INVESTIGATION OF SUITABLE METHODS TO EXTRACT THE FIBRES AND OPTIMIZATION OF TREATMENT METHODS FOR SRI LANKAN BANANA CULTIVARS FOR TEXTILE MATERIAL

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March 2021

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the Degree of Master of Philosophy in textile.

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March 2021

DECLARATION

I declare that Master of Philosophy thesis entitled "Investigation of suitable methods to extract the fibres and optimization of treatment methods for Sri lankan banana cultivars for textile material" is my original work and contains no material that has been previously submitted, in whole or in part, for the award of any other academic Degree or Diploma in any other University or institute of higher learning except where the acknowledgement is made in the text.

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Prof. U.G.S. Wijayapala
Date: ……………………...

ABSTRACT

The banana pseudostem is an ideal source of natural cellulose substitute fibre. This thesis investigates the effects of banana fibre extraction and treatment parameters on fibre fineness, and establishes suitable methods to reduce the fineness that enable the usage of banana fibres as textile materials. Ten popular Sri Lankan varieties of banana pseudostem were selected for this study. Among the fibre fineness of the mechanically extracted banana fibre of the ten varieties, Ambun (genome AAA) middle layers of the pesudostem was selected for further analysis since it gives the lowest fineness. Enzyme and chemical treatments was ministered to the mechanically extracted fibre of the middle layers of the pseudostem. The diameter of the scanning electron microscope and fibre linear density were used to observe and determine the fineness of the biologically and chemically extracted fibres and enzymes from the chemically treated banana fibres. This demonstrated that fibres treated with a combination of enzymes and chemicals to be the finest. Furthermore, it was discovered that due to this combined treatment of enzymes and chemicals (5% Enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH) treated banana fibres achieved fibre linear density of 4 tex. The diameter of the fibre was reduced from 168.4µm to 48.8µm, which is a 71% reduction compared to the diameter of the mechanically extracted fibre. All the experiments conducted on the reflectance curves of dyed banana fibres found that the dye absorption tendency of pre-treated banana fibres and it's dyeing behaviours to be similar to that of cotton. This leads the current study to posit that the process of dyeing cotton can be used to dye banana fibres as well. The outcome of this research is to help those working in the apparel industry to select Sri Lankan banana fibres based on strength and finesse suitable for their textile products.

Keywords: *Pseudostem, Natural fibre, Banana fibre, Mechanical extraction, Biological and Chemical treatments, and dyeing*

ACKNOWLEDGEMENT

My heart full gratitude goes to Prof. G.L.D. Wickramasinghe, Professor of University of Moratuwa and Prof. U.G. Samudrika Wijayapala, Associate Professor of University of Moratuwa, Department of Textile and Clothing Technology who immensely supported me and guided me throughout the journey with their priceless enlightening input and supervision given.

I take this opportunity to convey my sincere gratitude to express thanks to Department of Materials Science and Engineering for the tremendous help and support.

Also, some special thanks go to Chairman of SLITA, Mr. M.A. Thajudeen Ministry of Industry and Commerce and Director (Technical & Training) of Sri Lanka Institute of Textile & Apparel, Mr. S Ilangovan for providing the necessary facilities to carry out the research work.

Furthermore, I would want to express my warm thanks to Textile Department, Mechanical engineering department of University of Moratuwa lecturers and my colleagues who supported me throughout the research by providing the facilities required.

Finally, my sincere thanks to all whose names were not mentioned but provided in various ways to the completion of this project and I would like to acknowledge the all out, support and encouragement extended by my family that has enable me to achieve this today.

Subashini Balakrishnan.
168069L
29/03/2021

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LIST OF ABBREVIATIONS

AATCC	- American Association of Textile Chemists and Colourists
ASTM	- American Society for Testing and Materials
CIE	- International Commission on Illumination
DCS	- Department of Census and Statistics
GDP	- Gross Domestic Product
FTIR	- Fourier-transform infrared spectroscopy
IBPGR	- International Board for Plant Genetic Resources
ISO	- International Organization for Standardization
SEM	- Scanning electron microscope
JIS	- Japan Industrial Standards

1 INTRODUCTION

1.1 Background of the study

The apparel industry in Sri Lanka is the most significant contributor to Sri Lankan economy. Since 1986 it has developed into Sri Lanka's largest export industry. In order to produce ready-made apparels in Sri Lanka, grey fabrics, finished fabrics and accessories are imported from foreign countries. In 2019, it was reported that the textile and apparel sector imported raw materials that was equivalent to the value of US$ 5,205.25 million (Sri Lanka Trade Statistics Economic Indicators, 2019), which represented 44.25% of the total country's imports for that particular year. This is a burden on the country's economy. To better improve the apparel industry, one method would be to manufacture locally grown fabric. However, Sri Lankan textile industry is unable to cope with the demand for fabric that is required for the export market of the apparel industry (Sri Lanka Trade Statistics Economic Indicators, 2019).

