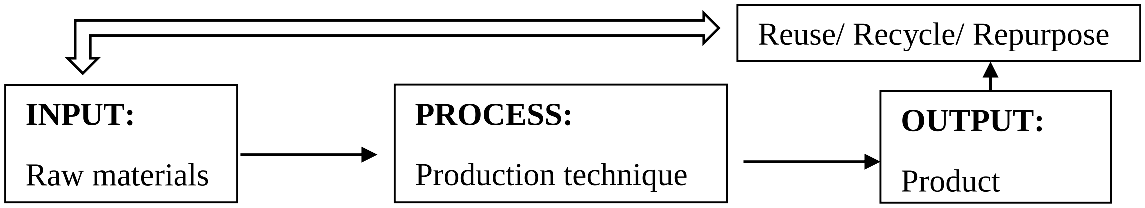

Figure 1. 1. **Improved systems theory by Von Bertalanffy adapted from the Organizational System Theory Model (from Hayajneh, 2007. p. 5)**

1.10 Conceptual Framework

The banana stem paper production is guided by the merged systems and circular economy theory (Refer to Figure 1.1). In the banana paper production process, the independent variables are banana variety and cellulose content (the input), the dependent variables are physical and mechanical paper properties that give the paper quality (the output). The delignification reagents (Lye as well as Caustic Soda) are moderating variables (part of the process) and are important as they alter the association between the independent and dependent variables (Bhandari, 2021). Essentially the quality of the banana paper was determined by the quality of the raw material. Additionally, the efficiency of the production process was enhanced as it incorporated waste elimination.

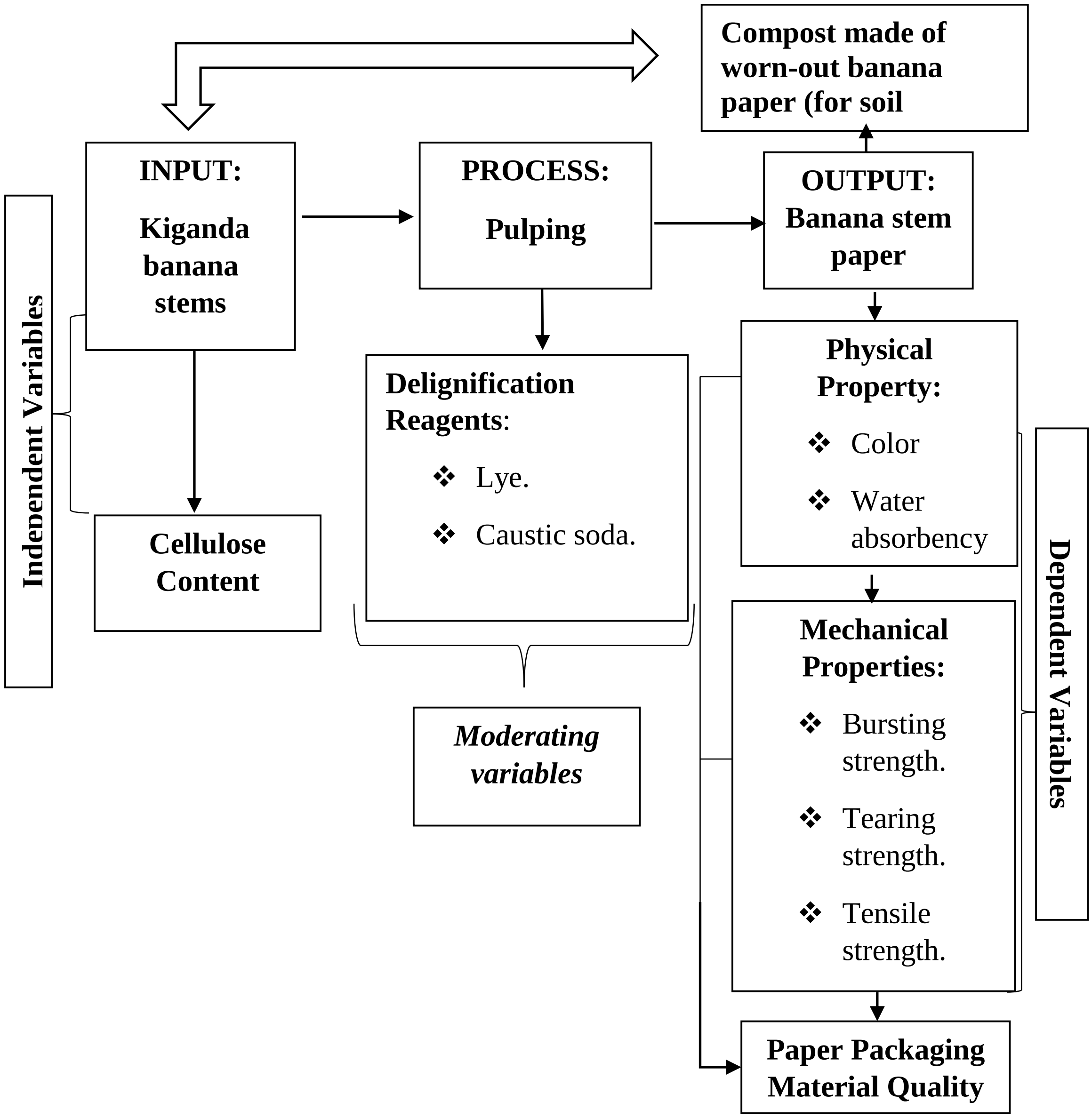

Figure 1. 2. **Relationship between Kiganda banana variety, cellulose content, delignification reagents, and packaging paper quality, illustration adapted from Organizational System Theory Model (Hayajneh, 2007. p.5)**

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter gives the insights drawn from literary works by other scholars that relate to this study. It highlights the gaps that are present in the fabrication of sustainable packaging in terms of the raw materials, methodology, and assessment of the properties of the final product.

2.1 Packaging and Sustainability

Packaging is a major constituent in litter accounting for more than half of the total weight of litter disposed (Morales-Caselles et al., 2021). In Europe alone, the total volume of packaging waste was estimated to be about 79.3 million tons in 2019 (Love, 2021). In the previous year, 359 million tons of plastic was produced for packaging, consequently less than 9% of this was recycled (Vidal, 2020).

In Kenya today the single-use plastic ban has left a gap in the packaging industry, furthermore, the increase of e-commerce in businesses has fueled demand for a range of packaging products, with biodegradable options being at the top of the list (Kisato, 2014). Plastic packaging has raised great economic concerns in Kenya due to its negative environmental effects. It caused solid waste management systems to be costly accounting for more than 40% of the revenue allocated for the municipality (Horvath et al., 2018). Getting rid of plastic bags has been impossible due to their non-biodegradability and lack of an effective disposal system (Horvath et al., 2018). Njuguna, (2018) points out that in Kenya non-biodegradable waste elements in landfills accumulate over time and thus become hazardous to people as well as the environment. This propels the bias on production of biodegradable packaging.

2.2 Plant Sources of Fiber for Packaging

The most popular plant source of fiber for packaging has inarguably been wood (Przybysz et al., 2018). A range of quality paper and packaging products are produced from wood sources and this has not been without a heavy cost. Markarian (2021), explains that the rate of deforestation has been on the rise, with about 40% of the world's traded wood being used just for making paper. This is what has made wood pulp an unfavorable fiber source for packaging. Przybysz et al. (2018), articulate that research shows that sustainability concerns have been brought up by the environmental impact from extensive use of wood. This concerns have in turn created an ongoing urgent need for analyzing the ecological footprint of wood pulp in comparison to non-wood pulp sources for the benefit of various industries.

Bhuyan and Gogoi (2020) go on to outline that one of the fashion industry’s strategies for promoting sustainability involves exploring less traditional sources of fiber to promote textile advancements. Non-wood sources of fiber for making paper have been gaining popularity over the years due to the unsustainability of wood pulp sources (Przybysz et al., 2018). This is because non-wood fibers have shown promise as alternatives to the popular wood option. For instance, Chollakup et al. (2020) established that the cellulosic pulp of rice cereal straw has a great ability to make biodegradable paper. Agricultural waste such as bagasse, wheat straw and corn stalks are highly abundant and their annual renewability makes them a possibly good replacement for wood options but they are not being fully utilized (Ghalia et al., 2020). To illustrate this further, some experiments on bagasse as a fiber source for packaging have further revealed that it is possible to derive pulp with satisfactory mechanical properties which can be used for packaging applications but bagasse packaging is still yet to be commercially produced (Mansoor et al., 2021).

Other non-wood sources include bamboo and grasses which have also presented promising outputs in terms of fiber sources for paper packaging (Abd El-Sayed et al., 2020). Non-wood fiber materials are desirable because; they grow faster, they contain lesser lignin compared to wood, they require less energy in the form of heat and chemicals for pulping, and given that they are often discarded as agricultural waste they are readily available (Abd El-Sayed et al., 2020). One such example of underutilized non-wood fiber sources are banana stems. Banana stem fibers have been determined to be potentially great fibers for various textile applications for both woven and non-woven products (Liu et al., 2018; Subagyo & Chafidz, 2018). These banana stems are usually left to rot in the farms post-harvest despite their potential to be produce viable fibers for packaging (Subagyo & Chafidz, 2018). Again, just demonstrating the neglect on potential non-wood fiber alternatives for packaging.

2.2.1 Banana Plant as a Source of Natural Fiber for Packaging

Bananas are grown mainly in hot and humid regions of a temperature of 20^0C- 30^0C, altitude of 0-1800m above sea level, 1000-2500mm of rainfall annually and well-drained soils with a pH of 5.5-6.5 (National Horticulture Board, 2021). Banana plant by-products mainly include the banana stem, leaves, rotten bananas, banana peels, and more. This biomass waste amounts to approximately 220 tons of waste per hectare (Subagyo &

Chafidz, 2018). *FAOSTAT* (2019b) recorded that in 2019 the total harvested area for bananas in Kenya was 76,912 hectares. This means that after harvesting about 16.9 million tons of banana biomass waste was produced. Banana stems are known to be great sources of textile fibers for various uses such as fabrics and paper (Tripathi et al., 2019). Banana fibers have been used in small-scale production of paper that is used for making craft paper, boxes, cardboard, currency notes, and other paper products. Banana fiber is characterized as having great elasticity, tenacity, stiffness, high moisture absorbency, and high cellulose content (Subagyo & Chafidz, 2018; Tripathi et al., 2019). Despite the facts established on the benefits of banana stems for packaging Kenya is yet to explore this green option for biodegradable packaging.

2.3 Properties of Papermaking Fibers

The properties of a fiber affect the properties of the products it will produce. Wathén, (2006) explains that since paper is made mainly by pulping which involves breaking the fibers into smaller units; it is hard for these fibers to maintain their full integrity. The fiber properties vary significantly after pulping but retain most chemical properties with the most essential for paper making being its chemical composition (Chen et al., 2021).

2.4.1. Chemical Composition

The chemical composition of natural vegetable fibers varies due to the complex nature of their compounds and also the hierarchical organization of these compounds which manifest differently in each fiber. These chemical compositions within natural fibers are diverse and even complex, thus influencing their suitability for sustainable material applications. The basic components include cellulose, hemicellulose, and lignin and very small quantities of pectin, wax, and ashes (Mishra et al., 2018).

Hemicellulose is an amorphous polymer that influences a fibers ability to bond when creating composites. It complements cellulose by contributing to its flexibility whereas lignin which is offers a plant its structural support contributes to the hydrophobic property attached to cellulose (Goh et al., 2021).

Cellulose is a linear polymer that is crystalline in nature and is contained in all plant fibers as an elemental material hence making it the most abundant organic polymer (Mishra et al., 2018). The cellulose type of the fibers determines the mechanical properties of the fiber. Cellulose is desirable in paper making because it is biodegradable, biocompatible, light in weight, pliable, and easy to fold (Mishra et al., 2018). According to Mishra et al. (2018), high cellulose content in constituent fibers is preferable because it makes them strong and durable in both dry and wet states. Banana fibers have been determined to have a relatively high cellulose content of up to 62% thus making them viable for paper-making (Goswami et al., 2008; Subagyo & Chafidz, 2018; Tripathi et al., 2019). Despite these findings on cellulose content, studies have shown that the amount of cellulose varies due to genetics and environmental factors (Zhao et al., 2022). Therefore, there is need to validate qualities of packaging material made from specific fiber varieties in relation to their cellulose content.

While significant progress has been made in characterizing the chemical composition of non-wood fibers such as banana fibers, several knowledge gaps remain. There is need for a comprehensive understanding of the variance in chemical composition across banana varieties, specifically cellulose content due to its desirable qualities.

2.5 Construction of Paper

Paper has been constructed over the years basically through the pulping technique (Hossain, Uddin, & Rahman, 2020) . This is where fibers are beaten into a pulp by either mechanical means, chemical means, or a combination of both to break down the fibers into a slurry substance known as pulp (Liu et al., 2018). To form the paper, the resultant pulp is usually matted on a base surface and dried.

2.5.1 Pulping Technique

Pulping is a process of treating and separating fibers to create pulp. According to (Hossain et al., 2020), pulp is retrieved by separating cellulose from the plant fibers by chemical or mechanical means. Pulping techniques include mechanical pulping, thermo-mechanical pulping, chemical pulping, chemo-mechanical pulping, organosolv pulping, chemo-thermo mechanical pulping, recycled pulping, and biological pulping (Liu et al., 2018).

Pulping for non-wood fibers is mainly done by chemical pulping specifically alkaline pulping. This is because research shows that methods such as thermo-mechanical pulping are unfavorable due to the energy demands and damage that the fibers sustain, thus the need for hybrid methods that combine chemical and mechanical processes to optimize fiber quality (Lian et al., 2020).

Chemical pulping has been studied widely for its ability to produce high quality fiber containing low lignin levels. Kraft pulping which is a common chemical pulping technique, has been used over a period of time with improvements of the process such as reduction in emission and black liquor recovery being made but there are still concerns on chemical waste and high energy consumption (Lian et al., 2020). Although the Kraft pulping technique has been commonly used for pulping wood, it is not as effective for non-wood fibers therefore alkaline pulping is preferred (Liu et al., 2018).

Lee et al. (2019), express that there have been experiments exploring alternative chemicals to decrease the toxicity associated with the pulping process but scaling the solutions while maintaining economic viability remains a gap.

2.5.2 Alkaline Pulping

Alkaline pulping is a form of chemical pulping that utilizes an alkaline chemical agent as an aqueous solution (cooking liquor) for the delignification process. Caustic Soda (Na OH), Lime (Ca $(OH)_2$), and Washing soda (Na_2CO_3) are common cooking liquors used for non-wood fibers (Liu et al., 2018). The technique involves preparing the alkaline solution (the cooking liquor) and then adding a given amount of the dry fibers which would then be heated for a given period to break down the lignin (Mishra et al., 2018; Liu et al., 2018). The biggest setback in alkaline pulping has been that it uses chemicals that when disposed of cause harm to the environment as well as to humans and animals. Few alternatives have been established to help mitigate this problem.

Based on various research, alkaline pulping is preferred for non-wood fibers such as banana stem fibers. This is because the alkaline pulping process of pulping non-woods is considered more efficient than other processes such as Kraft pulping (Liu et al., 2018). According to research by Nassar et al. (2021), 7% alkali concentration, 105^0C for the temperature and 120 minutes for pulping time is recommended for optimum yield in alkaline pulping.

2.5.3 Alkali Delignification Reagent

Caustic Soda is the most commonly used delignification reagent in alkaline pulping (Jiménez et al., 2019). It has been used over time due to its effectiveness in removing lignin resulting strong bright fibers. This has not been without setbacks as it has also been known to damage cellulosic fibers, causing lower paper quality and limiting paper application (Singh & Kaur, 2019). Jha et al. (2021), mention that to ameliorate the process addition of other chemicals or temperature adjustments can be introduced to improve the outcome but these factors often introduce complexities and increased costs indicating that there is a need for optimization.

In terms of fiber yield and quality research done to maximize on the same shows pulping with Caustic Soda continues to face challenges, especially non- wood fibers which are not favored by very strong alkaline levels. Furthermore, varying concentration and pulping time has proven to be a gamble where trade-offs are between achieving an efficient process while getting premium fiber quality (Sun et al., 2023). This further pushes for novel pulping conditions or a more precise and efficient process.

In various industries such as the soap-making industry Caustic Soda has been replaced with organic alkalis such as Lye. In a study by Olabanji et al. (2012), Lye was determined to be a fit replacement for Caustic Soda in soap making as it had a pH of 12.05 and 12.88, indicating it is a strong base just as Caustic Soda whose pH is 14. Research by Waithaka and Muriuki (2019) also establishes that Lye can be used as an alkali for alkali-based production such as soap making to replace Caustic Soda. This indicates that it may also be used in pulping as an alkali delignification reagent to replace Caustic Soda.

Despite, having studies that suggest mitigative measures to pacify the effect of Caustic soda very limited have attempted finding a total replacement once and for all. This highlights the need for standardized methodologies in evaluating the effect of alternative chemical treatments on factors such as yield and resultant paper properties.

2.6 Essential Properties of Paper for Packaging

These are the properties useful in evaluating the quality of paper (Popil, 2017). The requisite paper packaging properties include the physical properties: color and water absorbency and mechanical properties: bursting strength, tearing strength or tearing strength, and tensile strength (Akram et al., 2017). In general, banana stem paper has previously been described to have a lower density, higher stiffness, and good tensile strength compared to traditional wood pulp paper (Subagyo & Chafidz, 2018).

2.7 Physical Properties

These include properties that determine the appearance, compressibility, permeability, and handle of the paper (Akram et al., 2017). In paper packaging, color, and water absorptiveness are considered key properties in evaluating physical paper properties (Jirukkakul, 2019).

2.7.1 Color

The packaging of a fashion product will construct, communicate and conceive brand perceptions just by the color that it possesses (Swasty et al., 2021). It is essential to evaluate the natural color of a paper as this property affects aesthetic principles in processes such as printing and branding (Larkin, 2019). Color can be determined by various methods including visual testing, where a color of an object is established by picking out its replica on a reference color palette, sheet or board (Turk & Young, 2020; Zaidi & Bostic, 2008) . Naturally, the color of paper that has not been subjected to any form of bleaching or added pigmentation is often a shade of brown (Hu et al., 2017). The color of the paper reflects the color of the pulp and determines how additives such as bleach and dyes can be incorporated into the paper-making process for desired results (Hu et al., 2017).

The color of paper that is without any dyeing methods applied to it is influenced by the composition of its pulp. Many studies fail to report on the color of undyed paper despite being a base for exploring the increased demand on biodegradable dyes which are considered more eco-friendly (Goldsupplier, 2023).

2.7.2 Water Absorptiveness

Water absorptiveness or water absorbency is measured by the water vapor transmission rate (WVTR) which is also known as the water vapor transfer rate. In evaluating paper quality, it shows how easily moisture can penetrate through paper or rather how water is absorbed by paper (*Water Vapor Transmission Rate - Poly Print*, 2020). There are factors that determine the water absorbency rate of a given paper. These factors include but are not limited to paper thickness, chemical additives and coatings for aesthetics or function. (*Water Vapor Transmission Rate - Poly Print*, 2020).

Water absorptiveness of paper packaging is measured using a Cobb tester which uses a principle of water retention to deduce the Cobb value. It is done by exposing a conditioned dry sample with a known weight to water for a given time usually 60 seconds then draining the water, measuring the resultant weight (Tappi, 2009). The Cobb value is calculated by subtracting the initial weight from the resultant weight. This test is pertinent to establishing the suitability of papers for different functions by determining their ability to resist liquids (Popil, 2017). Often coatings and additives are infused in the paper making process to enhance water absorbency of paper products. The major challenge has been ensuring that the resultant paper product has high water resistance but still retains its biodegradability (Goldsupplier, 2023).

2.8 Mechanical Properties

Mechanical properties of paper are also considered strength properties as they determine the strength of the paper and specify its durability and resistance to applied forces (Akram et al., 2017). In paper packaging bursting strength, tearing strength, and tensile strength are considered reliable properties that can measure the permanence or life shelf of paper packaging (Akram et al., 2017; Jirukkakul, 2019).

2.8.1 Bursting Strength

Bursting strength is the minimum amount of hydrostatic pressure that is required to rupture paper (Adams, 2021). Bursting strength is a property of paper that measures how resistant it is to rupture (Adams, 2021). This property alludes to functionality of a packaging in relation to the weight or pressure that the packaging is expected to withstand. It increases with factors such as fiber type, fiber length, chemicals, and weight of paper (*Bursting Strength of Paper | Pulp Paper Mill*, 2018). The test used to measure bursting strength is known as a Mullen test or a pop test and is done on a bursting strength testing machine (Adams, 2021). The test is carried out by placing a paper packaging sample on the machine and operating it to release hydrostatic pressure to a rupture point (Adams, 2021). The pressure required rupture the sample is recorded. According to Popil (2017), this test is extremely valuable as it is one of the most common tests used for quality control in the production of papers made for various packaging products such as paper bags and envelopes.

Conventional chemical pulping methods produce weaker fibers, this demerit has led to the need to create an optimized pulping technique that would yield eco-friendly pulps to enhance the quality of fiber for paper packaging which affect its bursting strength (Smithers, 2023). The limited information on banana stem fiber paper packaging emphasizes the need to test the bursting strength.

2.8 2 Tearing Strength

Tearing strength is the resistance to ripping force by a paper. It is highly dependent on the fiber strength, extent of fiber bonding, fiber length, and filler quality and quantity (*Tear Strength of Paper | Pulp Paper Mill*, 2014). Tearing strength is a reflection of fiber quality and fiber bonding strength. To illustrate this Popil (2017) explains that if a paper is torn one can see fibers protruding through the edges of the tear, indicating that in this case fiber bonding strength is less than the individual fiber fracture strength. This confirms the value of the tearing strength test as it indicates the extent of fiber bonding in a paper. An increase in tearing strength means an increase in fiber bonding which is attributed to factors such as fiber length and fiber strength (Popil, 2017). Tearing strength is measured using a tear testing machine or Elmendorf testing machine. It is retrieved by accounting for the work done by a pendulum to tear an initial cut on a mounted paper packaging sample (Popil, 2017).

Some non-wood fibers such as bamboo and hemp have been established to have high tearing strength even in composites, however it is recommended that the same for niche paper applications such as for packaging and recycled paper tearing strength should be established to assess cost and performance (Padmanabhan et al., 2024). This tearing strength of these non-wood fibers just as mentioned earlier, could be attributed to their fiber length and strength, an illustration that even when establishing tearing strength for banana stem fiber paper it would indicate inherent fiber length and strength. Studies on the performance banana stem fiber paper as it relates to tearing strength alongside other properties remain sparse thus revealing a gap area.

2.8.3 Tensile Strength

Tensile strength is the amount of force required to rupture a strip of paper. It is an important property as it is also a great indicator of fiber length, strength, and bonding. It can be used to measure how well a paper can withstand printing or converting which are important processes for packaging (Akram et al., 2017). A tensile test is used to measure tensile strength and for paper packaging it is done using a tensile testing machine. Typically, for paper packaging the test is done by mounting a sample on a fixed gauge on a tensile testing machine which is pulled out by a moving gauge to a breaking point. Popil (2017) outlines that this test is considered an important measure of paper quality as it gives a measure of elasticity which is directly related to fiber quality and level of fiber bonding.

Different studies have highlighted tensile strength of non-wood fiber paper that has been made using fibers such as abaca and bamboo but have barely outlined the same for banana stem fiber paper especially the type crafted for packaging.

2.9 Summary of Literature Review

The above literature stipulates that in Kenya there is a great need for non-wood biodegradable packaging because just as it is globally the main source of biodegradable packaging material is wood pulp, which is unsustainable as it promotes deforestation (Markarian, 2021; Przybysz et al., 2018). Additionally, various studies reveal that non-wood fiber sources such as banana stems have not been fully exploited despite having been proven to be great sources of cellulosic fiber suitable for making paper (Abd El-Sayed et al., 2020; Chollakup et al., 2020; Przybysz et al., 2018). This therefore makes it relevant to further explore banana stem fibers as non-wood sources of fiber for paper.

The following gaps have been identified:

1. Non- wood fiber sources of packaging such as banana stems have been explored in limited studies despite their potential in replacing wood sources whose utility has raised environmental concerns on sustainability.
2. The biggest setback in alkaline pulping has been that it uses chemicals such as Caustic Soda that when disposed cause harm to the environment as well as to humans and animals. Few studies have extensively explored other alkaline alternatives such as Lye to mitigate the problem (Liu et al., 2018; Olabanji et al., 2012; Waithaka & Muriuki, 2019).
3. Exploration of banana peels as a source of Lyefor pulping will be beneficial in adding value to yet another underutilized by-product of banana farming. Thus, this called for experimentation with this Lye as a delignification reagent in the pulping process of making banana fiber paper.

4. The literature also reveals that the quality of paper can be classified to be good if it has great physical and mechanical properties (Akram et al., 2017; Popil, 2017). Despite that, limited studies outline the properties of banana stem paper. This therefore indicated the need to measure the essential physical and mechanical properties of banana stem paper packaging material to assess its quality.
5. Limited studies highlight the metrics of the decortication, pulping, and fabrication processes in the making of paper packaging material. This is addressed in this study.

It is distinct that banana waste though underutilized, has the potential of creating an alternative biodegradable paper packaging material to supplement the limited options available.

CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter describes the methodology used to identify, select, process, and collect data. It includes information on; research design, measurements of variables, study area, collection of stems, research instruments, validity and reliability, data collection procedures, data analysis and presentation, and logical and ethical considerations.

3.1 Research Design

The research design for this study was an experimental one. Rogers and Révész (2019) describe an experimental design as a research design where you examine the effects of the change of independent and or moderating variables on the dependent variables. They further state that for contrast a control group must be included. In this study the independent variables were banana variety and cellulose content, the moderating variables were the Lye and Caustic Soda and the dependent variable was paper packaging material quality measured through selected physical and mechanical properties against the control variables. The control was standard biodegradable Kraft paper packaging from KEBS whose physical and mechanical properties were already recorded under the KEBS EAS 859:2017 standard. The control KEBS EAS 859:2017 standard minimum requirements are listed in Appendix B.

3.2 Measurement of Variables

The variables were measured as follows: a baseline study was conducted in five counties to determine the banana variety (Refer to Appendix A). The baseline was done to identify the most popular banana variety, Kiganda banana variety was established as the most prevalent (Refer to Appendix A). Chemical characterization of Kiganda stems from the five counties revealed that Kiganda from Kisii had the highest cellulose content (See Appendix A). Paper packaging quality was established by determining selected physical and mechanical properties of the paper packaging material under standard conditions of 65% ± 2% humidity and temperature of 20^0C ± 2^0 C. For the physical properties; color testing was done by a visual test which involved identifying the color of the paper packaging material using a Pantone color chart. A Cobb testing machine was used for water absorbency g/m^2 (grams per square meter) under the standard; KS ISO 535. For the mechanical properties, each was tested using the following equipment: a Frank bursting strength tester for bursting strength kPa (kilopascals) under the standard; KS ISO 2758, a TexTest-FX 3750 Elmendorf tester for tearing strength mN (millinewtons) under the standard; KS ISO 1974 and a Tinius Olsen tensile testing machine for tensile strength N/mm (which is Newton per millimeter) under the standard; KS ISO 12625-4. For the Lye and the Caustic Soda, 7% of the concentration was prepared, and alkalinity and pH were tested (Soult, 2020). Refer to Appendix B & C.

3.3 Study Area

The banana stems were collected from Kisii County which was determined in the baseline study to have Kiganda banana variety (the most popular variety) with a very high cellulose content (See Appendix A). Kisii County was selected among five counties that were determined to be the major banana growing areas in Kenya. These were Embu, Kakamega, Kirinyaga, Kisii and Muranga (Wahome et al., 2021).The packaging material was constructed by the researcher in the National Research Fund (NRF) textile workshop at the Kenya Industrial Research and Development Institute (KIRDI). The paper packaging material was tested at the KEBS packaging laboratory in Nairobi which offers reliable testing conditions and is accredited by the International Standards Organization (ISO).

3.4 Collection of Banana Stems

40 one-meter Banana stems of the Kiganda variety were collected by the researcher from various farms in Kisii County as it was determined to be the County with the most popular variety (Kiganda variety) with the highest cellulose content (Refer to Appendix A). The banana stems for the sample were purposively collected from specific participants who had the Kiganda banana variety since not all farms had the Kiganda banana variety. These stems were cut into pieces of 1 meter, which was measured from the base of the stem where it was cut due to its uniformity and was done to ensure ease of transportation and handling during decortication (Mumthas et al., 2019).

Forty (40) one-meter stems weighing an average of 160kgs was estimated to be able to give (4,324g) of dry fiber enough to produce 80 A4 paper sheets of 50g each which will need a total of (4,000g). This is drawn from the findings that stems of 37kgs produce 1Kg of fiber (*Banana Fiber*, 2021). The stems collected were those that had matured after 9 months and the banana fruits bananas had been harvested. The stems were cut from 30 inches above the ground level to ensure regeneration of the banana plant (Carter, 2020; Bhende & Kurien, 2016). The process is presented in Figure 3.1.

3.4.1 Exclusion criteria

The Inner core sheaths of the banana stem were excluded since they contain weak fibers with lower cellulose content and more ash content (Pereira et al., 2014).

3.4.2 Inclusion criteria

The sheaths from the collected stems were taken apart, the outer and middle sheaths were selected, leaving out the inner sheaths. This is because these sheaths have stronger fibers with higher cellulose content (Pereira et al., 2014). The process is presented in Figure 3.1.

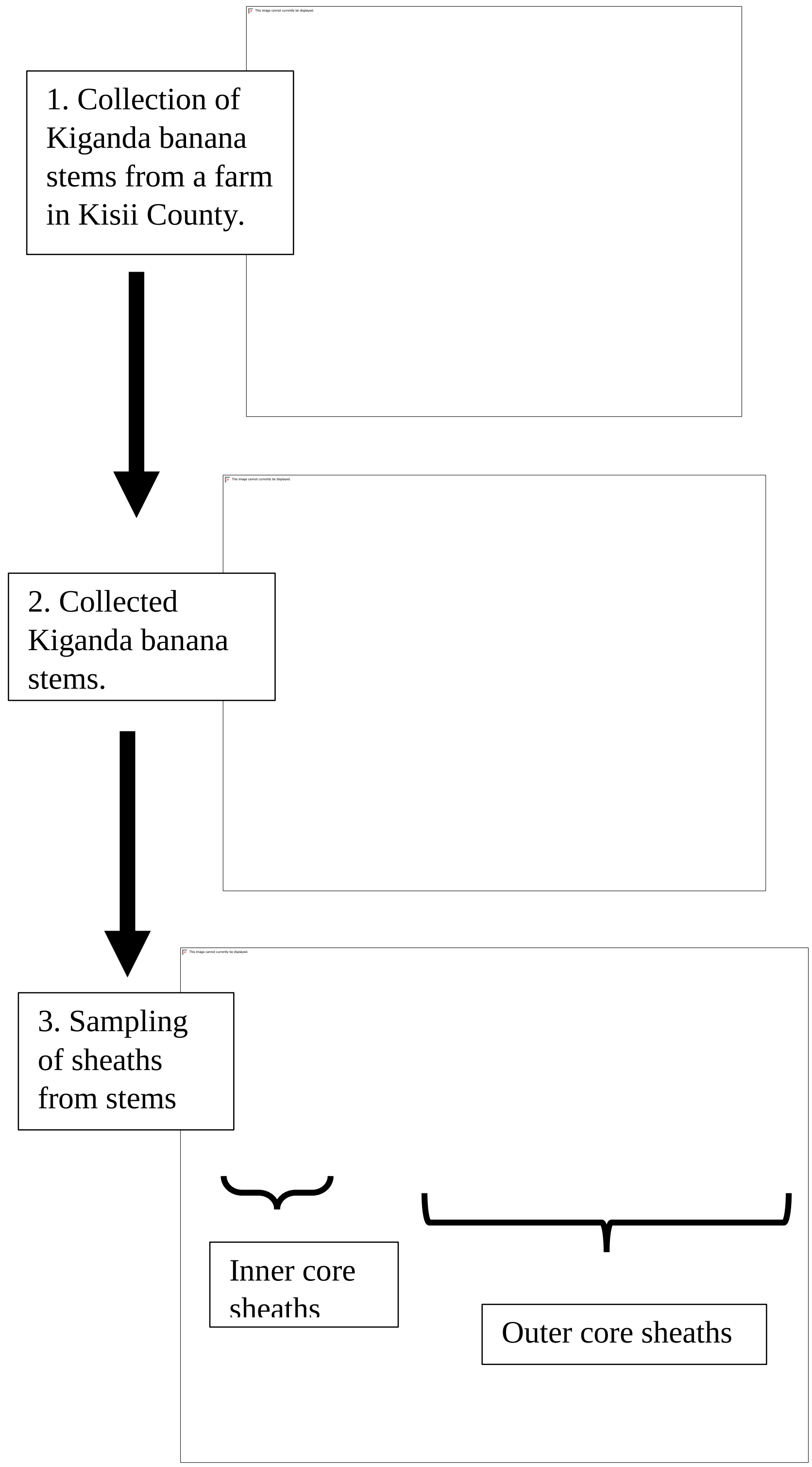

***Figure 3. 1*. The Process of Collection and Sampling of Banana Stems**

Source: Photograph by the researcher at a KIRDI workshop in 2022

3.5 Research Instruments

The research instruments for this study were: a Cobb testing machine for water absorbency (g/m^2) under the standard; KS ISO 535, a Frank bursting strength tester for bursting strength (kPa) under the standard; KS ISO 2758, a TexTest-FX 3750 Elmendorf tester for tearing strength (Mn) under the standard; KS ISO 1974 and a Tinius Olsen tensile testing machine for tensile strength (N/mm) under the standard; KS ISO 12625-4. The instruments were all from the KEBS testing labs. The KEBS labs were selected because they provide services that are verified. This equipment was used to establish the selected physical and mechanical properties of the paper packaging material.

Additionally, tools and apparatus used included a decorticator for extraction of fibers (Appendix D), for pulping: a bio-digester (Appendix E), an electric mechanical pulper for blending (Appendix F), cooking sticks, a large water trough, and buckets. Tools and materials for constructing the paper packaging material included: a flat firm table, a 1.5-liter calibrated measuring jug, an A4 size mold, and deckle, cardboards (3m by 1m), a sponge, cutter or scissors, a basin, buckets and 5 cotton cloths (1m by 1m).Table 3.1 on the next page also specifies equipment, materials, and tools used for the physical and mechanical tests.

Table 3. 1 ***Equipment, Materials, and Tools for the Physical and Mechanical Tests***

TEST	**EQUIPMENT, MATERIALS AND TOOLS**
Color	*A Pantone color chart*
Cobb Test	*Cobb tester, stopwatch, graduated cylinder, balance machine, distilled water, bloating paper, and circular cutter.*
Bursting Strength	*A Frank bursting strength tester, a ruler, and a pair of scissors.*
Tearing strength	*A TexTest-FX 3750 Elmendorf tearing machine, paper scissors, ruler, and sample stencil mold.*
Tensile Strength	*A Tinius Olsen tensile testing machine, ruler, cutter/ scissors.*

3.6 Validity and Reliability

To ensure the validity of the process the researcher consulted with experts in Biochemistry, lecturers in the field of fashion design and marketing, and technicians from KEBS for guidance on procedures and measures. The testing of the packaging paper material was carried out in KEBS-conditioned laboratories under standard conditions of temperature of $20^{0}C \pm 2^{0}C$ and 65% ± 2% humidity (Parameter Generation & Control, 2023). This enhanced the accuracy of the results. These tests were carried out in compliance with set KEBS EAS 859:2017 standard minimum requirements so that all procedures were standardized. For reliability, all measurements were triplicated and results were averaged to reduce the impact of analytical imprecision (Mohajan, 2017).