One main reason for this is the lack of raw materials sourced for the manufacturing of garments in the Sri Lankan apparel industry. This significant drawn back has highlighted the need to develop a yarn manufacturing industry in Sri Lanka. However, Sri Lanka does not produce any fibres, which is the raw material required for yarn manufacturing. But if Sri Lanka were to utilize the local raw materials that are available, such as pineapple fibres, jute fibres, flax fibres, bamboo fibres, coir fibres, sisal fibres, abaca fibres and banana fibres, it can boost the local apparel industry and reduce the economic burden as well. Countries such as Japan, Australia and Germany manufacture textile fabrics using cotton, flax, jute, bamboo and banana fibres (Subagyo & Chafidz, 2018). Currently, many famous designers and renowned fashion brands are moving towards eco-friendly fibres in the production of clothing and other apparel as well (Jain *et al*., 2016). This is encouraging news for countries like Sri Lanka to begin sourcing raw materials that are locally grown, which will create a niche market for banana textile and apparel products.

Banana is the most commonly grown fruit crop in tropical countries, including Sri Lanka (Wasala *et al*., 2014). Sri Lanka is known to cultivate banana in 50,000 hectares of land (Wasala *et al*., 2014). In Sri Lanka, cities such as Rathnapura, Kurunegala, Badulla, Monaragala, Kandy, Gampaha, and Hambantota have large banana crops that grow all year round. Due to the vastness of the geographically distributed harvest of banana plants, this banana pseudostem has the potential to be employed as a natural fibre to be extracted for the purpose of manufacturing fibres in Sri Lanka (Department of Agriculture, 2016).

There are further advantages of making use of banana pseudostem to manufacture fibre. Banana cultivation generates large quantities of biomass. Pseudostem and peduncle of banana crop contain significant amount of natural fibre. Due to the lack of appropriate technology, the natural fibre ends up as agricultural waste without an economic application. Therefore banana-pesudostem fibre can also be used as a natural cellulose substitute for other bast fibres such as hemp, flax, kenaf, jute, and ramie (Sinha, 2015). The banana pseudostem contains 60% of cellulose (Gupta *et al*., 2015) and due to the higher availability of this plant in Sri Lanka banana fibres can easily be produced here (Wasala *et al*., 2014).

Furthermore, banana fibre has proven to be very effective in several other aspects in the global apparel industry. With the recent move towards green technology banana fibre has a high potential to become a sustainable raw material for the textile industry (Padam *et al*., 2014). Banana fibre is an environmental friendly fibre, similar to that of jute fibre, which has a huge export demand in several countries such as Japan, Australia, Germany (Sheikh & Awate 2016). And in India, the use of banana fibre for manufacturing textiles is an innovative concept which has helped to develop the living standards of the rural community by uplifting the farmers by converting the disposable banana stems into a value added product, while generating extra income to banana cultivators and catering to the demand of eco - friendly textile materials. Recently India (Angel college of Engineering and Technology, Tirupur) exhibited a silk grade banana fibre that was manufacture using a separator machine (Vadivel *et al*., 2017). This demonstrated that the silk grade banana fibre can be utilized in the handcraft and textile industries. Additionally, banana fibre can be easily blended with cotton or other man-made fibres to produce fabrics (Mohammad, 2017). Banana fibres are utilized as a raw material in small-hold industry, namely in the making of products such as paper, cardboard, tea bags, and handcrafts in Sri Lanka (Preethi *et al*., 2013). The major banana fibre textile items are produced for large-scale manufacturing in Philippines and Japan (Ray *et al*., 2012).

However, in Sri Lanka, there is no significant research that was carried out to investigate the benefits of using banana fibre for textile application. It is imperative to identify and investigate naturally available fibres so that it can provide the sustainable textile raw materials to manufacture fibres that are suitable for the textile applications (Bai & Yu, 2011). Moreover, it is necessary to identify and evaluate the application of using natural fibres in the textile production to cope with the demand for textile raw materials.

This research work is to investigate the methods of extracting banana fibre from the Sri Lankan banana pesudostem varieties that are abundantly available island wide. The focal point of the present work is to investigating the effect of banana fibre extraction and treatment methods to produce a fibre suitable for textile application.

1.2 Statement of the problem

This research on pseudostem fibres was motivated by the following five reasons:

- the growing environmental awareness and preference for green textiles & apparels (Fatma, 2019),
- the demand for natural cellulose substitute fibre (Reddy & Yang, 2015),
- the enormous amount of banana pseudostem biomass waste in Sri Lanka and around the world (Milani *et al*., 2016),
- the added value to pseudostem waste and the extra income it will generate for cultivators
- the application and research on banana fibre to enrich the textile field in Sri Lanka.

Banana fibre fits perfectly with all of the above points. Moreover, banana pseudostem fibres is an alternative natural cellulose substitute found in Sri Lanka (Kun Li *et al*., 2010). And the lack of research work on banana fibre and previous research leave us much room to develop notable project questions and objectives. For example, after the banana fruit is harvested, banana pseudo-stem will be cut and become agro-waste (Gan *et al*., 2004), therefore it is necessary to develop a suitable technology to effectively utilize banana pseudostem waste. In order to make full use of this natural resource, banana pseudostem can be utilized as an alternative for the bast fibres (Aseer *et al*., 2013). Banana fibres from the plant of pesudostem has an export potential fibre source in fibre industry and it is gaining interests with researches (Sengupta *et al*., 2019).