3.7 Data Collection Techniques

Observations and measurements were taken in the decorticating, pulping, and paper construction phases. These were recorded in the form of photographs and manual recording of measurements and findings. The testing of the packaging paper material was carried out in KEBS-conditioned laboratories under standard conditions of temperature of $20^0C \pm 2^0C$ and 65% ± 2% humidity. Data was collected using the testing equipment which included a Pantone color chart, a Cobb testing machine for water absorbency g/m^2 under the standard; KS ISO 535, a Frank bursting strength tester for bursting strength kPa under the standard; KS ISO 2758, a TexTest-FX 3750 Elmendorf tester for tearing strength mN under the standard; KS ISO 1974 and a Tinius Olsen tensile testing machine for tensile strength N/mm under the standard; KS ISO 12625-4 sourced from KEBS because they provide services that are verified. All measurements were triplicated and averaged to reduce the impact of analytical imprecision.

3.7.1 Fiber Extraction through Decortication

In this stage the researcher first separated the sheaths of the 40 banana stems to isolate the inner core layers from the outer layers. The first 10-13 layers are what were needed, the inner core layers were excluded as they are weak and have low cellulose content.

The selected sheaths were decorticated on a decorticating machine to isolate the fibers from the matrix thus removing most of the lignin. The resultant fibers were sun-dried to remove remaining moisture and to bleach the fibers naturally. The dried fibers weighed a total of 4,200 g on a weighing scale. The dry decorticated banana stem fibers were chopped into bits of approximately 3cm by 3cm. The process is presented in Figure 3.2.

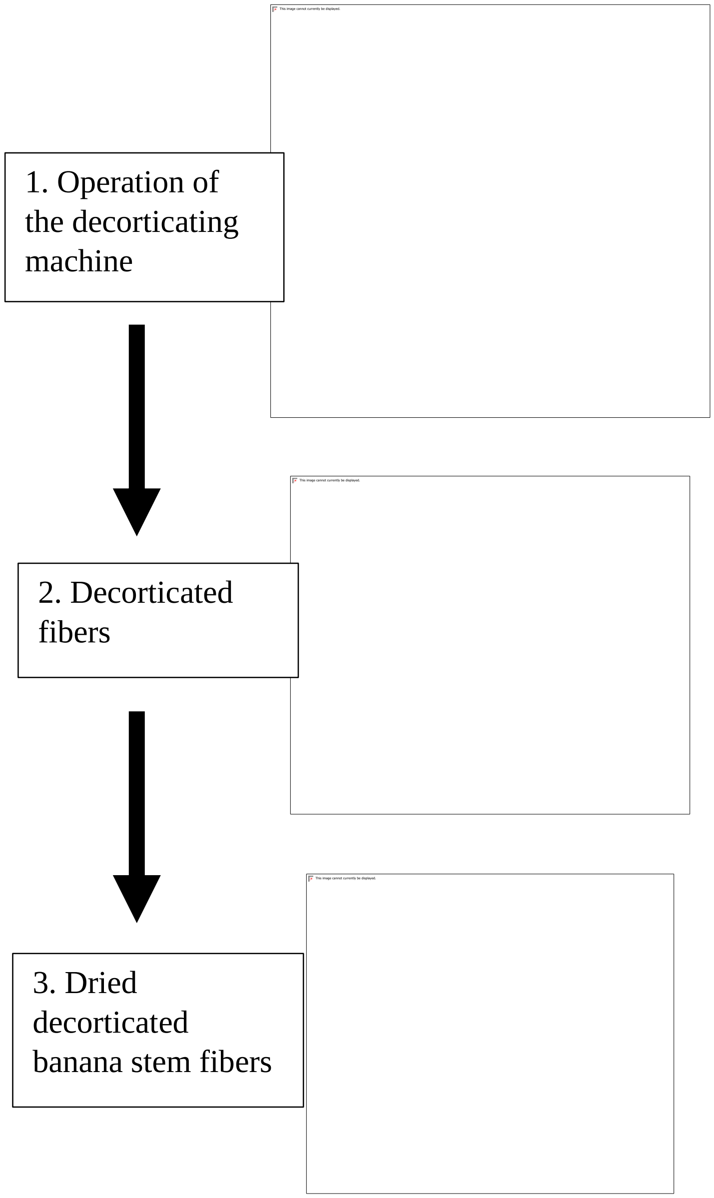

***Figure 3. 2*. Decorticating and Drying of Banana Stem Fibers**

Source: Photograph by the researcher at a KIRDI workshop in 2022

3.7.2 The Alkaline Pulping Process

The alkaline pulping process was done under the standard conditions of 65% ± 2% humidity and a temperature of 20^0C ± 2^0 C. The time taken, the amount of fiber, and the concentration of the delignification reagents were kept constant. However, the type of delignification reagent was varied, that is one pulping process utilized [Lye and the other Caustic Soda] to assess the delignification ability of the Lye against that of the Caustic Soda, was used in this study because is the most commonly used delignification reagent in alkaline pulping (Jiménez et al., 2019). The Lye was obtained from dried banana peel ash, refer to Appendix C. The Caustic Soda was purchased from a commercial chemicals store. In terms of the concentration 7% was prepared as it was determined to be suitable for optimum yield to Nassar et al. (2021) .

According to Kalyoncu (2022), the fiber to liquor ratio used was 1:6 thus determining that the ratio of the fiber: 7 % concentration of alkali as 1: 0.48, this meant that the ratio of fiber (g): alkali (g): distilled water (g) for 7% concentration is 1:0.48:6. For pulping with the Lye, the materials included; 2000g of dry banana stem fiber (Chopped), 960g of Lye and 12 liters of distilled water. The ratio of fiber (g): alkali (g): distilled water (g) for 7% concentration is 1:0.48:6. Distilled water was used to ensure the experiment is not affected by minerals and other impurities which could skew the results (Clifton, 2024).

In order to get 7% concentration for the Lye, the mass of solute in the solution was determined then multiplied by 100%. Soult (2020), describes the formula for the concentration as below:

Percent concentration by mass = mass of solute/mass of solution×100%

= 960/12960×100= 7.4 approximated to 7%

The same was applied for pulping with the Caustic Soda where the materials included; 2000g of dry banana stem fiber (Chopped), 960g of Caustic Soda, and 12 liters of distilled water. The ratio of fiber (g): alkali (g): distilled water (g) for 7% Concentration is 1:0.48:6.

Likewise in order to get 7% concentration for the Lye, the mass of solute in the solution was determined then multiplied by 100%. Soult (2020), describes the formula for the concentration as below:

Percent concentration by mass = mass of solute/mass of solution×100%

= 960/12960×100= 7.4 approximated to 7%

Tools and apparatus used included: a bio-digester, an electric blender, cooking sticks, a large water trough, and buckets. To prepare the liquor, 960g of the alkali (either Lye or Caustic Soda) was added to 12 liters of water. The mixture was stirred thoroughly to ensure all the alkali dissolved. 2 kg of dry banana stem fibers were measured on a scale. The fibers were then put in the bio-digester. The alkali liquor was added to the fibers in the bio-digester and mixed using a cooking stick. The temperature of the bio-digester was set at 105^{0}C then the mixture was allowed to cook for 120 minutes. The cooking process optimizes the removal of remnant lignin and impurities by softening the fibers thus enabling optimal chemical reaction. The resultant solution known as the cooking liquor was removed from the bio-digester then it was washed thoroughly several times under running water to purify the pulp. The cooked fibers were then dried and weighed to determine the fiber yield. The fibers were then soaked in water for 18 hours before they were blended into a smooth pulp using an electric blender to beat down the fibers into a smooth pulp. Soaking was done to ensure the fibers remain turgid and are easier to break down in a blender. The process is presented in Figure 3.3.

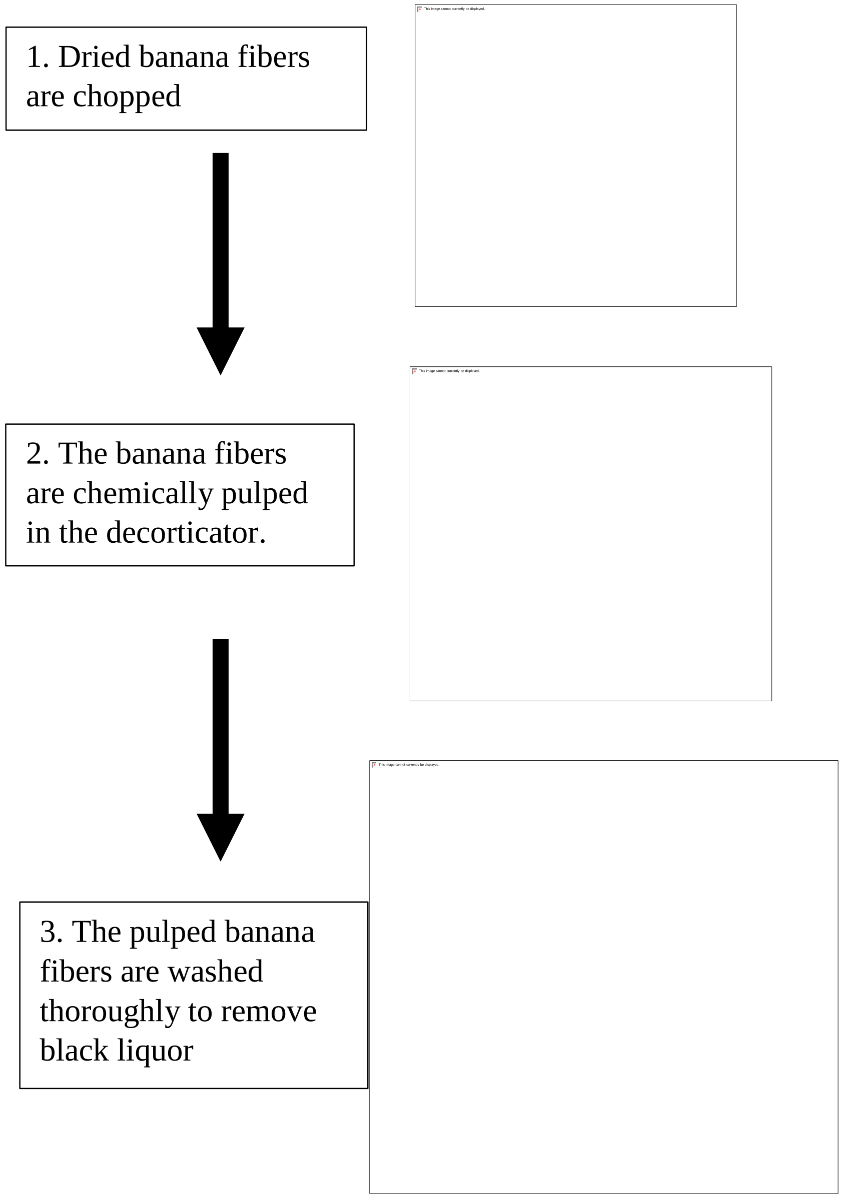

Figure 3. 3. **Chemical Pulping of Dry Banana Stem Fibers**

Source: Photograph by the researcher at a laboratory in KIRDI in 2022

3.7.3 The Paper Packaging Material Construction Process

The paper packaging material was constructed using a handmade craft method. Each of the 4 tests demanded a minimum of 5 sheets therefore a minimum of 20 sheets was required for testing samples from one process (that is Lye or Caustic Soda). In order to cater for faults and errors the researcher constructed 40 sheets for the Lye sample tests 40 sheets for the Caustic Soda sample tests. This informed the construction of 80 sheets, that is 40 sheets for the Lye sample tests and 40 sheets for the Caustic Soda sample tests.

3.7.4 The Lye Paper Packaging Material Construction Process

The method employed was adapted from methods specified by Babcock (2020) and TAPPI (2002). For this, the requirements included: a flat firm table, a 1.5-liter calibrated measuring jug, an A4 size mold and deckle, cardboards (3m by 1m), a sponge, cutter or scissors, a basin, buckets and 5 cotton cloths (1m by 1m).

In the calibrated measuring jug, 500ml of Lye treated pulp was measured, and 1 liter of water was added to increase the viscosity of the pulp which in turn ensures a homogenous, even layer when laying out on the mold and deckle. The Lye treated pulp-water mixture was then poured onto a mold and deckle which was mounted on a sturdy basin where the water would drain out. Once most of the water had drained out and the Lye treated pulp was settled the mold and deckle were placed carefully onto the table top.

The deckle was removed and the Lye treated pulp on the mold was transferred to an even layered piece of cotton fabric by laying the fabric over the mold and turning it over such that the mold lay on top of the fabric. This is done to transfer the Lye treated pulp and absorb any excess water held by the mold and deckle. The Lye treated pulp on the cloth was then transferred in the same way onto the cardboard to dry. The excess water was removed using a sponge. This procedure was repeated for the 40 sheets of paper. The Lye treated pulp preparation, laying of pulp on mold and deckle, and couching took an average of 12 minutes in total for each sheet of paper.

The Lye treated pulp sheets on the cardboards were left to air dry outdoors in the sun (on a day of average temperature 24^0C) on the cardboard for 8 hours then were carefully peeled out when completely dry to get the paper packaging material. The edges were then trimmed using a cutter and scissors. The process is presented in Figure 3.4.

3.7.5 The Caustic Soda Paper Packaging Material Construction Process

Similar to the Lye treated pulp, the method employed to construct paper packaging from the Caustic Soda treated pulp was adapted from methods specified by Babcock (2020) and TAPPI (2002). For this, the requirements included: a flat firm table, a 1.5-liter calibrated measuring jug, an A4 size mold and deckle, cardboards (3m by 1m), a sponge, cutter or scissors, a basin, buckets and 5 cotton cloths (1m by 1m).

In the calibrated measuring jug, 500ml of pulp was measured, and 1 liter of water was added to increase the viscosity of the pulp which in turn ensures a homogenous, even layer when laying out on the mold and deckle. The Caustic Soda treated pulp-water mixture was then poured onto a mold and deckle which was mounted on a sturdy basin where the water would drain out. Once most of the water had drained out and the Caustic Soda treated pulp was settled the mold and deckle were placed carefully onto the table top.

The deckle was removed and the Caustic Soda treated pulp on the mold was transferred to an even layered piece of cotton fabric by laying the fabric over the mold and turning it over such that the mold lay on top of the fabric. This is done to transfer the Caustic Soda treated pulp and absorb any excess water held by the mold and deckle. The Caustic Soda treated pulp on the cloth was then transferred in the same way onto the cardboard to dry. The excess water was removed using a sponge. This procedure was repeated for the 40 sheets of paper. The Caustic Soda treated pulp preparation, laying of pulp on mold and deckle, and couching took an average of 12 minutes in total for each sheet of paper.

The Caustic Soda treated pulp sheets on the cardboards were left to air dry outdoors in the sun (on a day of average temperature 24^{0}C) on the cardboard for 8 hours then were carefully peeled out when completely dry to get the paper packaging material. The edges were then trimmed using a cutter and scissors.

The construction process is presented in Figure 3.4

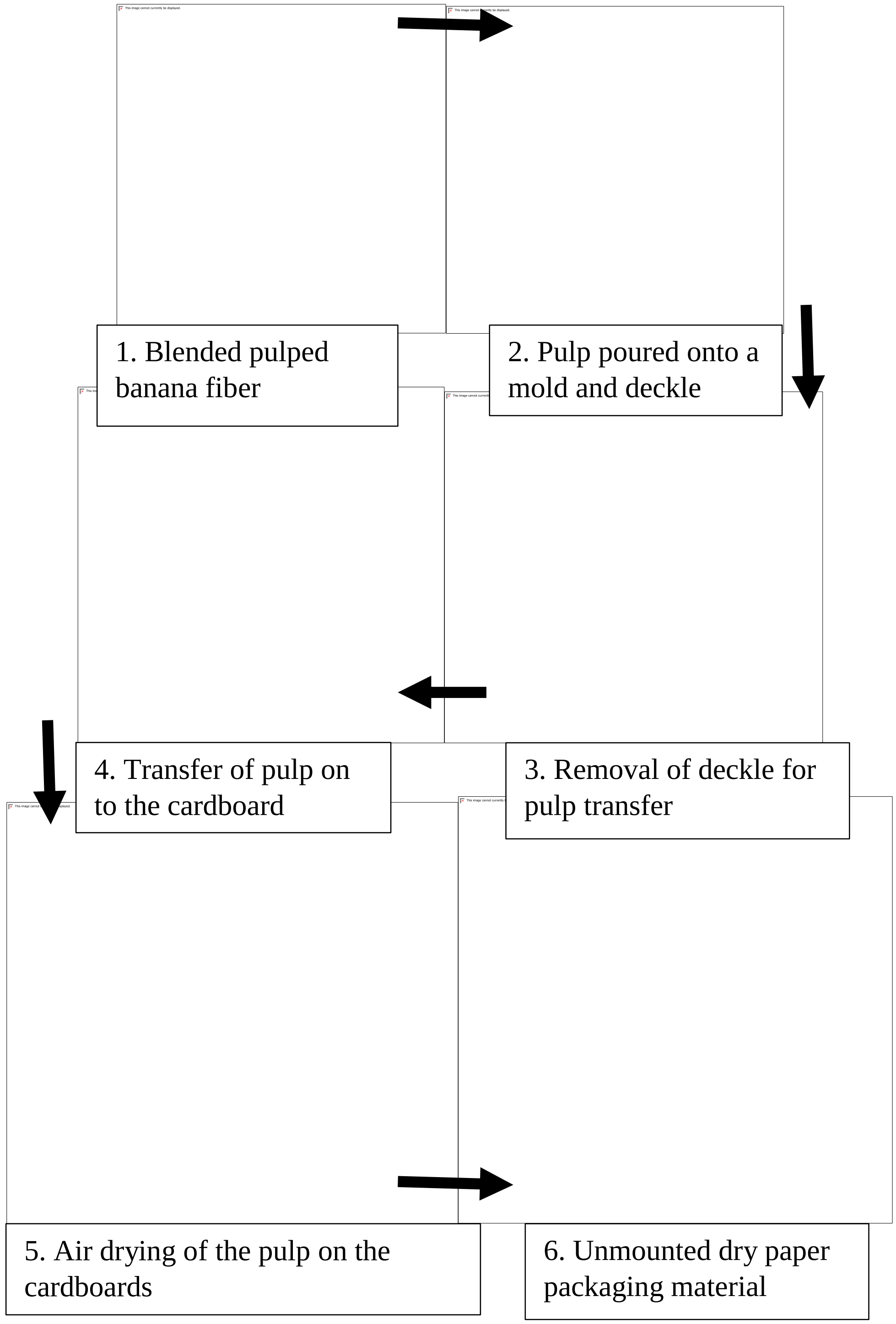

Figure 3. 4. **The Paper Construction Process**

Source: Photograph by the researcher at KIRDI in 2022

3.7.6 Color

A Pantone color chart was used by the researcher to determine the color shade of the paper packaging material by being laid side by side (Turk & Young, 2020; Zaidi & Bostic, 2008). A Pantone color chart of brown shades was selected as the closest to mimic natural banana Kraft paper. A visual test was done to select from the Pantone color chart the color shade that is similar to that of the packaging material. The Pantone color chart used is shown in Figure 3.5.