Through a methodological review of existing research, the current study aims to answer the following questions:

- What are the existing banana fibre extraction methods in the global fibre industry?
- What are the effects of banana fibre extraction parameters on fibre properties?
- What are the most suitable methods to extract the banana fibres for textile materials?

1.3 Objectives of the research

In order to fulfil the aims of this research project, the following objectives have to be completed:

- Literature review on existing methods to extract banana fibres
- Investigate the effect of banana fibre extraction and treatment parameters on fibre properties.
- Determine the optimum parameters on extraction and treatment methods to produce banana fibres for textile materials
- Determine the reduced fiber fineness to meet textile requirements

1.4 Significance of the Study

1.4.1 Practical Importance

Sustainability is a recent concept fast gaining recognition amongst customer and manufacturer alike, on the advantage it brings to stakeholders. This research was motivated due to the high demand for natural-fibre-based products. This demand is currently solved by using bast fibres which are biodegradable fibres (Bai & Yu, 2011). Banana (Musa) plant is basically grown for consumption as a fruit. Once the fruit is harvested, it was found that an agricultural residue remains behind, the pseudostem being one of the agricultural waste. Since the fibre extracted from banana pseudostem plant is natural cellulose fibre (Malinen *et al*., 2014), this fruit is ideal in the manufacturing of natural fibre.

Therefore this study will examine the sustainability of banana fibre in textile production, by comparing how the biodegradable and environmentally beneficial aspects of banana fibre is to that of the synthetic textile fibres (Bai & Yu, 2011). Stem waste gives a value addition to the disposable banana stems. This research also aims to help increase the market value of banana fibres by highlighting the above mentioned advantages for fabric manufacturing process and give extra income to cultivators. This research caters to the demand of eco - friendly textile materials which can reduce the impact of synthetic material usage in Sri Lanka.

1.4.2 Theoretical Contribution

This study will put forward the environmental friendly nature of the extraction of the fibre from the banana stem. The study aims to ensure the commercial applicability of this research and how naturally extracted fibre contributes towards a more sustainable world (Mostafa & Uddin, 2015).

Fibre properties of Sri Lankan banana varieties have not yet been researched and reported, hence this study commenced by gathering data from cultivars on the fibre properties, such as surface structural features, fineness, tensile strength, chemical composition, fibre linear density and moisture content. Mechanical behaviour in between the layers of pesudostem (Sri Lankan banana varieties) properties have not yet been researched. This research identifies and tests the variability of mechanical behaviour in between the layers of pesudostem properties, such as fineness and strength. Both theoretical and empirical findings contributed to the understanding of the characteristics of banana pseudostem cultivars methods of extracting fibre. The physical and chemical characteristics of the extracted banana fibre can be obtained layer by layer. This data highlighted that the characteristics of banana fibre vary with the position of the leaf sheath, method of extractions and species. It was discovered that the peeling of these full length interior sheaths is difficult because of their poor strength and their brittle nature. Investigation in to the middle layer uncovered that it was very strong, full length (stem height) and fine fibres compared to that of the outer layers.

Next, it is vital to establish a grading system of banana fibre cultivars, so that each fibre can be allocated its specific purpose for textiles production. The fibre grading test is a very notable factor for research and improvement (Ghosh & Das, 2013). The identification of physical and chemical properties required to find the composition of different fibres is important (Khan *et al*., 2017). Bast fibres are commonly used as a textile material around the world. Nevertheless, the method of grading the different banana species has been questionable. Different grading methods were introduced for different kinds of fibres, but none for banana fibres. This research work introduces a grading system for banana fibres and the banana pesudostem fibres are graded through a technical and non-technical test.

Furthermore, this study provides a greater understanding of factors that influence the extraction and treatment of banana fibre. Investigating in to the combined treatment of enzymes and chemicals revealed that the fibre linear density is 5.6 tex, diameter is 48.8µm and the strength value is 2.931 gf. This treatment gives the fibre a level of spin ability (fineness) and show cases novel treatment method for banana fibres. However, to the best of the researcher's knowledge there are no significant investigative work carried out in Sri Lanka on banana fibre for textile applications, hence bringing the empirical novelty factor to the current study. The results of the color properties of treated and mechanically extracted banana fibre have not yet been researched. Suitable dyeing process for the banana fiber and dyeability properties have not yet been researched. This research also aims to evaluate the suitable dyeing process for the banana fibre by comparing the dyeing behaviour between banana fibres with that of cotton fibres. Furthermore, the effect of colorimetric (CIELAB) values and washing fastness on the dye concentration between banana fibre and cotton fibre samples were also examined.

1.5 Scope of the Study

The main focus of this research is the extraction of banana fibres for textile applications and to investigate the relationship between banana fibre extraction and treatment parameters and fibre properties. The scope of study covers the identification of properties and characteristics of extracted and treated banana fibres, such as their strength, fibre fineness, fibre structure, moisture content, water absorbency, FTIR analysis, X-ray diffraction properties and dyeability.

The study also looked in to identifying the possible end-use of banana fibres for textile industry by considering their properties and characteristics. Properties of other bast fibres such as jute, flax, ramie, hemp and Kenaf were compared with the banana fibres for a more rounded examination.

Due to their popularity and cultivation of large crops, and therefore availability for extensive study, this research was limited to the most popular ten Sri Lankan cultivars of banana plants namely, Embul, or Ambul (Mysore type, AAB group), Kolikuttu (AAB), and from the Cavendish subgroup: Anamalu (AAA), Rathambala /Rath kehel (AAA) and Ambon, or Amban (AAA). Ambun, Atamuru, Seeni, Alu kehel, Poowalu and Suwandel.

1.6 Organization of the report

Chapter 1: Introduction

Chapter 1 outlines the characteristics of the research problem. In this chapter, introduced five main significant viewpoints, which form the background of this research.

Chapter 2: Literature Review

This literature survey is organized into four main areas such as banana plants in Sri Lanka, banana fibre extraction techniques, banana fibre treatments and banana fibre properties. The chapter is specified the major ideas and findings that concern to the fibre extraction and treatments.

Chapter 3: Methodology of study

This Methodology is organized into four main areas such as research philosophy, research design, population and experimental design. This chapter gives clearly identifiable points on methods of fibre extraction, fibre treatments, instruments, techniques, testing methods and investigated properties.

Chapter 4: Data Analysis and discussion of results

This section introduces the data collected in the conducting different extraction and treatments methods for the statistical exploration to the research question.

Chapter 5: Conclusions and Recommendations

This chapter determines findings to help the writing overview and answer to the research question through the finding that cover these report objectives. The conclusion of this study, recommendation, limitation, and future research are presented here. It summarized the whole research project and conclusions remarks which can be made based on the results and discussions are presented.

2 LITERATURE REVIEW

2.1 Introduction

The literature review is organized into the following thematic areas: (1) types of banana (*Musa*) plants in Sri Lanka, (2) techniques used to extract banana fibre, (3) treatments methods for the banana fibre and (4) physical and chemical characteristics of banana fibre. Initially the chapter will summarise the theoretical knowledge of each thematic area and then examine the existing research on banana fibre. The chapter will then present methodological issues within the mechanical, biological, chemical extraction methods and treatment (enzyme and chemical) methods of banana fibres.

2.2 Textile Industry in Sri Lanka

The apparel industry in Sri Lanka is an active and a major contributor to the Sri Lankan economy. Over the last three decades, there has been a significant growth in the apparel industry and it has transformed in to the number one foreign exchange earner and the largest single employer in the apparel manufacturing industry (Samarasinghe *et al*., 2015).

The Sri Lankan apparel industry faces increasing competition within the existing global markets and it aims to enhance its prospects by increasing the raw material supply for the manufacturing process. This would eliminate the lead time in the manufacturing process, which is currently hindering the prospects of the Sri Lanka apparel industry in the global market. Furthermore, any delays encountered in obtaining raw material can be eliminated by inviting world-class fabric manufacturers, accessory manufacturers etc., to work with the stakeholders of the local market. This also indicates that there is a definite room to improve the textile industry in the region through development of the supply of raw materials and accessories for the apparel industry (Samarasinghe *et al*., 2015).

The production, usage and disposal of textile materials carried out within the textile industry has lead it to be one of the most ecologically harmful industries in the world. To overcome this, the use of natural fibres, which is known to cause a minimal damage to the environment is under consideration (Tandon & Reddy, 2013). Therefore, the role of introducing new raw materials for textile products is vitally important. Instead of producing fibres through raw materials in a mass scales, the production of niche items using various natural fibres that are available in Sri Lanka will give more economical advantages to the textile and apparel sector.

Sri Lankan textile industry had identified several natural fibres as a source of supply to provide a sustainable textile material. An investigation was carried out to investigate the suitability of the banana fibres for the textile industry in Sri Lanka, and due to its vast cultivation and accessibility in the country, banana fibre was chosen to be manufactured as a potential raw material (Rubasinghe, 2013).

2.3 Banana (*Musa*) in Sri Lanka

The banana fruit is popular amongst different economic classes thanks to its simplicity and suitability for any event. It is cultivated in 120 nations and 86 million tons of the banana fruit bunches is harvested annually around the World (National Horticulture Board, Ministry of Agriculture, India, 2016).

There are around 1000 assortments of bananas on the planet, subdivided into 50 groups (Liyanage *et al*., 1998). Sri Lanka boasts of 29 varieties, all of which is original to the island nation (Liyanage *et al*., 1998).

The banana (*Musa sp*.) is the world's fourth largest developed organic product and the largest natural product prevalent in Sri Lanka. The most commonly known banana is the Cavendish assortment, produced for the use in business sectors (Wasala *et al.*, 2014).

The banana varieties can be identified by their different skin hues, for example, ruddy purple, yellow, green and silver. The size of each variety varies as well, from a length of 3 to 40 cm (Perming, 2013).

Perming, (2013) recognises six popular varieties in Sri Lanka. Amongst them, farmers categorised Embul, Kolikuttu, and Seenikesel as the most widely consumed of the varieties. Figure 2-1 shows a banana plantation unit at Peradeniya.