Figure 3. 5. Pantone Color Chart for Used Color Determination on Visual Survey

Source: https://icolorpalette.com/43200e_bb9e7d_be8959_4a3c2e_996a4f

The Lye and Caustic Soda Kiganda banana stem (KBS) paper packaging material (**P1 & P2**) are juxtaposed against the Pantone color chart with various color codes for various shades of brown coded as **A**; deep oak (#43200e), **B**; mongoose/ sand brown (#bb9e7d), **C**; twine (#be8959), **D**; Mondo (#4a3c2e) and **E**; leather (#996a4f) (iColorpalette, 2022) this is shown in Figure 3.6.

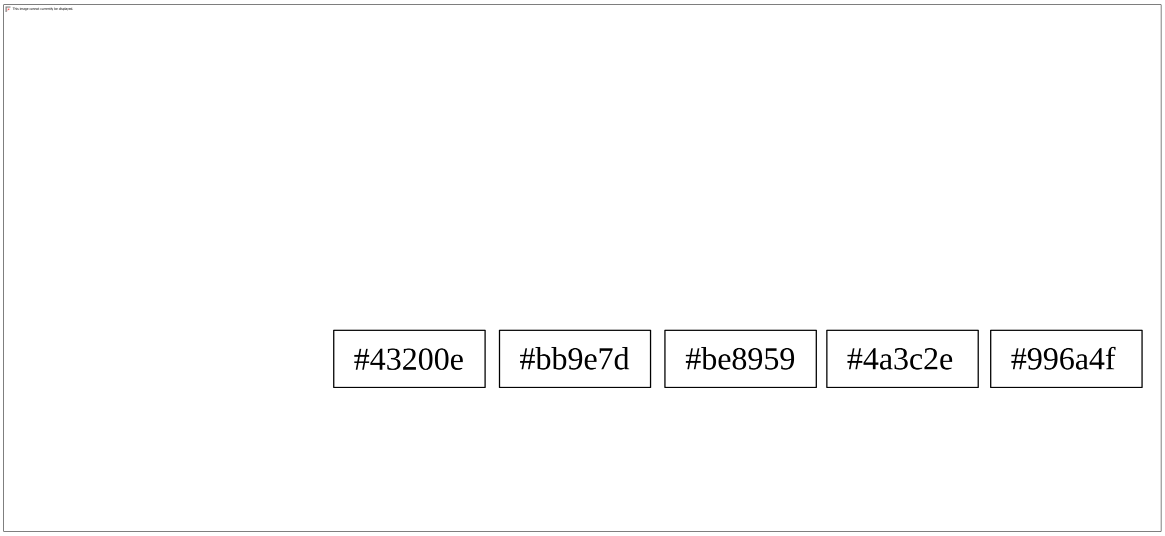

Figure 3. 6. The Paper Packaging Material (P1 & P2) Juxtaposed against the Pantone Color Chart

Source: https://icolorpalette.com/43200e_bb9e7d_be8959_4a3c2e_996a4f

3.7.7 Water Absorbency

This is a test that tests the ability of a paper to resist penetration of water by determining its absorbency over a specified amount of time. This test was done according to the KS ISO 535 standard. This test was done for both the Lye paper packaging samples and the Caustic Soda paper packaging samples. The procedure below outlines the process for a singular test.

Materials, tools, and apparatus included: Cobb tester, stopwatch, graduated cylinder, balance machine, distilled water, bloating paper, and circular cutter.

i. Sample Preparation

Sample preparation was done by the researcher and a KEBS laboratory technician.5 circular sample papers were cut using a circular cutter. The standard area of the circle was

100 cm^2. The samples prepared were checked to ensure they were free from folds, wrinkles, or blemishes that were not inherent in the paper.

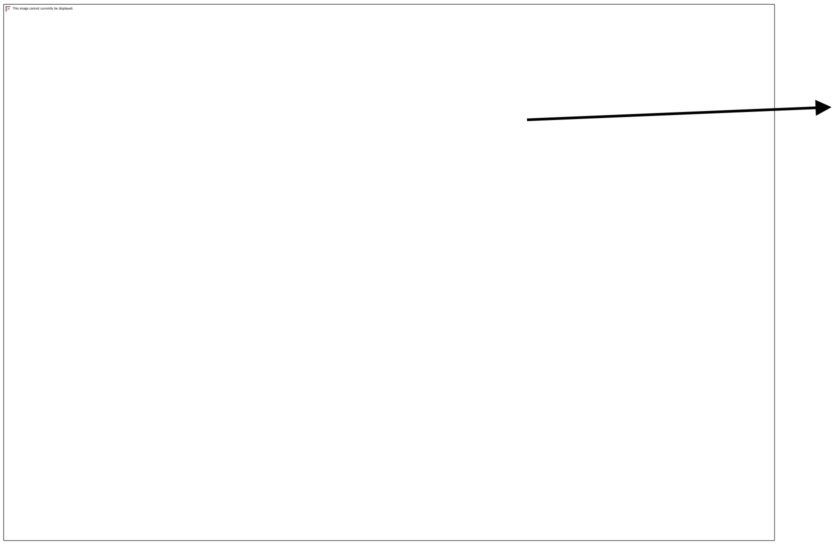

Figure 3. 7. Sample Preparation for Water Absorbency

Source: Photograph by the researcher KEBS laboratory in 2023

ii. Procedure

Each sample paper was weighed to the nearest 0.01g because the area of the sample used was 100 cm^2 (0.01 m^2) this was done to equate the result to the unit for Cobb value; grams per square meter (g/m^2) by multiplying the final result by 100 (Tappi, 2009).

One of the weighed sample papers was mounted on the removable ring cylinder on the cob test machine. The sample was clamped firmly to prevent any leakage between the sample and the cylindrical rings from taking place. The removable cylindrical ring was mounted onto the fixed cylindrical ring.

100 ml of distilled water (of temperature 23 ± 1^0C) was poured into the removable cylindrical ring as rapidly as possible taking care not to drip any water on the outside portion of the sample. The stopwatch was started immediately and the sample stayed for 60 seconds. Samples that showed signs of leakage or spillage were rejected because they would affect the precision of the results since they were exposed to a different volume of water i.e., less than 100ml.

After 50 seconds that is just at 10 ± 2 seconds before time elapsed, the water was poured out rapidly. The fastening system was loosened the sample paper was removed from the cylindrical ring and placed in between two bloating papers on a flat surface. With the help of the roller excess water was drained by rolling it once forward on the paper sample and once in the backward direction, ensuring you exert no added pressure. This was done for 60 seconds. This was repeated for 3 samples for reliability and to reduce the impact of analytical imprecision and an average of the three results was taken.

The sample paper was weighed to the nearest 0.01g because the area of the sample used was 100 cm^2 (0.01 m^2) this was done to equate the result to the unit for Cobb value; grams per square meter (g/m^2) by multiplying the final result by 100.

The Cobb value was calculated by the formula:

(Final weight of sample paper – Initial weight of sample paper)

To obtain the weight of water absorbed in grams per square meter g/m^2 the following formula was used:

(Final weight of sample paper – Initial weight of sample paper) × 100

To obtain the water absorption percentage: the following formula was used:

(Final weight of sample paper – Initial weight of sample paper)/ Initial weight of sample paper $\times$ ***100***

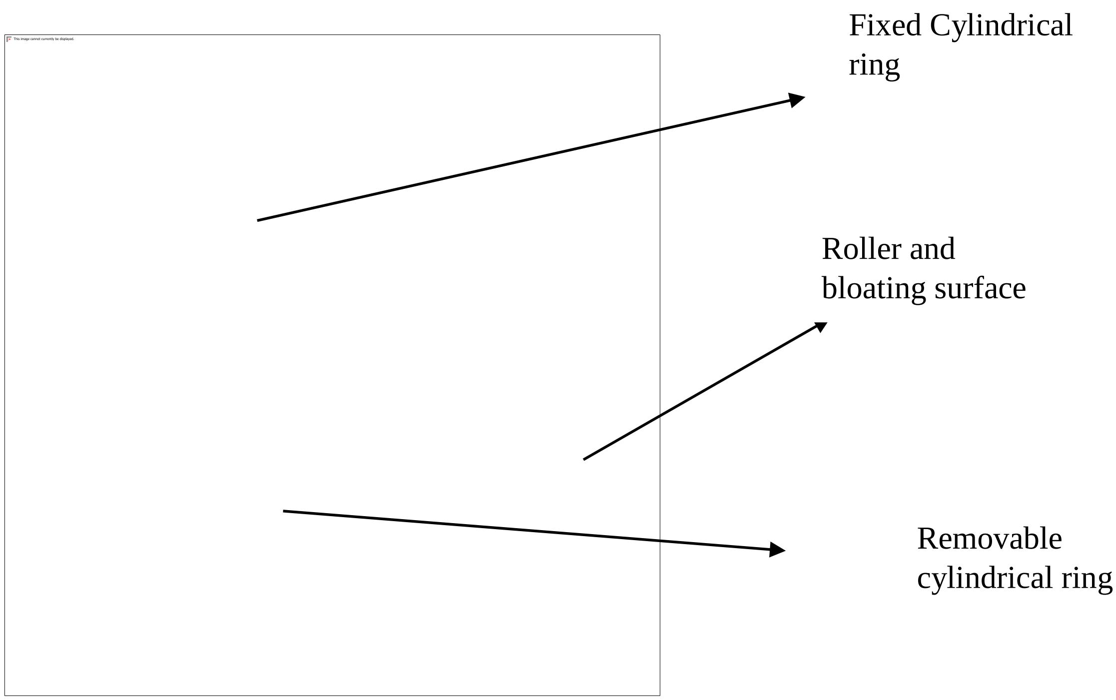

Figure 3. 8. **Cobb Tester**

Source: Source: Photograph by the researcher KEBS laboratory in 2023

3.7.8 Bursting Strength

The bursting strength test is a test used to measure a papers resistance to rupture. It measures the maximum hydrostatic pressure required to rupture a material when a controlled amount of increasing pressure is applied through a rubber diaphragm to a circular area. This test was done according to the KS ISO 2758 standard. The testing of the packaging paper material was carried out in KEBS-conditioned laboratories under standard conditions of temperature of $20^0C \pm 2^0C$ and 65% ± 2% humidity (Parameter Generation & Control, 2023).

Materials, tools, and apparatus include a Frank bursting strength tester (Figure 3.6), a ruler, and a pair of scissors.

i. Sample Preparation

10 sheets of A4 size paper for samples were randomly selected for testing, they were checked to ensure that they had no creases, folds, or visible damage.10 samples of A5 size papers were cut from the sheets (SGS-IPS Testing, 2018).

ii. Procedure

The paper sample was secured on the bursting strength tester by clamping it in position ensuring that it overlapped all clamp sections and that the sample being tested was over the opening in the lower clamping surface of the bursting strength tester.

The machine was started to apply hydrostatic pressure as required, till the paper ruptures. The maximum pressure attained at rupture was recorded. The pressure indicator was gently returned to zero after each test was done then the procedure was repeated for 5 sample papers. 3 successful test results were selected.

The average results for the 3 tests were done and the bursting strength was recorded in kilopascals (kPa) this was done to ensure reliability and to reduce the impact of analytical imprecision (Mohajan, 2017).

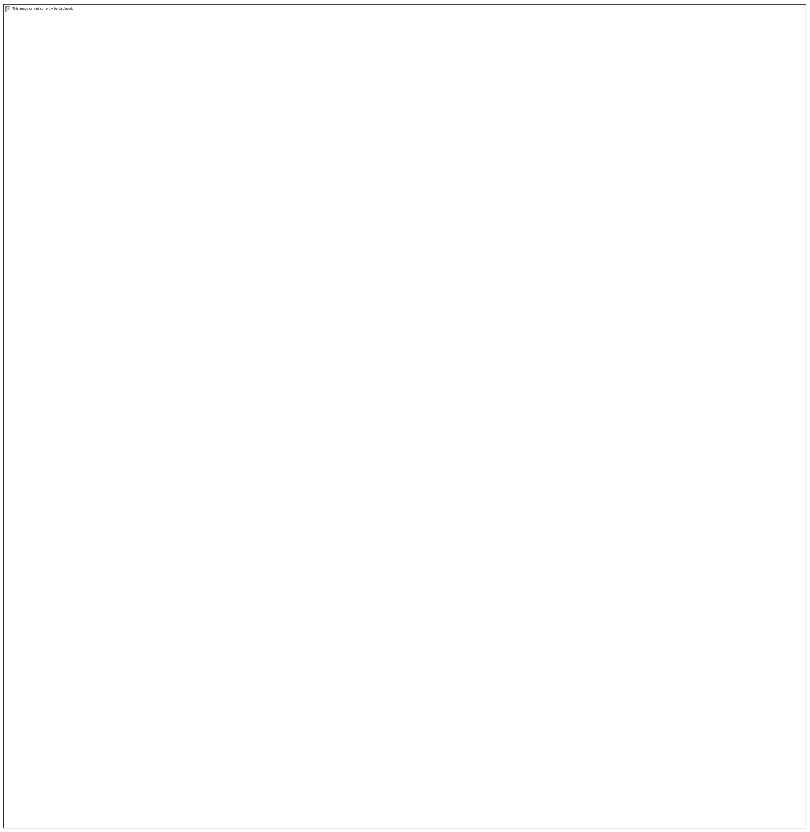

***Figure 3. 9*. Bursting Strength Tester**

Source: Photograph by the researcher KEBS laboratory in 2023

3.7.9 Tearing Strength

The tearing strength test is a test for the mean force per sheet required to continue tearing the tear started by an initial cut in the piece being tested. This test was done according to the KS ISO 1974 standard. The testing of the packaging paper material was carried out in KEBS-conditioned laboratories under standard conditions of temperature of $20^0C \pm 2^0C$ and 65% ± 2% humidity (Parameter Generation & Control, 2023).

Materials, tools, and apparatus included: TexTest-FX 3750 Elmendorf tearing machine, paper scissors, ruler, and sample stencil mold.

i. Sample Preparation

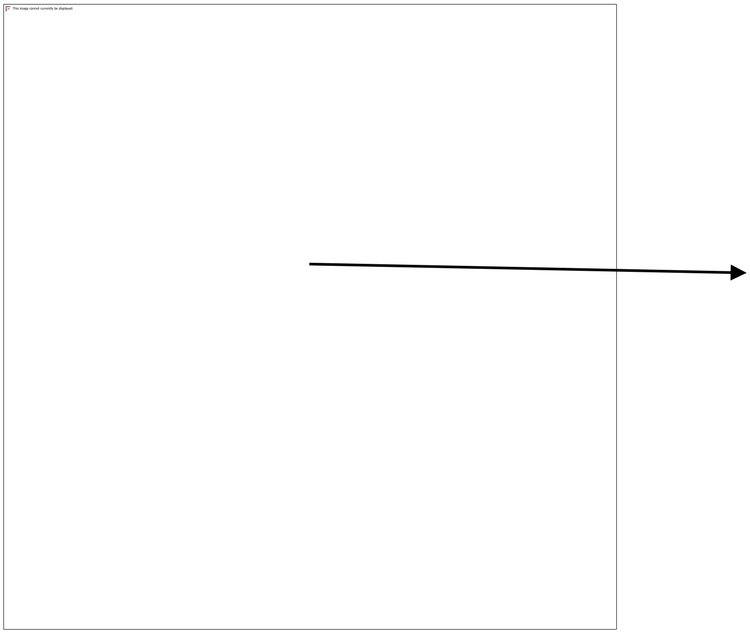

***Figure 3. 10*. Sample Preparation for Tearing Strength**

Source: Photograph by the researcher KEBS laboratory in 2023

10 pieces of sample paper were cut out by tracing out the sample stencil mold that came with the machine and cutting out the sample with a pair of scissors.

ii. Procedure

The paper samples were secured on the Elmendorf tearing tester, by placing them in between the jaws of the tester. The machine was set to operate, and a tear in the middle of the sample was introduced automatically by a blade embedded in the machine. The Elmendorf machine works by determining the force in millinewton (mN) required to continue tearing an initial cut.

The action caused the sample to tear right through the slit introduced. The reading was taken on the display screen. This procedure is repeated for the 5 samples. 3 successful test results were selected. This was done to ensure reliability and to reduce the impact of analytical imprecision (Mohajan, 2017).