Figure 2-1 A banana plantation in Peradeniya. Image courtesy: skyscrapercity.com

Life of a banana crop significantly depends upon the level of crop administration. A few producers in Sri Lanka harvest only the first bunch of the crop (Bolduc *et al*., 2018). Banana cultivation in Sri Lanka is recognized as a potential alternative sub-sector to boost the rural economy.

The policies and strategies for agricultural development used by the Sri Lankan government have focused on crop diversification and facilitating the creation of self-supporting, self-reliant and prosperous transformation of the rural sector with subsistence agriculture into profitable commercial ventures. Many countries use bananas as a food crop for its health benefits.

Bananas are rich in starch. Banana fruits are dried and grounded into flour, which is used to make bread. Flowers from certain bananas are considered a delicacy in some parts of India. They are usually cooked in curries. Banana leaves are also used as plates, mats, packaging material. For example, the Japanese make paper using banana fibres. The fibres of the plant can be wound into twine.

Abaca/Manila variety of banana used as a source of fibre in the Philippines. The aim of this research is to help identify the banana cultivars who can supply the best quality fibre to make yarn for textile products that can help them earn an extra income.

2.4 Agricultural waste from banana plantations

Agriculture is an essential sector of the Sri Lankan economy (Nanayakkara *et al*., 2018) and banana is a popular crop harvested all year around island wide. Banana plant in Sri Lanka is cultivated mainly for their fruits. After the cultivation, banana plantations generate tons of agricultural waste. Without a proper practice of agricultural waste management, a vast amount of perilous waste creates serious ecological damage (Padam *et al*., 2014). Agriculturists frequently face issues due to climate conditions, such as, floods and substantial breeze, and these climate conditions fluctuates the value of the banana fruit. Frequently farmers utilize labourers to either cut or abandon the banana pseudostem. These are usually thrown away by the roadside. A farmer has to bear the cost of this labour and many of them deem it as a wasted investment in banana fruit cultivation (Kumar, 2011). Moreover, dumping the banana stems adds to street pollutions and the pseudostem waste that are dropped in the plantation soil transforms to organic waste, all of which contributes to environmental pollution (Kun Li *et al*., 2010). Furthermore, pesudostem biomass is usually dumped in the agriculture areas, which encourages the breeding of banana pests and causes additional environmental problems (Brindha *et al*., 2017).

The banana pseudostem is perilous waste in Sri Lanka since it is not put to a better use. A small proportions of the waste have been utilized for few bio-items such as paper, crafted works, pickles, etc. (Kumar, 2011), but the majority is left as waste. The benefit of utilizing banana stem is many, from contributing to the GDP (Gross Domestic Product), of the country by producing various biodegradable items from banana wastes, to creating new job opportunity for women in the plantation sector. The income from the small holder production can support their livelihoods. Aside from these, all banana stem can be separated and changed over as a fibre, through basic machinery, enzyme, and chemicals methods (Ray *et al*., 2012).

This can be a supportable source of income for agriculturists, as well as the development of the surrounding area as fibre manufacturing industry (Vigneswaran *et al*., 2015). Figure 2-3 and figure 2-4 show that banana fibre wastes.

Figure 2-2 Banana Harvesting

Figure 2-3 Banana stem wastes

Figure 2-4 Banana crop destroyed by Cyclone Larry outside Innisfail in 2006.

2.5 Banana varieties of Sri Lanka

Musa cavendishii, Musa paradisiaca and Musa sapientum (the scientific term for the banana plant) are a few of the widely grown common species of musa (Mohapatra *et al*., 2010). Musa Cavendish is known as a pure triploid acuminate genome AAA group. Musa acuminate gives the “AA genome”. Musa balbisiana produces the “BB genome”. The dessert banana and plantain or cooking banana may become combinations of these sets of the genome and it can range from triploid (AAA, BBB, AAB, ABB) to several tetraploid blends (Padam *et al*., 2014). Musa paradisiaca and Musa sapientum species is known as a triploid acuminate AAB group (Mohapatra *et al*., 2010).

The banana variety groups with the genome AA, AAA, AB, AAB, ABB, AAAA, AAAB and AABB are the main varieties found in Sri Lanka and they are registered on IBPGR (International Board for Plant Genetic Resources). The *M. acuminata and M. balbisiana* varieties of the banana plant are edible prime varieties. *M. acuminata* diploids on the other hand, were introduced to Sri Lanka from the Indonesia region. *M. acuminata* diploids combines with *M. balbisiana* to form several hybrids of AAB and ABB triploids on Sri Lanka cultivations (Langhe *et al*., 2019).

Sri Lankan banana varieties can be classified into the following four main groups:

Genome type AAB	: Mysore group: - Ambul and Seeni
Genome type AB	: Kolikuttu group: -Kolikuttu, Suwandel, Rathkehel and Puwalu
Genome type AAA	: Cavendish group: - Anamalu, Embon or Ambun, and Nethrampalam
Genome type ABB	: Plantain varieties or cooking varieties: - Alukehel, Atamuru, Hambanpuwalu, Marathamana, Mondon and sambel. (Weerasooriya, 2016)

Ambul banana or 'Acrid banana' is the most commonly consumed fruit in Sri Lanka. Ambul banana is slightly sour and is grown everywhere on the island (Chandraratne *et al*., 2016). Many consumers prefer ambun (Pisang Ambon) banana for its sweetness. A Single ambun banana tree can produce a yearly gather of 7-10 clusters, each containing 140-200 bananas (Chandraratne *et al*., 2016). The Cavendish (AAA) banana variety is the most commonly cultivated variety worldwide (1/3) and it produces a harvest of 24,000,000 tonnes annually (Oliveira *et al*., 2007).