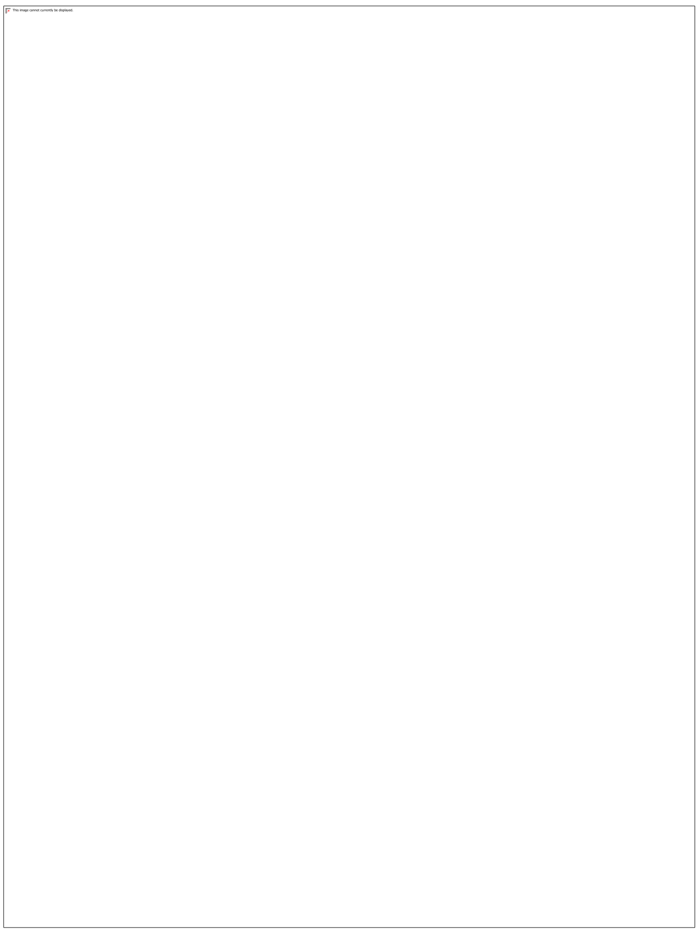

***Figure 3. 11*. Elmendorf Tearing Strength Testing Machine**

Source: Photograph by the researcher KEBS laboratory in 2023

3.7.10 Tensile Strength

The tensile strength test is one where a strip of paper is pulled at a constant rate until it fails. The load at failure is what is described as the tensile strength (Popil, 2017). This test was done according to the KS ISO 12625-4 standard.

Materials, tools, and apparatus included: Tinius Olsen tensile testing machine, ruler, cutter/ scissors.

i. Sample Preparation

A4 size paper to be tested was placed on a flat table. On the A4 size paper, 10 strips of length 160mm and width 15 mm were measured and cut out.

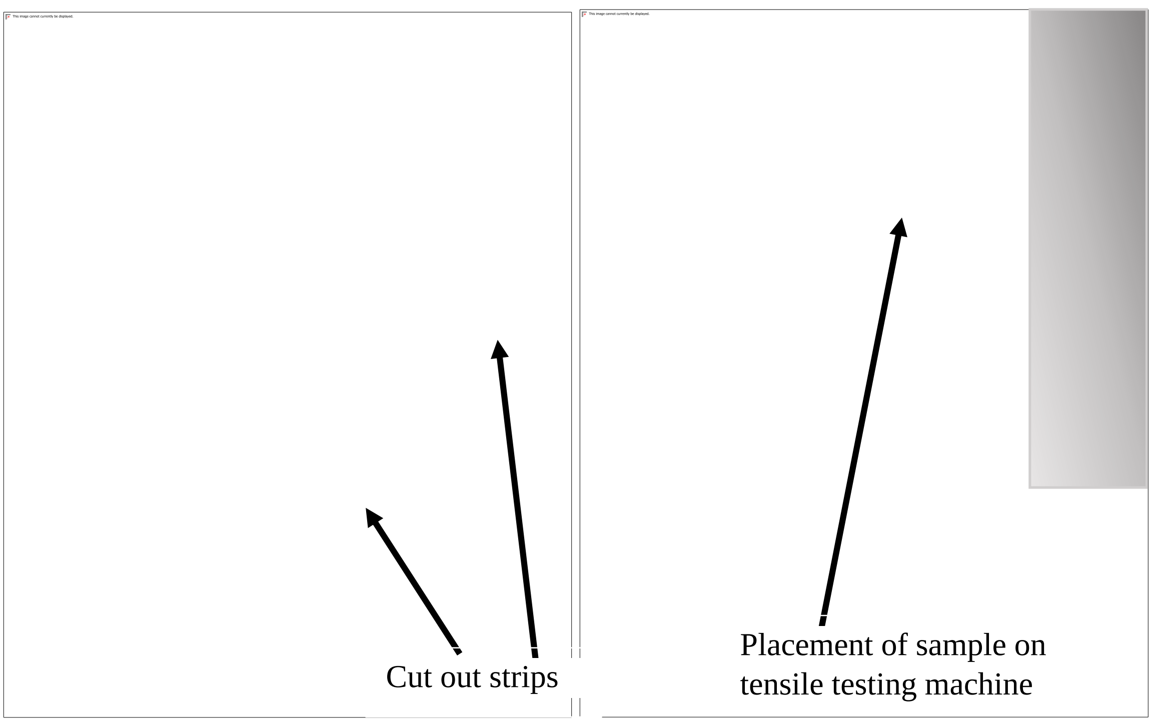

***Figure 3. 12*. Sample Preparation and Placement for Tensile Strength Test**

Source: Photograph by the researcher KEBS laboratory in 2023

ii. Procedure: Constant Rate of Elongation Method

The first paper sample was aligned and clamped in one jaw then carefully while removing slack, the other end of the sample was aligned and clamped on the other jaw. The tensile testing machine was then started. Force was automatically applied by the machine and the paper sample was pulled until the paper sample reached a breaking point. The machine auto-generated the tensile strength of each sample and recordings were taken. The procedure was repeated for 5 paper samples and the average for 3 successful test results was determined. This was done to ensure reliability and to reduce the impact of analytical imprecision (Mohajan, 2017).

The machine calculates the tensile strength using the formula below:

Tensile strength= (Force (Newton N)) /Width of the sample (Millimeters mm)

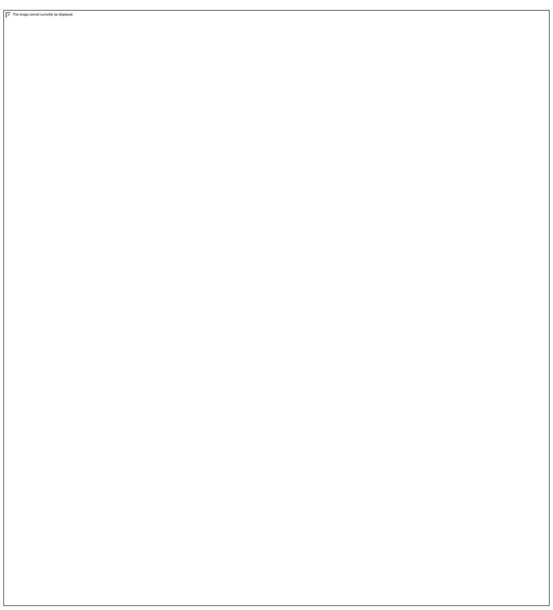

***Figure 3. 13*. Tensile Strength Testing Machine**

Source: Photograph by the researcher KEBS laboratory in 2023

3.8 Data Analysis and Presentation

The data was analyzed using the Excel 2013 software for the two sample T-tests and the statistics kingdom website software (https://www.statskingdom.com/130MeanT1.html) for the one-sample T-tests because the excel software does not perform one sample T-test (One Sample T Test Calculator, n.d.; Statistics How To, 2022).

The two-sample and one-sample T-test analytical tests were used to test the hypotheses. This is because the two-sample T-Test was useful in comparing the means of the data collected from the two samples that were created using two different methods, the Lye and Caustic Soda alkaline pulping methods. The one-sample T-test was used to compare the mean of the sample made using the Lye sample against the set value (mean) outlined by the KEBS standard for each test. The tests were used to establish whether there was a significant difference in paper packaging material quality made from pulping with Lye and that made from pulping with Caustic Soda. It also tested whether there was a significant difference in paper packaging material quality made from pulping with Lye and established KEBS standards for Kraft paper packaging quality (the control). In terms of the analysis the data, the results from each of the five tests that is; pulp yield, water absorbency, bursting strength, tearing strength, and tensile strength was manually inputted in the software and each result was computed automatically and recorded.

A significance level of 0.01 was used to test the hypothesis. This was selected in order to reduce the risk of incorrectly rejecting the null hypothesis as the significance level of 0.01 is considered stricter than for instance that of 0.05 thus ensuring a higher accuracy. In this study confirming the integrity of the quality of the banana stem fiber paper packaging material. The summary of the statistical tests is given in Appendix G. The data is presented in the form of detailed discussions and tables.

3.9 Logical and Ethical Considerations

An approval letter from Kenyatta University Post Graduate School and Kenyatta University Ethical Review Committee to carry out the research was secured as well as permission from the relevant authorities to use the KEBS laboratories and NRF laboratories at KIRDI laboratories for testing and experiments. The purpose of the research was explained to the farmers and consent was sought to photograph and collect the bananas within the farms.

CHAPTER FOUR: FINDINGS

4.0 Introduction

This chapter contains findings on the fabrication and testing of the Kiganda banana stem fiber paper packaging material. The findings are drawn from all the processes that include fiber extraction through decortication, the alkaline pulping process of the fibers, and the construction process of the paper packaging material. They also include findings from the testing phase where selected physical and mechanical properties of the constructed paper packaging material were tested.

4.1 Fiber Extraction through Decortication

In the fiber decortication process, the following data was recorded: number of stems decorticated, time taken to decorticate one-meter stem, average weight of fiber retrieved after decorticating one-meter stem, average weight of fiber retrieved after drying the wet fiber retrieved from decortication, average weight of waste lignin and moisture retrieved after decorticating one-meter stem, the average weight of dry waste lignin after decorticating one-meter stem and weight of dry decorticated fiber from 40 one-meter stems before pulping.

The findings were as follows 40 one-meter banana stems were decorticated, each stem took 10 minutes to decorticate, the average weight of fiber retrieved after decorticating one-meter stem (wet) was 725g, the average weight of fiber retrieved after drying the wet fiber retrieved from decortication was 105g. The average weight of waste lignin + moisture retrieved after decorticating one-meter stem was 4,150g, Average dry waste lignin after decorticating one stem was 495g and the total weight of dry decorticated fiber from 40 one-meter stems was 4,200g.

4.2 The Alkaline Pulping Processes

The Lye and Caustic Soda alkaline pulping processes were both done under the following constant conditions: alkali; 7%, temperature; 105^{0}C, and time was 120 minutes. 2000g of fiber was pulped in each cycle. The resultant weight of the dry pulps from the two alkaline pulping processes was measured and compared to the original dry weight of the fiber before pulping to determine the yield (Briggs, 1994).

The Lye alkaline pulping process had a higher yield (by mass) at 1360g compared to the Caustic Soda alkaline pulping process which yielded 1120g (Table 4.1). These translated to a percentage yield of 68% for the Lye pulping process and 56% for the Caustic Soda pulping process. A Summary of yield produced by the Lye pulping process and Caustic Soda pulping processes is presented in Table 4.1.

Table 4. 1 ***Summary of Yield Produced by the Lye and Caustic Soda Pulping Processes***

Pulping Process	**Original Dry Weight of the Fiber in grams (g) (DW)**	**Dry Pulp Yield in grams (g) (DP)**	**% Yield (%Y=DP/DW ×100)**
Lye	2000	1360	68%
Caustic Soda	2000	1120	56%

From the statistical analysis using a two-sample T-Test, the results revealed that there is no significant difference in the yield from the Lye alkaline pulping process and that from the Caustic Soda alkaline pulping process ($p = 0.8982$, $p > 0.01$).

4.3 The Paper Packaging Material Construction Process

In constructing the paper packaging material, the time taken by one person for each of the processes was recorded. Pulp preparation took 3 minutes, laying of pulp on mold and deckle; 2 minutes, couching; 5 minutes, Air drying; 8 hours and Unmounting; 2 minutes.

4.4 Selected Physical Properties

The physical properties of paper are those that can be observed or measured without changing the identity of the paper (Akram et al., 2017). In this study, color and water absorbency were the physical properties measured because they justify the aesthetic and durability performance of the packaging respectively (Jirukkakul, 2019). It was necessary to determine the color of the material as this would affect recommendations for finishing and printing which are affected by the hue, lightness, and saturation of the packaging material (Jirukkakul, 2019). The water absorbency of the paper packaging material was also tested as this property is used to estimate and predict a product's shelf life, thus indicating what products can be catered for by the packaging material (Jirukkakul, 2019). The properties selected to be tested were determined to be the requisite properties described under the KEBS EAS 859:2017 standard for paper packaging tests.

4.4.1 Color

The visual test revealed that the Pantone chart color code: **B**; mongoose/ sand brown (#bb9e7d) was selected to be similar to the color shade of the paper packaging material **(P1** and **P2)**.

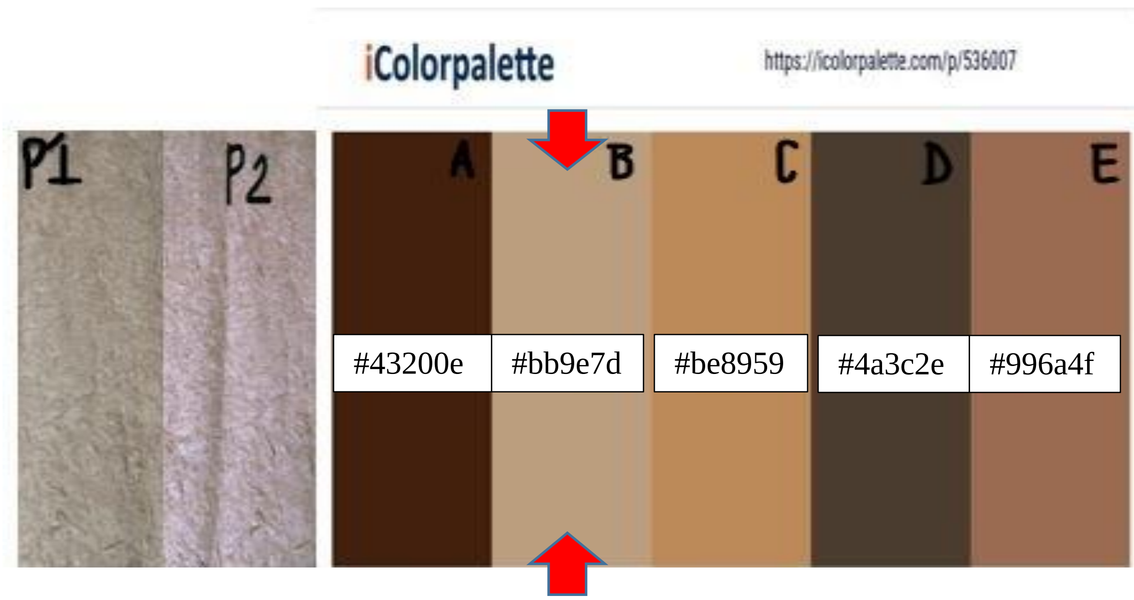

Figure 4. 1. **The Pantone Color Chart Highlighting Selected Color Code for the Paper Packaging Material (P1 & P2)**

4.4.2 Water Absorbency

The water absorptiveness of Lye and Caustic Soda Kiganda banana stem (KBS) paper packaging material was tested.

The results are presented alongside the KEBS EAS 859:2017 standard minimum requirement in Table 4.2.

Table 4. 2 ***Comparison of Water Absorptiveness of Lye KBS Packaging Material, Caustic Soda KBS Packaging Material and KEBS EAS 859:2017 Standard Minimum Requirement***

Sample Parameter	**Lye**	**Caustic Soda**	**KEBS EAS 859:2017 Standard Maximum Requirement**
Water Absorptiveness (Cobb Value)	463g/m^2	205g/m^2	30g/m^2
Water Absorption %	293%	98%	N/A

The findings indicate that the KBS paper packaging material constructed using Lye had a higher Cobb value of 463g/m^2 compared to paper packaging material constructed using Caustic Soda which had a Cobb value of 205g/m^2 (Table 4.2). However, statistical analysis using a two-sample T-test, revealed that there is no significant difference in the water absorptiveness of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p=0.0452$, $p>0.01$).

The percentage of water absorbency was determined to be 293% for the paper packaging material constructed using Lye and 98% for the paper packaging material constructed using Caustic Soda (Table 4.2).

The statistical analysis using a one-sample T-Test, also assessed whether the Cobb value of the paper packaging material constructed using Lye 463g/m^2 was lower or equal /higher than the KEBS EAS 859:2017 standard minimum requirement Cobb value of 30g/ m^2. The KEBS EAS 859:2017 standard minimum requirement for water absorbency outlines that the maximum Cobb value should be 30 g/m^2. It revealed that the Cobb value of the paper packaging material constructed using Lye 463g/m^2 is higher than 30g/m^2 therefore not meeting the KEBS EAS 859:2017 standard minimum requirement for Cobb value ($p=0.9995$, $p>0.01$) (Table 4.2).

4.5 Selected Mechanical Properties

Mechanical properties of paper are the inherent attributes that the paper has in relation to durability and resistance to applied forces exhibited by the paper during manufacturing operations, converting processes, and end-of-use performance. They are also referred to as strength properties (Akram et al., 2017).

This study measured the following mechanical properties: bursting strength, tearing strength, and tensile strength from the constructed banana fiber packaging paper. These properties were selected as they determine the strength and durability of the packaging material essential for storage, handling, and shipping purposes (Akram et al., 2017; Jirukkakul, 2019).

4.5.1 Bursting Strength

The results for the bursting strength test of Lye paper packaging material, Caustic Soda paper packaging material, and the KEBS EAS 859:2017 standard minimum requirement are presented in Table 4.3.

Table 4. 3 ***Comparison of Bursting Strength sample of Lye Packaging Material, Caustic Soda Packaging Material, and KEBS EAS 859:2017 Standard Minimum Requirement***

Sample Parameter	Lye	Caustic Soda	KEBS EAS 859:2017 Standard Minimum Requirement
Bursting Strength	98kPa	293kPa	90kPa

The findings show that the paper packaging material constructed using Caustic Soda had a higher bursting strength of 293 kPa compared to paper packaging material constructed using Lye which was 98 kPa. The statistical analysis using a two-sample T-Test revealed that there is no significant difference in the bursting strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p=0.0132$, $p>0.01$).

Additionally, the statistical analysis using a one-sample T-Test, to assess whether the bursting strength of the Lye paper packaging material 98 kPa was lower or equal /higher than the KEBS EAS 859:2017 standard minimum requirement 90 kPa revealed that the bursting strength of the paper packaging material constructed using Lye was higher than that of the KEBS EAS 859:2017 standard minimum requirement ($p=0.8397$, $p>0.01$) (Table 4.3).

4.5.2 Tearing Strength

The results for the tearing strength test of Lye, Caustic Soda KBS paper packaging material, and the KEBS EAS 859:2017 standard minimum requirement are presented in Table 4.4.

Table 4. 4 ***Comparison of Tearing Strength sample of Lye KBS Packaging Material, Caustic Soda KBS Packaging Material, and KEBS EAS 859:2017 Standard Minimum Requirement***

Sample Parameter	Lye	Caustic Soda	KEBS EAS 859:2017 Standard Minimum Requirement
Tearing Strength	2252mN	1958mN	320mN

The findings indicate that the KBS paper packaging material constructed using Lye had a higher tearing strength of 2252 mN compared to KBS paper packaging material constructed using Caustic Soda which was 1958 mN (Table 4.4). The statistical analysis using a two-sample T-test revealed that there is no significant difference in the tearing strength of the KBS paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p=0.0570$, $p>0.01$).

Additionally, the statistical analysis using a one-sample T-Test, to assess whether the tearing strength of the Lye KBS paper packaging material 2252 mN was lower or equal /higher than the KEBS EAS 859:2017 standard minimum requirement of 320 mN.

It was revealed that the Lye packaging material tearing strength of 2252 mN was higher than the KEBS EAS 859:2017 standard minimum requirement for tearing strength of 320 mN ($p=0.9994$, $p>0.01$) (Table 4.4).

4.5.3 Tensile Strength

The tensile strength of Lye and Caustic Soda KBS paper packaging material were tested. Table 4.5 presents the results alongside the KEBS Standard minimum requirement in the table.

Table 4. 5 ***Comparison of Tensile Strength sample of Lye Packaging Material, Caustic Soda Packaging Material and KEBS EAS 859:2017 Standard Minimum Requirement***

Sample Parameter	Lye	Caustic Soda	KEBS Standard Minimum Requirement
Tensile Strength (CD)	1.63N/mm	6.2N/mm	4.0N/mm
Tensile Strength (MD)	1.63N/mm	8.5N/mm	5.0N/mm

The findings show that the KBS paper packaging material constructed using Caustic Soda had a higher tensile strength of 6.2 N/mm on the cross direction (CD) than that of Lye with a tensile strength of 1.63N/mm on the (CD) (Table 4.5). The statistical analysis using a two-sample T-test revealed that there is a significant difference in the cross-direction CD tensile strength of the KBS paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p=0.0039$, $p<0.01$).

The findings also show that the KBS paper packaging material constructed using Caustic Soda had a higher tensile strength of 8.5 N/mm in the machine direction (MD) than that of Lye with a tensile strength of 1.63N/mm in the (MD) (Table 4.5). The statistical analysis using a two-sample T-Test, also revealed that there is a significant difference in the MD tensile strength of the KBS paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p=0.0002$, $p<0.01$).

Additionally, the statistical analysis using a one-sample T-test was used to assess whether the CD tensile strength of the KBS paper packaging material constructed using Lye 1.63N/mm was equal to or higher than the KEBS EAS 859:2017 standard minimum requirement for CD tensile strength 4.0N/mm. It was revealed that the Lye packaging material cross-direction CD tensile strength of 1.63 N/mm was lower than the KEBS EAS 859:2017 standard minimum requirement for cross-direction CD tensile strength of 4.0 N/mm ($p=0.0064$, $p>0.01$) (Table 4.5).

The statistical analysis using a one-sample T-Test, also assessed whether the MD tensile strength of the KBS paper packaging material constructed using Lye 1.63N/mm was lower or equal /higher than the KEBS EAS 859:2017 standard minimum requirement for the MD tensile strength 5.0N/mm. The Lye packaging material MD tensile strength of 1.63 N/mm was lower than the KEBS EAS 859:2017 standard minimum requirement for MD tearing strength of 5.0 N/mm ($p=0.0032$, $p>0.01$). This is presented in Table 4.5.

CHAPTER FIVE: DISCUSSION OF FINDINGS

5.0 Introduction

This chapter discusses the findings of the study presented in chapter 4 in relation to the study objectives. The findings are also related to known literature for each objective being discussed.

5.1 Fiber Extraction through Decortication

The metrics involved in the fiber extraction process are insufficiently discussed in many studies. Therefore, this study purposed to collect metrics on the fiber extraction process. These metrics would be beneficial in generating detailed and specified information on the making of paper packaging from banana stems.

The information collected was on:

1. The number of stems decorticated.
2. The rate of decortication for one meter stem.
3. The average weight of fiber retrieved after decorticating a one-meter stem (wet).
4. The average weight of fiber retrieved after drying the wet fiber retrieved from decortication.
5. The average weight of waste lignin and moisture retrieved after decorticating a one-meter stem.
6. The weight of dry decorticated fiber from 40 one-meter stems before pulping.

The average time taken to decorticate one meter stem was ten minutes giving a total time of 400 minutes (6 hours 40 minutes) for the 40 one-meter stems. The findings revealed that for the one-meter stem, an average of 105g of dry fiber was retrieved and from the 40 one-meter stems decorticated 4200g of dry fiber that was retrieved. This is comparable to findings on extracted fiber by Jirukkakul (2019), which revealed that 10 to 13 stems produce about 1 to 2 kg which translates to about 100g to 200g per stem.

The weight of wet fiber from a meter stem was 725g. This indicates that the higher percentage of the fiber weight was moisture accounting for 86% of the wet fiber weight, given that upon drying the fiber was 105g (14% of the wet fiber weight). Likewise, the waste lignin weighed 4150g when wet and 495g when dry (12% of the wet lignin weight) thus the moisture that was present was 88% of the original 4150g. This is similar to a study by Zhang et al. (2023) who determined that banana stems usually contain majorly moisture. Compared to other fiber extraction methods, mechanical decortication is preferred due to its efficiency in time and yield (Badanayak et al., 2023).

5.2 The Alkaline Pulping Processes

In this study, two delignification alkali reagents were used for two separate experiments. Caustic Soda, which is commonly used and the other was Lye which was organically derived from the ash component of banana peels. The results revealed that the Lye alkaline pulping process had a higher yield (by mass) at 68% compared to the Caustic Soda alkaline pulping process which yielded 56%. This is in line with a similar study by Goswami et al. (2008), who noted that the unbleached pulp from a Caustic Soda process generally has a yield of 50.8%. Kalyoncu (2022), determined that the yield of various Lye pulping processes ranged from 47.4% to 53.17%.

Similar studies on the viability of Lye as a replacement alkali, determine that Lye is a suitable replacement for Caustic Soda in the soap-making process (Kalyoncu, 2022; Olabanji et al., 2012; Waithaka & Muriuki, 2019). The results of this study also demonstrate that Lye is a viable replacement for Caustic Soda as a delignification alkali because it was used for the chemical delignification of the banana stem fibers and produced a high yield. The Lye alkaline pulping process had a higher yield (by mass) at 68% compared to the Caustic Soda alkaline pulping process which had a 56% yield. The high yield value of the Lye pulping process illustrates that the fibers retain their core strength structure (cellulose) when using this pulping process. The lignin of the fibers is what is mainly detached and the fibers retain more of their cellulose and hemicellulose layers, thus contributing to a high yield. In contrast, Caustic Soda has a lower yield as more of the cellulose and hemicellulose layers are broken down and lost during the pulping process (Subagyo & Chafidz, 2018).

Pulping KBS with Lye would be a more economically viable choice compared to pulping with Caustic Soda as the former process produces more yield than the latter and therefore provides more pulp for papermaking. Additionally, given that the Lye is obtained from a byproduct of banana utilizing it will ensure added value to the waste (banana peels) (Kalyoncu, 2022).

5.3 The Paper Packaging Material Construction Process

The pulping technique is a process of breaking down fiber into a slurry paste-like substance that is matted to form paper. In this study, hand-made paper sheets were constructed by laying the pulp on the mold and deckle, couching, air drying, and unmounting the dried paper (Tappi, 2002).

The results showed that to hand make an A4-sized paper a total time of 8 hours and 12 minutes are required, of which the 8 hours are allocated for air drying of the paper and would be the same time taken by either one or a thousand papers to dry. The 12 minutes are for the preparation of the paper before drying. This means that within an hour five papers can be prepared. This implies that for a more efficient paper-making process, it would be ideal to mechanize the process by using a paper-making machine.

5.4 Selected Physical Properties

The physical properties of paper are those that can be observed or measured without changing the identity of the paper (Akram et al., 2017). In this study, color and water absorbency were the physical properties measured. The properties selected to be tested were determined to be the requisite properties described under the KEBS EAS 859:2017 standard for paper packaging tests.

5.4.1 Color

Packaging design is a core marketing or selling point of a product and color is considered an important aspect that qualifies packaging for this marketing role. This is because color has the ability to get the consumers' attention, evoke an emotional appeal, and differentiate a brand from the other (Swasty et al., 2021). Determining the color of the material is necessary as this would inform recommendations for finishing and printing which are affected by the hue, lightness, and saturation of the packaging material (Jirukkakul, 2019).

The visual test in this study reveals that the color of banana stem paper is light sand brown, referenced as the Pantone chart color code: **B**; mongoose/ sand brown (#bb9e7d) as shown in Figure 4.1. The findings reveal that the natural color of paper packaging material produced from banana stems without any bleaching process or additive is sand brown. These findings compare to those by other scholars on the color of unbleached banana stem paper who mention that natural banana Kraft paper is a light sand brown color (Jirukkakul, 2019; Subagyo & Chafidz, 2018).

Some studies describe paper packaging material produced from banana stems as being cream-white or white. However, it is vital to note that in these studies a bleaching process was introduced in the making of the paper packaging material to make the paper whiter (Goswami et al., 2008).

Maintaining the paper packaging materials natural color which is brown would be a desirable perceptive marketing strategy for sustainable packaging especially one that would replace plastic packaging which has been established to be a major environmental hazard (Daggar, 2022; Vidal, 2020). The findings also indicate that if the paper packaging material is desired in other colors, then a bleaching process would be an essential pre-requisite during the construction process.

5.4.2 Water Absorbency

The water absorbency of a substance is a measure of how easily moisture can penetrate a surface (*Water Vapor Transmission Rate - Poly Print*, 2020). It is referred to as the water vapor transmission rate (WVTR) which is also known as the water vapor transfer rate and is determined via a Cobb test.

The results of this study indicated that there is no significant difference in the water absorptiveness of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda. This is to imply that both paper packaging material samples had a similar water absorbency rate. The water absorption percentage rate was determined to be 293% for the paper packaging material constructed using Lye and 98% for the paper packaging material constructed using Caustic Soda. These findings are in line with previous research that proves that banana fibers are highly hydrophilic (Motaleb et al., 2020).

The results also revealed that the Cobb value of the paper packaging material constructed using Lye is higher than the KEBS EAS 859:2017 standard minimum requirement Cobb value. This means that it surpassed the minimum Cobb value requirement specified by the KEBS EAS 859:2017 for paper packaging, making the water absorbency of Lye paper packaging material very high. Nonetheless, this result is well aligned with that of previous research by other researchers. Research by Liu et al. (2018) highlights that paper made from non-wood pulp fiber such as banana stem fibers often has poor paper properties including poor water filtering.

Begum et al. (2021), deduced that alkali delignified banana fibers have a water absorption percentage rate of 248.5% to 480%, just as is denoted in the results which show that the percentage of water absorbency of Lye paper packaging material was determined to be 293% for the paper packaging material constructed using Lye. Banana fibers are naturally hydrophilic and are known to have a high water absorption rate (Motaleb et al., 2020). Being that the paper packaging material was made from 100% banana fiber, it is reflective that the paper packaging material has this inherent water absorption quality.

Begum et al. (2021) further attribute the high absorption rate to the fact that during alkali treatment the banana fibers are de-lignified thus allowing water to be absorbed much more than before. The lignin on the fibers usually acts as a barrier to prevent excessive water absorption. Elimination of the lignin allows the fibers to take in more water than before.

Furthermore, Motaleb et al. 2020, deduce that banana non-woven materials have very high water absorption rates, and to remedy this, water-repellent treatment is recommended. This is because even though high absorbency is desirable in products such as sanitary towels, diapers, and hand wipes it is less desirable in products such as packaging materials. This implies that the quality of the paper packaging material in terms of water absorbency was unsatisfactory and would need improvement.

5.5 Selected Mechanical Properties

The mechanical properties establish the limits of a material's functionality when subjected to end-use or manufacturing processes. The selected mechanical properties of paper packaging that were tested are; bursting strength, tearing strength, and tensile strength.

5.5.1 Bursting Strength

The findings of this study show that the bursting strength of the paper packaging material constructed using Lye and Caustic Soda were 98 kPa and 293 kPa respectively. This ranges close to the findings of Sakare et al. (2020), which show that the average bursting strength of uncoated banana stem paper was 1.61 kg/cm^2 (157.8 kPa). The paper packaging material constructed using Caustic Soda has higher bursting strength indicating that the paper packaging material constructed using Lye is likely to rupture quicker compared to Caustic

Soda. This can be attributed to stronger fiber bonding in the paper packaging material constructed using Caustic Soda. Nonetheless, the findings show that both the paper packaging material constructed using Caustic Soda and Lye met the KEBS EAS 859:2017 standard minimum requirement which was 90 kPa, which means that both Lye and Caustic Soda samples qualify to make quality packaging in terms of burst strength.

According to Nassar et al. (2021), banana paper has very good mechanical properties such as bursting strength which can be attributed to the high cellulose content and long length of the paper-forming fibers. This corroborates the findings of this study on bursting strength.

Bursting strength stipulates the ability of a packaging material to retain its contents. This therefore implies that because the Lye paper packaging material meets the minimum requirement for packaging paper given by KEBS EAS 859:2017 and even surpasses the minimum threshold, then it can retain its contents without bursting prematurely.

5.5.2 Tearing Strength

The findings for tearing strength indicate that Lye paper packaging material had a higher tearing strength of 2252 mN compared to paper packaging material constructed using Caustic Soda which was 1958 mN. It was also significantly higher than the KEBS EAS 859:2017 standard minimum requirement for tearing strength of 320 mN. Tearing strength or tearing strength is determined by the number of fibers per unit weight of material, this is often contributed by a high cellulose content (Nassar et al., 2021). This means that it is likely that the Lye paper packaging material had a high number of fibers per unit weight of material, thus contributing to it having a greater tearing strength.

Generally, banana stem fiber paper has good tearing strength. This is evident in previous studies such as one by Goswami et al. (2008) which shows that the tearing strength of grease-proof banana paper is 980 mN. Similarly, work by M. Z. H. Khan et al. (2014), denotes the tearing strength of banana paper as an average of 1036 mN. These metrics range closely to the findings of this study which indicate great tearing strength of both the Lye and Caustic Soda banana fiber paper packaging material. Thus, indicating that banana paper generally has very good tearing strength and would produce packaging with great resistance to tearing.

5.5.3 Tensile Strength

Tensile strength is considered the amount of force that is required to rupture a strip of paper. It is a good indicator of fiber length, strength, and bonding and this is why it is an important paper property (Popil, 2017).

The findings show that the paper packaging material constructed using Caustic Soda had a higher tensile strength on the cross direction (CD) and machine direction (MD) which were 6.2 N/mm and 8.5 N/mm respectively than that of Lye with a tensile strength of 1.63N/mm on both the (CD) and (MD).

This revealed that there is a significant difference in the CD tensile strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda as well as the MD tensile strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda, with the Caustic Soda paper packaging material having a superior tensile strength.

Different studies give various findings on the tensile properties of banana stem paper. For instance, M. Z. H. Khan et al. (2014) conclude that Caustic Soda banana stem paper has very low tensile strength with an average of 2.82 N/mm and this is attributed to poor pulp quality. According to Sakare et al. (2020), the tensile strength of Kraft method banana stem paper is derived to be 0.90 N/mm which is close to that of the Lye paper packaging material which is 1.63N/mm. Nassar et al. (2021), established the tensile strength of the Sodium Oxide (Na_2O) banana stem paper as 3.5 N/mm. This shows that tensile strength is dependent on various factors including delignification reagent, additives such as coatings, and pulp quality (Jirukkakul, 2019; Kalyoncu, 2022; M. Z. H. Khan et al., 2014; Sakare et al., 2020).

Additionally, the findings show that the Lye KBS paper packaging material did not meet the KEBS EAS 859:2017 standard minimum requirement which was 4 N/mm and 5 N/mm for the CD and MD respectively. Kalyoncu (2022), concluded that banana stem paper pulped with LYE-based delignification reagents produces good quality paper with a tensile strength that ranges between 3.9 N/mm and 4.8 N/mm. In contrast, Caustic Soda KBS paper packaging material in turn had a higher tensile strength and this could be due to a higher degree in the bonding of fibers during the papermaking process. Jirukkakul (2019), established that to improve the tensile strength of banana stem paper, coating it through either a wet or dry laminating process is highly recommended.

5.6 Testing the Hypotheses

H_{01} –There is no significant difference in paper packaging material quality made from pulping with Lye and that made from pulping with Caustic Soda.

Color:

The hypothesis is not rejected because both Lye paper packaging material and Caustic Soda paper packaging material were determined to have a similar color code denoted as the Pantone chart color code: **B**; mongoose (#bb9e7d) which is a light sand brown color. The color code chosen was determined to be significantly different from the rest.

Water Absorbency:

The hypothesis is not rejected because the results revealed that there is no significant difference in the water absorptiveness of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p>0.01$).