The Kolikuttu banana size is bigger than Seeni and Ambul bananas, but it is shorter than Anamalu banana. Kolikuttu is an extravagance banana (Chandraratne *et al*., 2016). Rath Kesel (Red Banana) on the other hand is a variety of banana with rosy purple skin. They are smaller and plumper than a basic Cavendish banana. In Sri Lanka these red bananas are usually cultivated in Kandy (Chandraratne *et al*., 2016). 'Seeni Kesel' or 'Elastic Kesel' (Sweet Banana / Pisang Awak ABB) are smaller in size. Much the same as general bananas, this assortment is regularly eaten crude as a treat after a dinner or in the middle of dinners (Chandraratne *et al*., 2016).

Some uncommon varieties like nethrappalm are categorised with the Cavendish group, Anamalu, and are for the most part offered as poojas, same as Suwandel and Puwalu. Atamuru, Alu kehel, Poowalu and Suwandel are other banana assortments which are available in Sri Lanka (Chandraratne *et al*., 2016).

2.6 Pseudostem

The pseudo stems of a banana plant is a large perennial herb with leaf sheaths that form the trunk and carry 8 - 12 leaves that are up to 9 ft long and 2 ft wide (Chaitanya *et al*., 2016). When the leaves spread out the stem of the banana is a green, stringy expulsion; with a softball-measure redbud that develops towards the end. Petal-like bracts develop between the covering scales encompassing this bud. They fall away, uncovering bunches of blooms. Elongated organic product rises out of the base of these blossoms.

The tips of the organic product develop towards the sun, giving the bananas their bow shape. Each plant delivers a solitary stem. The banana bunches that develops from the stems are called "hands” (Galan, 2010). Sony (2015) discovered that the leaf sheath of the banana pseudostem is covered in layers. Also the pseudostem sheaths of similar varieties of banana species have different measurements. Banana pseudostem consists of 13 layers of the sheath and 11 leaf sheath in the outer layer in the pseudostem can be utilized for extracting fibres.

The pseudo-stem comprises of a soft central core and is tightly covered up by 25 leaf sheaths. The height of the banana plant can range around 7.5 m (Asmanto and Achmad, 2016). After 18–24 months, the outer pseudo-stems of the banana plant are mature and the flower comes out, then the pseudostem are finally ready for harvesting (Asmanto and Achmad, 2016). Figure 2-5 shows banana pseudostem.

Figure 2-5 Banana Pseudostem

The chemical composition of banana pseudostem produce fibres that are of high quality, and therefore it was selected for this study. Jayaprabha *et al*., (2011) reported that lignin content in the outer sheath of pseudostem is higher than other layers due to the presence of mature cells in the outer region. Different sheath layers contain different percentages of cellulose, lignocellulose and hemicellulose 60% of the pseudostem contains cellulose and nearly 20% of lignin. Moisture content of banana pseudostem is 93.2-94.6% due to the lignin content the moisture content also decreased (Shivashankar *et al*., 2006). Banana pesudostem have lower lignin content than wood and straw and higher ash and extractive content than wood fibre. Pesudostem containing 96% of moisture content due to the chemical composition of lignin (Kun Li *et al,* 2010).

Fibres produced from the extracted banana pesudostem is attracting the interest of researches thanks to its export potential as a source of fibre (Aseer *et al*., 2013). Banana fibres are also completely biodegradable and more environment friendly than synthetic fibres (Malinen *et al*., 2014).

The fibre properties of produced from the extracted pseudostem differ according to the to the variety, soil conditions, climatic, irrigation (soil water content), and use of the type of fertilizer (Livifile *et al.*, 2019).

Subagyo and Chafidz (2018) studied the cross section view of banana pseudostem and listed the parts as follows (Figure 2-6):

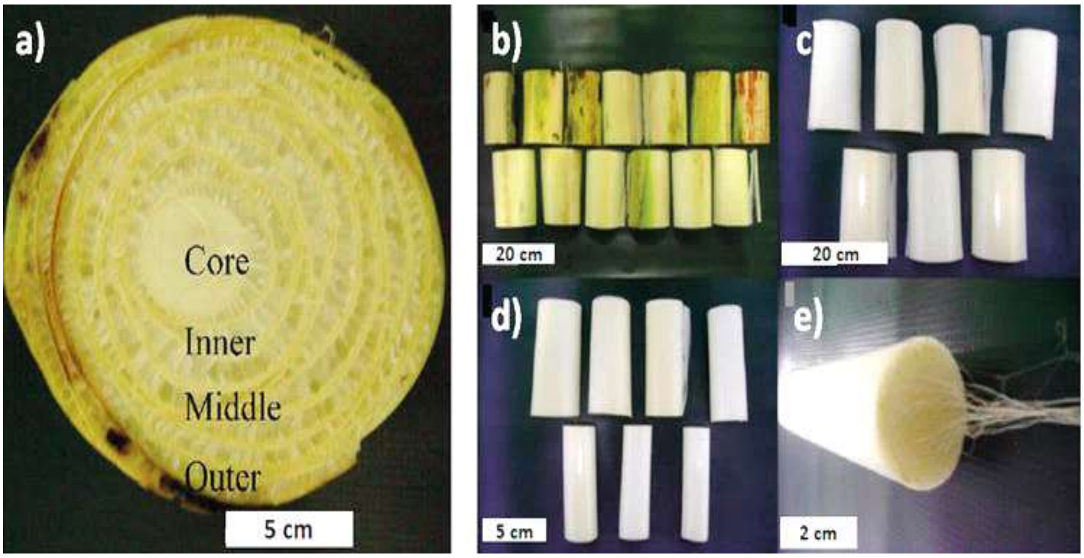


Figure 2-6 Cross section view of pseudostem

a) Banana pseudo-stem trunk cross section
b) Outer parts
c) Middle parts
d) Inner parts and
e) Core parts

2.7 Top Banana Producing Countries

India is the largest banana producer with a yearly yield of around 14.2 million tons, followed by China, Indonesia, Brazil, Ecuador, Philippines, Angola, Guatemala, Tanzania, Rwanda (National Horticulture Board, Ministry of Agriculture, India, 2020). Subagyo and Chafidz's (2018) study reveals the production of banana fibre in the world has reached approximately 100,000 tons/year. Production of banana worldwide was 113,212,452 per year in 2020.

India is the largest banana producer in the world with 29,124,000 tonnes of production volume per year. China comes second with 13,324,337 tonnes of yearly production. Rwanda comes last with 3,037,962 (National Horticulture Board, Ministry of Agriculture, India, 2020).

Table 2-1 Top banana producing countries

Rank	Country	Production 2019 (Tones)	Production per person	Acreage (Hectare)	Yield (Kg/Hectare
1.	India	29,124,000	21.792	846,000	34,425.5
2.	China	13,324,337	9.559	430,046	30,983.5
3.	Indonesia	7,007,125	26.44	139,964	50,063.7
4.	Brazil	6,764,324	32.283	469,711	14,401
5.	Ecuador	6,529,676	382.6	180,337	36,208.2
6.	Philippines	5,829,142	54.781	456,641	12,765.3
7.	Angola	3,858,066	131.9	131,455	29,348.9
8.	Guatemala	3,775,150	218.19	78,206	48,271.6
9.	Tanzania	3,559,639	65.677	468,470	7,598.4
10.	Rwanda	3,037,962	253.14	322,009	9,434.4

(Sources: Food and Agriculture Organization, 2020)

2.8 Land used for banana cultivation in Sri Lanka

The data presented in table 2-2 outlines the land used for banana cultivation in Sri Lanka from different provinces and districts. Table 2-2 shows, the Monaragala and Kurunagala districts have allocated the largest land areas, up to 6,900 hectares, for the cultivation of banana plants compared to other districts.

Around 2,000-3,000 hectares of land is allocated for the banana plantation in Hambantota, Kandy, Matara, Badulla, and Kegalle, each. Sri Lanka cultivates about 56,216 hectares in the banana cultivation and the cultivation produces about 44,177 bunches annually (DCS, 2015). This is a strong sign that Sri Lanka has the potential to extract banana fibres for the use of its textile industry.

Table 2-2 Land used for banana cultivation in Sri Lanka

Province	District	Land used for banana cultivation (ha)
Central	Kandy	3166
Central	Nuwara Eliya	771
Central	Matale	1685
Eastern	Ampara	611
Eastern	Batticaloa	461
North Central	Anuradhapura	1571
Northern	Kilinochchi	172
North Western	Kurunegala	6981
Northern	Mannar	362
Northern	Jaffna	531
Northern	Mullaitivu	382

Sabaragamuwa	Kegalle	2707
Southern	Hambantota	3534
Southern	Matara	2338
Southern	Galle	1700
Western	Colombo	908
Western	Gampaha	2709
Western	Kalutara	1182
Uva	Monaragala	6962
Uva	Badulla	2464

Source: (Department of Census and Statistics, 2016)

2.9 Banana fibre properties

This section will now examine in detail the different properties of the banana fibre such as fineness, tensile strength, surface structural features, chemical components and moisture content. The banana fibres can be extracted from the pesudostem by mechanical, biological and chemical extraction methods. These fibres can then be used as a cellulosic fibre (Soni *et al*, 2016) which this study has established as a sustainable raw material for the use of the textile industries in countries like Sri Lanka.