Bursting Strength:

The hypothesis is not rejected because the results show that there is no significant difference in the bursting strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p>0.01$).

Tearing Strength:

The hypothesis is not rejected because the results show that there is no significant difference in the tearing strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p>0.01$).

Tensile Strength:

The hypothesis is rejected because the results show that there is a significant difference in the tensile strength of the paper packaging material constructed using Lye and that which was constructed using Caustic Soda ($p<0.01$).

H_{02} – There is no significant difference in paper packaging material quality made from pulping with Lye and the KEBS standard for Kraft paper packaging materials.

Color:

The hypothesis is not rejected because the Lye paper packaging material has a similar color to unbleached Kraft paper whose properties are outlined by the KEBS EAS 859:2017 Standard minimum requirement for Kraft paper packaging materials which is a light sand brown color.

Water Absorbency:

The hypothesis is rejected because the results showed that there is a significant difference in the water absorptiveness of the paper packaging material constructed using Lye and the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging materials ($p<0.01$). The value of the water absorptiveness of the paper packaging material exceeds the KEBS EAS 859:2017 standard minimum requirement as a desirable outcome would be that it does not go beyond the specified water absorbency rate.

Bursting Strength:

The hypothesis is not rejected because the results show that there is no significant difference in the bursting strength of the paper packaging material constructed using Lye and the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging materials ($p>0.01$). The value of the bursting strength of the paper packaging material meets and exceeds the KEBS EAS 859:2017 standard minimum requirement.

Tearing Strength:

The hypothesis is not rejected because the results show that there is no significant difference in the tearing strength of the paper packaging material constructed using Lye and the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging materials ($p>0.01$). The value of the tearing strength of the paper packaging material exceeds the KEBS EAS 859:2017 standard minimum requirement.

Tensile Strength:

The hypothesis is rejected because the results show that there is a significant difference in the tensile strength on both Machine direction and Cross direction of the paper packaging material constructed using Lye and the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging materials ($p<0.01$).

The hypotheses test results above show that the tensile strength of the paper packaging material constructed using Lye is significantly low when compared to both Caustic Soda paper packaging material and the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging materials. Therefore, the paper packaging material made from Lye will need fortification to refine its tensile properties.

Additionally, the paper packaging material made from Lye as well as Caustic Soda have very high-water absorbency and therefore would also require additives to improve this quality.

Three of the properties meet the requirements; that is color, bursting strength, and tearing strength therefore it is possible to get good quality paper packaging material from Lye pulping if the tensile strength and water absorbency properties are improved.

CHAPTER SIX: SUMMARY, CONCLUSION AND RECOMMENDATION

6.0 Introduction

This chapter outlines the following; the summary of findings in line with the objectives, conclusions from the findings, recommendations for and suggestions for further research.

The purpose of this study was to fabricate and test the properties of paper packaging material made from Kiganda banana stems from Kisii, Kenya.

6.1. Summary

The research objectives were:

1. Extract banana stem fibers using a decorticating machine.
2. Pulp banana stem fibers using; a) Lye. b) Caustic Soda.
3. Construct samples of paper packaging material from; a) Pulp treated with Lye. b) Pulp treated with Caustic Soda.
4. Test selected physical and mechanical properties of the constructed paper packaging materials made from a) Pulp treated with Lye. b) Pulp treated with Caustic Soda.
5. Compare the properties of the paper packaging material made from pulp treated with Lye to those made from pulp treated with Caustic Soda.

6. Compare the properties of the paper packaging material made from pulp treated with Lye to established standard Kraft paper packaging properties of the Kenya Bureau of Standards (KEBS).

6.1.1 Extraction of Banana Stem Fibers using a Decorticating Machine

The banana stem fibers were decorticated using a decorticating machine. Forty-one-meter banana stems were decorticated using a decorticating machine. The findings revealed that a one-meter stem took an average time of 10 minutes to decorticate. The average weight of the wet fibers from the one-meter stem was 725g. The average dry weight of fiber from one-meter stem was 105g which accounted for 14% of the wet fiber weight and the moisture accounted for 86% of the wet fiber weight. The waste lignin weighed 4200g when wet and 495g when dry (12% of the wet lignin weight) thus the moisture that was present was 88% the wet lignin weight. These findings indicate that the banana stem has a higher moisture-to-fiber ratio.

6.1.2 The Alkaline Pulping Processes

In this study, two delignification alkali reagents were used for two separate experiments Caustic Soda and Lye. Caustic Soda, which is the commonly used alkali and the other Lye which was organically derived from the ash component of banana peels. The results showed that the Lye alkaline pulping process had a higher yield (by mass) at 68% (1360g) of the original dry mass of the fiber (2000g) compared to the Caustic Soda alkaline pulping process which yielded 56% (1120g) of the original dry mass of the fiber (2000g). This proves that Lye qualifies to be a good delignification reagent and that Lye pulping is an efficient alkaline pulping process as it leads to a higher yield.

6.1.3 The Paper Packaging Material Construction Process

In preparing the paper packaging material the steps included; pulp preparation, laying of the pulp on the mold and deckle, couching, air-drying, and unmounting. The results showed that to hand make an A4-sized paper packaging material a total time of 8 hours and 12 minutes is required of which the 8 hours are allocated for air drying of the paper packaging material. The time taken to prepare the A4-sized sheets was 12 minutes.

6.2 Selected Physical Properties

The physical properties of paper are those that can be observed or measured without changing the identity of the paper (Akram et al., 2017). In this study, color and water absorbency were the physical properties measured because they justify the aesthetic and durability performance of the packaging respectively.

6.2.1 Color

The findings reveal that the color of banana stem paper is light sand brown, referenced as the Pantone chart color code: **B**; mongoose/ sand brown (#bb9e7d) as shown in Figure 4.1. This was confirmed via a visual test where the color code: **B**; mongoose/ sand brown (#bb9e7d) was selected as the color code that was similar to that of the paper packaging materials.

6.2.2 Water Absorbency

The water absorption percentage rate was determined to be 293% (463 g/m^2) for the paper packaging material constructed using Lye and 98% (205g/m^2) for the paper packaging material constructed using Caustic Soda. The KEBS requirement stipulates that for packaging paper, the Cobb value should not exceed 30g/m^2. These findings show that banana stem paper packaging materials constructed using Lye and Caustic Soda pulping processes have a high-water absorption rate. Naturally, banana stem fibers are hydrophilic. This is maintained by the banana stem paper packaging materials which were established to retain this hydrophilic quality. Therefore, water absorbency properties of banana stem paper packaging materials will need refinement.

6.3 Selected Mechanical Properties

Mechanical properties of paper are the inherent attributes that the paper has in relation to durability and resistance to applied forces exhibited by the paper during manufacturing operations, converting processes, and of-use performance. They are also referred to as strength properties (Akram et al., 2017).

This study measured the following mechanical properties: bursting strength, tearing strength, and tensile strength from the constructed banana fiber packaging paper.

6.3.1 Bursting Strength

The findings show that the bursting strength of both the paper packaging material constructed using Lye and Caustic Soda met the minimum standard requirement for packaging with bursting strength of 98 kPa and 293 kPa respectively. This qualifies the Lye paper packaging material as having good bursting strength, especially because it surpassed the minimum requirement which was 90 kPa.

6.3.2 Tearing Strength

The tearing strength of the Lye paper packaging material was determined to be 2252 mN which was higher than that of the Caustic Soda paper packaging material which was 1958 mN. It was also significantly higher than the KEBS EAS 859:2017 standard minimum requirement for tearing strength of 320 mN. This means that the Lye paper packaging material had a stronger fiber-to-fiber bonding and a high number of fibers per unit weight of material. Tearing strength is considered a greater strength property of packaging paper therefore this implies that good tearing strength shows that the strength quality of the paper packaging material is good.

6.3.3 Tensile Strength

The findings show that the paper packaging material constructed using Caustic Soda had a higher tensile strength on the (CD) and (MD) which were 6.2 N/mm and 8.5 N/mm respectively than that of Lye with a tensile strength of 1.63N/mm on both the (CD) and (MD). Given that the KEBS EAS 859:2017 standard minimum requirement was 4.0 N/mm on the CD and 5 N/mm and MD respectively the Lye paper packaging material did not meet the tensile requirement. This points out that being that the tensile strength of the Lye paper packaging material is low, and would need improvement.

6.4 Conclusions

The following conclusions were drawn based on the findings of this study.

i. Decortication of one meter banana stems takes an average of 10 minutes and the average weight of the resultant dry fiber is 105g. This means that given that a banana stems ranges from between 2 to 3 meters then you can get 210g to 315g dry fiber per stem.

ii. The Lye solution retrieved from banana peel ash is better than the Caustic Soda for delignification in the alkaline pulping process in terms of yielding a higher percentage of pulp.

iii. The hand-crafted paper packaging material construction process is labor intensive. It takes 12 minutes to prepare the pulp for one A4-sized paper and 8 hours to dry. For commercial purposes, the process would be expedited by the use of a more mechanized system such as using a paper-making machine to increase the output.

iv. The Lye paper packaging material has excellent bursting strength and tearing strength and an attractive color but high-water absorbency just like the Caustic Soda paper packaging material.

v. Compared to the Caustic Soda paper packaging material, the Lye paper packaging material has a lower tensile strength.

vi. In terms of the KEBS EAS 859:2017 standard minimum requirement for Kraft paper packaging, the Lye paper packaging material was established to have satisfactory bursting strength and tearing strength but undesirable water absorbency and tensile strength. To upgrade its quality, its water absorbency and tensile strength properties need to be improved.

vii. The findings add value to the paper packaging industry that is shifting to greener processes of production to meet consumer demands for sustainability, corporate social responsibility or regulatory demands as is in the case of the industry in Kenya post the plastic ban.

6.5 Recommendations

The following recommendations are made based on the conclusions made from this study.

6.5.1 Recommendations for Practice

i. The paper packaging manufacturing industry should explore making paper packaging from extracted banana stem fibers due to their proven viability for various industries such as the fashion industry.

ii. The paper packaging-making industry should explore Lye (Potassium Hydroxide) as a viable replacement for Caustic Soda in the pulping process of fibers such as banana fibers, for a process with an increased yield and that is less toxic to the environment.

iii. The fashion industry should consider producing Lye banana stem fiber packaging with improved water absorbency and tensile strength as a biodegradable packaging option that is much needed in the fashion industry especially in Kenya due to the single–use plastic ban.

6.5.2 Recommendations for Further Research

i. Further research could be done to improve the quality of the banana stem fiber paper packaging in terms of water absorbency and tensile strength.

ii. Research could be carried out on pulping the banana stem fibers using different Lye concentrations and other organic delignification reagents.

iii. A comparative study where banana stems paper packaging is made from the whole un-decorticated stem as opposed to only fibers from a decorticated stem should be carried out.

iv. Further research should be done on the dyeing capabilities of the paper packaging to establish the possibility of having branding variety in terms of color.

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APPENDICES

Appendix A: Summary of Baseline Study on Banana Farming in Kenya

A baseline study was done before developing this thesis to establish the area of the study where the banana stems would be collected. Five counties known to be banana-growing counties were selected for the baseline. These were Embu, Kakamega, Kirinyaga, Kisii and Muranga (Wahome et al., 2021).

An interview guide was used to gather information from 30 farmers from each county (Bekele & Ago, 2022). The 30 farmers were selected purposively from various sub-counties within the five counties, banana farmers growing more than one variety were selected for the study. Stems of popular varieties were collected from these areas for chemical characterization. For this study information on variety and chemical characterization were the relevant items needed to establish the study area. These two items also formed the independent variables for the study. For this, the following criteria were used:

1. Information on variety; the most popular variety.
2. Chemical characterization; the highest cellulose content.

Measurement of Study Variables

1. Banana Variety

This was determined by using an interview guide to gather information on the names of banana varieties from farmers. The most popular banana variety that is recurring in all counties surveyed would be considered for the study. Kiganda was determined to be the most popular variety, appearing in all five counties (see Table 1).

2. Cellulose Content

The cellulose content of the samples was determined in the JKUAT biotechnology laboratory. This was done with the help of the laboratory assistants. To determine the cellulose content of the fibers separation of the cellulose from the matrix was done by first separating holocellulose and lignin. The cellulose was then separated from the holocellulose in the following way:

Determination of Cellulose Content

Two grams of oven-dried holocellulose were weighed and placed in a 250ml volumetric flask. 25 ml of 17.5% Caustic Soda solution was added and heated at 20°C with continuous addition of 10 ml of 17.5% Caustic Soda solution to the holocellulose in the 250-ml beaker and thorough shaking of the contents. The contents were then left standing at 20°C for 30 min, making the total time for Caustic Soda treatment 45 min. 33 ml of distilled water was added to the mixture, shaken thoroughly, and allowed to stand at 20°C for 1 h, and filtered using a muslin cloth. The contents were continuously washed with acetic acid and further with distilled water until all the lignin and sodium hydroxide had been removed. Cellulose was washed repeatedly until it was free of acid as indicated by litmus paper. The samples were placed in dry pre-weighed glass wares and placed in an oven at 100-105°C overnight. The samples were cooled and the cellulose content was determined (Han & Rowell, 2008).

$$\%\ cellulose = final\ mass\ \ /\ initial\ mass\ \times 100$$

Kiganda stem samples from the five counties were subjected to chemical characterization which revealed that the Kiganda stem from Kisii County had the highest Cellulose content thus making it the most suitable area for the collection of Kiganda stems (see Table 2).

Table 1 Banana Varieties Found in Five Popular Banana-Growing Counties

REGION (COUNTY)	**BANANA VARIETY (common names)**
EMBU	Muraru, Kambara, Gicagara, ***Kiganda,*** Sweet banana, Williamson, Kampala, Nyoro.
KAKAMEGA	Shikwimbi, Sweet banana Lisamuli, ***Kiganda,*** Shitsikhame, Mshirakwangoi, Munule, Lusolio, Bokoboko, Shinali, Konja, Shivembe, Mboya, Esraeli, Eshilamuli, Esikame, Namakoto, Muralu.
KIRINYAGA	Muraru, Kambara, Gicagara, ***Kiganda,*** Sweet banana, Williamson, Kampala, Nyoro.
KISII	*Ekeganda* ***(Kiganda),*** Ekegusi, Ndizi ngombe, Sweet banana, Obogeke, Opokopoko, Egesabara, Murwaru
MURANGA	Muraru, Kambara, Gicagara, ***Kiganda,*** Sweet banana, Williamson, Kampala, Nyoro.

Table 2 The Percentage of Cellulose in Kiganda Samples from Five Counties

Sample Counties	**Percentage of Cellulose in the Sample**
Embu	20%
Kakamega	32%
Kirinyaga	25%
Kisii	54%
Muranga	33%

Appendix B: Standards for Paper Packaging Testing and Test Results

KEBS Standards for Paper Packaging Testing

(Standard specification: KS EAS 859:2017 East African Standard for Paper Bag Packaging)

PROPERTY	***MINIMUM REQUIREMENT***	***TEST METHOD NO***
Water Absorptiveness	25-30 g/m^2 (Range allowed)	ISO 535
Bursting Strength	90 kPa	ISO 2758
Tearing Strength	320 mN	ISO 1974
Tensile Strength - CD	4 N/mm	ISO 12625-4
Tensile Strength - MD	5 N/mm	ISO 12625-4

KEBS TEST RESULTS

LYE PAPER SAMPLE

Kenya Bureau of Standards
Standards for Quality life

Fax: +254 (0) 20 6009660
E-Mail:info@kebs.org
Website: www.kebs.org

Laboratory Test Report

KEBS Centre, Popo Road
P.O. Box 54974, 00200 Nairobi
Tel.: +254 (0) 20 6005490, 6005506

REPORT UID: 20230224160127-V1
KEBS Sample Ref. No: BS202305530
Date : 24 February, 2023

1. Description of Sample: KRAFT PAPER

2. Sample Submitted by: MUSOMBI STEPHANIE KOBEHLO

3. Customer Contact:
4. Customers Ref No: KEBS/HQ/TES/PRIVATE

5. Customer's Address: KENYA

6. Lab Ref: KEBS/TES/POL-NAR/P/23

7. Date of Receipt: 15 February, 2023
8. Date Analysis Started: 20 February, 2023
9. Sample Submission Form No:

10. Additional Information provided by the customer:
SAMPLE Y

11. Acceptance criteria-title and number of specification against which it is tested:
EAS 859:2017 East African Standard Specification for Paper Bags

12. Parameters tested and Method(s) of test: as listed in the report below:

LABORATORY TEST REPORT

No.	Parameters		Results	Requirements	Test Method No.	LOD
1.	Bursting Strength	kPa	98	90Min	ISO 2758	
2.	Tearing Resistance	mN	2252	320Min	ISO 1974	
3.	Tensile Strength					
I	Tensile Strength - CD	N/mm	1		ISO 12625-4	
II	Tensile Strength - MD	N/mm	2		ISO 12625-4	
4.	Water absorptiveness	g/m²	463	25-30	ISO 535	

COMMENTS/REMARKS:
The sample performed as shown

Tabitha Orwa - Manager Polymer Laboratory
FOR: MANAGING DIRECTOR

24 February, 2023
Date of Issue

CAUSTIC SODA PAPER SAMPLE

Kenya Bureau of Standards
Standards for Quality life

Fax: +254 (0) 20 6009660
E-Mail:info@kebs.org
Website: www.kebs.org

KEBS Centre, Popo Road
P.O. Box 54974, 00200 Nairobi
Tel.: +254 (0) 20 6005490, 6005506

Laboratory Test Report

REPORT UID: 20230302123124-V1
KEBS Sample Ref. No: BS202305520
Date : 2 March, 2023

1. Description of Sample: KRAFT PAPER

2. Sample Submitted by: MUSOMBI STEPHANIE KOBEHLO

3. Customer Contact:
4. Customers Ref No: KEBS/HQ/TES/PRIVATE

5. Customer's Address: KENYA

6. Lab Ref: KEBS/TES/POL-NAR/P/23

7. Date of Receipt: 15 February, 2023
8. Date Analysis Started: 23 February, 2023
9. Sample Submission Form No:

10. Additional Information provided by the customer:
SAMPLE X

11. Acceptance criteria-title and number of specification against which it is tested:
EAS 859:2017 East African Standard Specification for Paper Bags

12. Parameters tested and Method(s) of test: as listed in the report below:

LABORATORY TEST REPORT

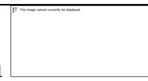
No.	Parameters		Results	Requirements	Test Method No.	LOD
1.	Bursting Strength	kPa	293	90Min	ISO 2758	
2.	Tearing Resistance	mN	1958	320Min	ISO 1974	
3.	Tensile Strength					
I	Tensile Strength - CD	N/mm	6.2		ISO 12625-4	
II	Tensile Strength - MD	N/mm	8.5		ISO 12625-4	
4.	Water absorptiveness	g/m²	205	25-30	ISO 535	

COMMENTS/REMARKS:
The sample performed as shown

Tabitha Orwa - Manager Polymer Laboratory
FOR: MANAGING DIRECTOR

2 March, 2023
Date of Issue

SUMMARY OF TEST RESULTS

PROPERTY	***Lye Paper Sample***	***Caustic Soda Paper Sample***
Color	Sand brown 	Sand brown 
Water Absorptiveness	463g/m^2	205 g/m^2
Bursting Strength	98 kPa	293 kPa
Tearing Strength	2252 mN	1958 mN
Tensile Strength - CD	1.63 N/mm	6.2 N/mm
Tensile Strength - MD	1.63 N/mm	8.5 N/mm

Alkalinity of the Lye	3120 ppm
pH of the Lye	11.3

Appendix C: Preparation of Lye

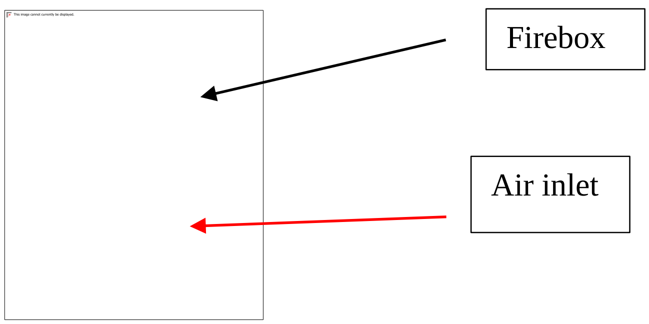
Materials, Tools, and Apparatus:

Clay stove, banana peels of green bananas, containers, newspapers, distilled water

Sample Preparation

Sun-dry banana peels until they are completely dry. The color of the dry peels will be black.

Procedure



A Photograph of Burning of Banana Peels to Retrieve Ash

Source: Source: Photograph by the researcher 2022

Dry peels were gathered and placed in the firebox on the clay stove as would place charcoal. Dry banana stems were placed in the air inlet of the clay stove and ignited. To ignite the dry banana peels. The banana peels were allowed to ignite and burn completely to form ash. The ash was left to cool and was retrieved upon cooling from the stove and placed in containers.

To prepare the Lye the banana peel ashes were put in a 2-liter container distilled water was added. 7% concentrated lye, 80g of the banana peel ashes were weighed and added to each 1 liter of water.

Appendix D: Decorticating Machine

This image cannot currently be displayed.

Source: Photograph by the researcher KEBS workshop in 2022

Appendix E: Bio-digester Machine

This image cannot currently be displayed.

Source: Photograph by the researcher KEBS workshop in 2022

Appendix F: Mechanical Pulping Machine

This image cannot currently be displayed.

Source: Photograph by the researcher KEBS workshop in 2022

Appendix G: Summary of Statistical Tests

Two-Sample T-Tests

PULP YIELD

t-Test: Two-Sample

	Lye	*Caustic Soda*
Mean	453.3333	373.3333
Variance	616533.3333	418133.3
Observations	3.0000	3
Hypothesized Mean Difference	0.0000	
df	4.0000	
t Stat	0.1362	
P(T<=t) two-tail	0.8982	

WATER ABSORBENCY

t-Test: Two-Sample

	Lye	*Caustic Soda*
	water x	*water y*
Mean	462.6667	205
Variance	554.3333	9100
Observations	3.0000	3
Hypothesized Mean Difference	0.0000	
df	2.0000	
t Stat	4.5421	
P(T<=t) two-tail	0.0452	

BUSRTING STRENGTH

t-Test: Two-Sample

	Lye	*Caustic Soda*
	burst x	*burst y*
Mean	98	293.3333
Variance	112	1433.333
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	-8.606486708	
P(T<=t) two-tail	0.013233065	

TEARING STRENGTH

t-Test: Two-Sample

	Lye	*Caustic Soda*
	tear x	*tear y*
Mean	2252	1980
Variance	13132	700
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	4.00578	
P(T<=t) two-tail	0.05704	

TENSILE STRENGTH CD

t-Test: Two-Sample

	Lye	*Caustic Soda*
	tensile x2	*y2*
Mean	1.6300	6.24
Variance	0.2212	0.0273
Observations	3.0000	3
Hypothesized Mean Difference	0.0000	
df	2.0000	
t Stat	-16.0176	
P(T<=t) two-tail	0.0039	

TENSILE STRENGTH MD

t-Test: Two-Sample

	Lye	*Caustic Soda*
	tensile x1	*tensile y1*
Mean	1.6300	8.53
Variance	0.2212	0.0576
Observations	3.0000	3
Hypothesized Mean Difference	0.0000	
df	3.0000	
t Stat	-22.6341	
P(T<=t) two-tail	0.0002	

One-Sample T-Test

WATER ABSORBENCY

t-Test: One-Sample	
	Lye
	water x
Mean	462.6667
Variance	554.3333
Observations	3
Hypothesized Mean	30
df	2
t Stat	31.8294
P(T<=t) one-tail	0.9995

BURSTING STRENGTH

t-Test: One-Sample	
	Lye
	burst x
Mean	98
Variance	112
Observations	3
Hypothesized Mean	90
df	2
t Stat	1.3093
P(T<=t) one-tail	0.8397

TEARING STRENGTH

t-Test: One-Sample	
	Lye
	tear x
Mean	2252
Variance	13132
Observations	3
Hypothesized Mean	320
df	2
t Stat	29.2013
P(T<=t) one-tail	0.9994

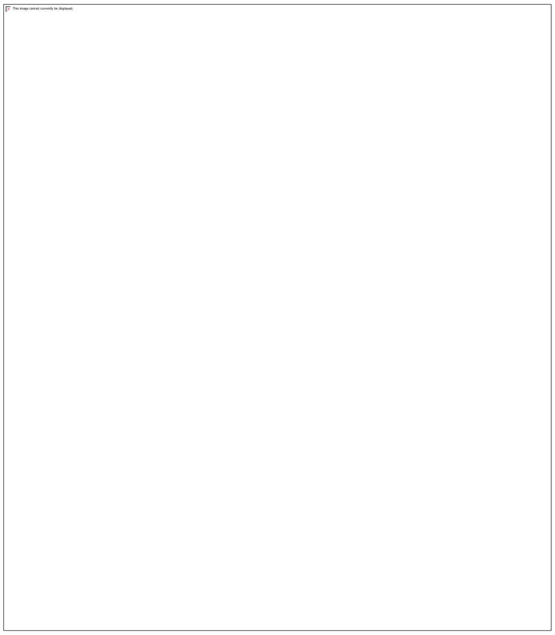
TENSILE STRENGTH (CD)

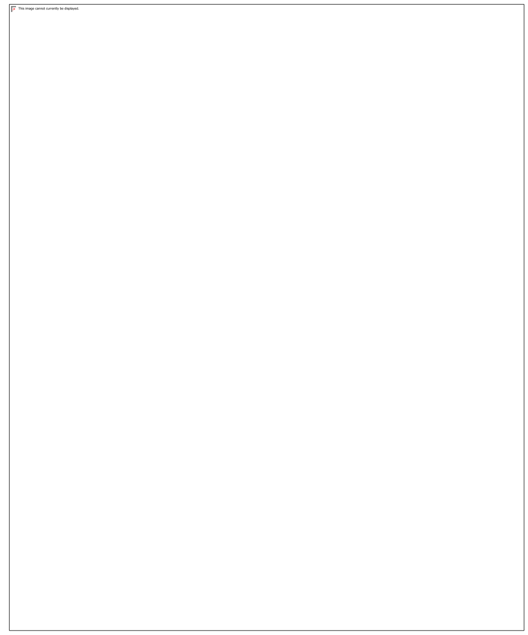
t-Test: One-Sample	
	Lye
	tensile x2
Mean	1.6300
Variance	0.2212
Observations	3
Hypothesized Mean	4
df	2
t Stat	-8.7280
P(T<=t) one-tail	0.0064

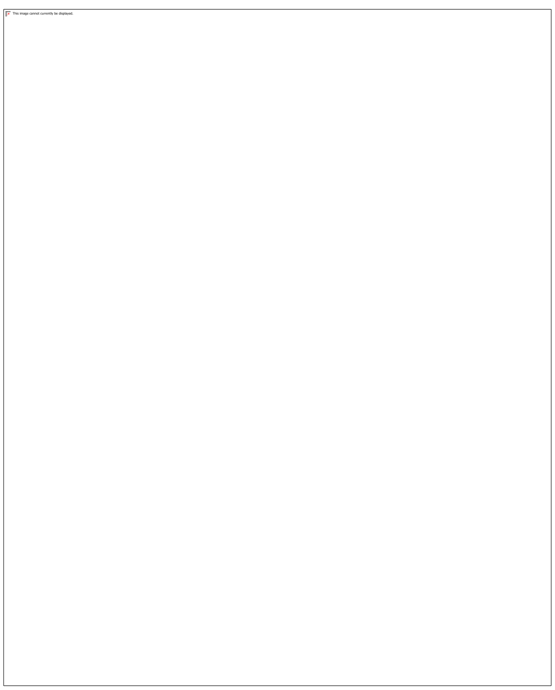
TENSILE STRENGTH (MD)

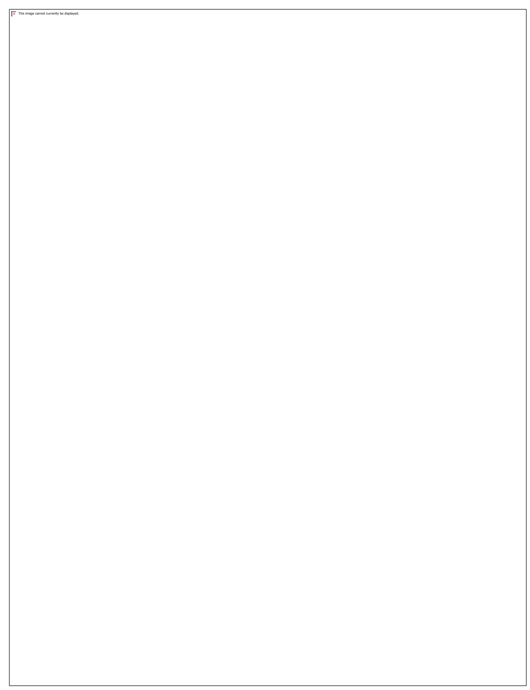
t-Test: One-Sample	
	Lye
	tensile x1
Mean	1.63
Variance	0.2212
Observations	3
Hypothesized Mean	5
df	2
t Stat	-12.4107
P(T<=t) one-tail	0.0032

Appendix H: Branded Packaging Prototypes Constructed from the Fabricated Lye Paper



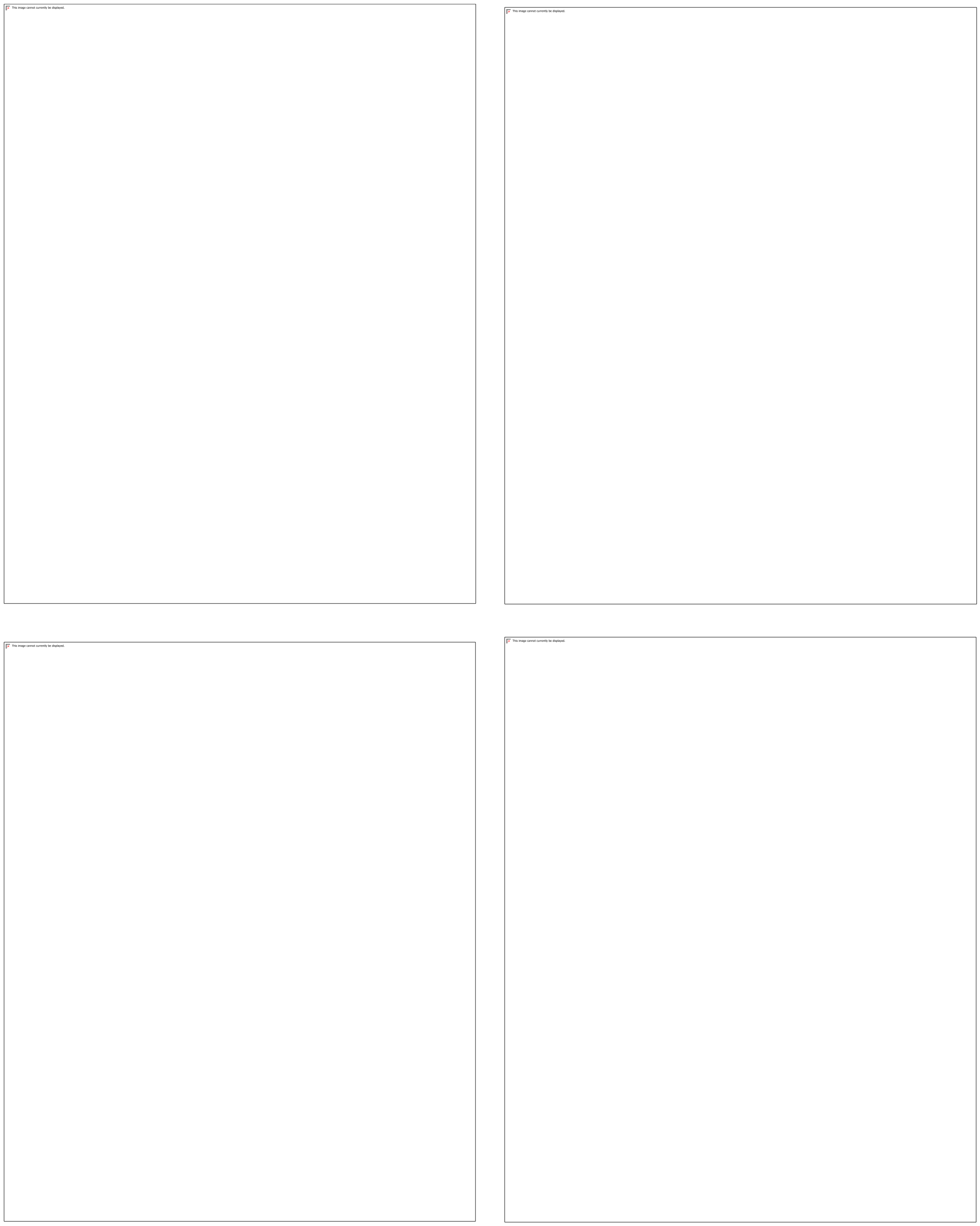






Prototype 1: Carrier Bag

Source: Photograph by the researcher 2023



Prototype 2: Shoe Box

Source: Photograph by the researcher 2023

Prototype 3: Jewelry Box

Source: Photograph by the researcher 2023

Appendix I: Approval of Research Proposal and from Graduate School

KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke
Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Internal Memo

FROM: Dean, Graduate School

DATE: 31st August, 2022

TO: Ms. Musombi Stephanie Kobehlo
C/o Department of Fashion Design & Marketing

REF: H60/25500/2018

SUBJECT: APPROVAL OF RESEARCH PROPOSAL

We acknowledge receipt of your Research Proposal after fulfilling recommendations raised by the Graduate School Board of 27th July, 2022.

You may now proceed with your Data collection, subject to clearance with the Director General, National Commission for Science, Technology & Innovation.

As you embark on your data collection, please note that you will be required to submit to Graduate School completed Supervision Tracking and Progress Report Forms per semester. The forms are available at the University's Website under Graduate School webpage downloads.

Also, please ensure that you publish article(s) from your thesis before submitting it to Graduate School for examination as per the Commission for University Education and Kenyatta University guidelines.

Thank you.

KENYATTA UNIVERSITY OFFICE OF DEAN 14 SEP 2022 GRADUATE SCHOOL NAIROBI

REUBEN MURIUKI
FOR: DEAN, GRADUATE SCHOOL

CC. Chairman, Department of Fashion Design & Marketing

Supervisors:

1. Dr. Mercy Wanduara
   C/o Department of Fashion Design & Marketing
   Kenyatta University

2. Dr. Jacqueline Kisato
   C/o Department of Fashion Design & Marketing
   Kenyatta University

Appendix J: Research Authorization Request to NACOSTI by Graduate School

KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke
Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Our Ref: H60/25500/2018

DATE: 31st August, 2022

Director General,
National Commission for Science, Technology and Innovation
P.O. Box 30623-00100
NAIROBI

Dear Sir/Madam,

RE: RESEARCH AUTHORIZATION FOR MS. MUSOMBI STEPHANIE KOBEHLO – REG. NO. H60/25500/2018

I write to introduce Ms. Musombi Stephanie Kobehlo who is a Postgraduate Student of this University. She is registered for M.Sc. degree programme in the **Department of Fashion Design & Marketing.**

Ms. Musombi intends to conduct research for a M.Sc. thesis Proposal entitled, **"Fabricating and Testing Properties of Paper Packaging Material Made from Kiganda Banana Stems from Kisii County, Kenya."**

Any assistance given will be highly appreciated.

Yours faithfully,

KENYATTA UNIVERSITY OFFICE OF DEAN
14 SEP 2022
GRADUATE SCHOOL
P.O. Box 43844-00100, NAIROBI

PROF. ELISHIBA KIMANI
DEAN, GRADUATE SCHOOL

Appendix K: Ethics Exemption Letter

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Appendix L: NACOSTI Research Permit

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Appendix M: Map of Kisii County