The banana fibre is a lingo-cellulosic fibre which is known to have superior mechanical properties, such as, lightweight, slighter extension, fire resistance, solid humidity, absorption quality, low density, appropriate stiffness, high disposability and biodegradability (Gupta *et al*, 2015 : Kumar *et al*., 2013). Furthermore, the banana fibre is highly breathable, has a microbial resistivity and a smaller elongation ability to dry quickly (Soni *et al*., 2016). The banana fibre has strong mechanical properties due to its high alpha cellulose and low lignin composition (Aseer *et al*., 2013 : Amir *et al*., 2017). Suhaib (2016) reveals that the banana fibre is naturally degradable like jute fibre. Ray *et al*., (2012) study highlights the similarity between the banana fibre, bamboo fibre and ramie fibre, but they found that the fineness and spin ability of the banana fibre is better than the other fibres. This has lead countries like Japan, Australia and Germany to increase their demand for the banana fibre (Gupta *et al*, 2015).

The banana fibre also has a greater stiffness, it is less cohesiveness, has a higher irregularity, and it is multi-cellular in nature. However, these properties affect the spin ability of a textile yarn. In addition, banana fibres are also used as a textile material for their excellent properties of tenacity, increased wet strength, luster, microbial resistivity, easy drying (Shroff & Karolia, 2015).

Figure 2-7 Banana fibre

Based on the optical microscopy analysis, a banana fibre has four kinds of cells arrangements, namely xylem, phloem, schlerenchyma and parenchyma (Kulkarani *et al*., 1983: Aseer *et al*., 2013).

The cell shape fluctuates from circular to polygonal with rounded balanced corners or a circular shape to an elliptical (Mukhopadhya, 2008: Kulkarani *et al*., 1983). The diameter of a raw banana firer varies between 100 µm to 200µm (Kulkarani *et al*., 1983).

Figure 2-8 displays the cross-section of the banana fibre, whereas Figure 2-9 exhibits the shape of the cell structure of the banana fibre (Aseer *et al*., 2013). The individual fibre comprises of numerous long fibres that are covered in some sheath-like structure (Aseer *et al*., 2013). The lumen is huge, unmistakable, round and uniform across the fibre. This fibre contains epidermal cell, which is nearly rectangle, sticks together shaping a little part of the fibrous cell (Aparna, 2007)

The cross-section of a banana fibre is a rough surface and has a hollow inside structure (Aseer *et al*., 2013). Jagadeesh *et al*., (2015) study reveals that the cross sectional structure of the banana fibre has an elliptical shape hoses. The cells spread over 100-

200 µm in diameter. The banana fibre cells inner cell wall thickness is 0.25µm and is in contrast to coir cells, which has a thickness of 8µm.

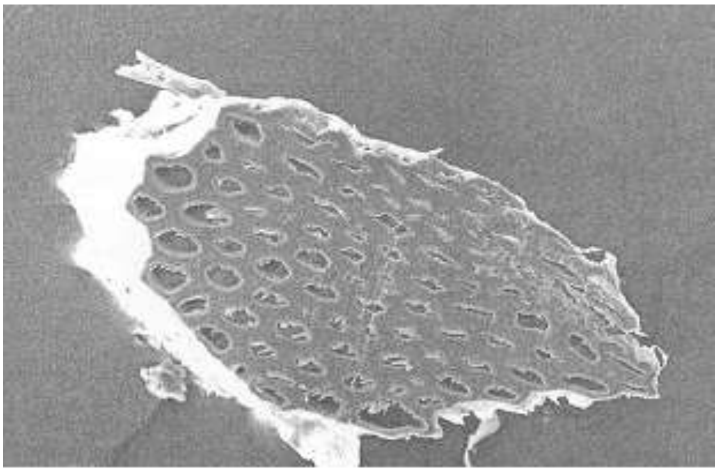


Figure 2-8 Cross section of banana fibre is magnified (250x)

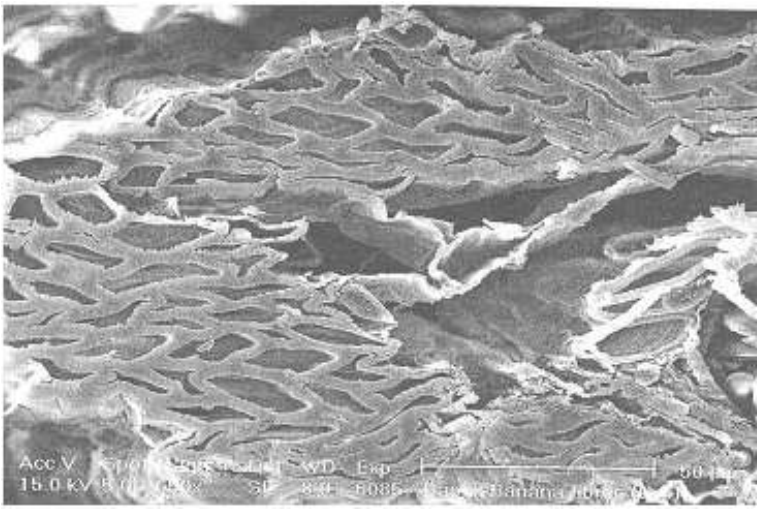


Figure 2-9 Structure of cell from banana fibre in shape wise (650X)

Figure 2-10 compares the images of the cross-section of banana fibres from different varieties scanned using an electron micrograph: (a) 'Ambul' (Mysore AAB), (b)'Ambun' (Cavendish AAA), (c) 'Seenikesel' (PisangAwak ABB), (d) 'Kolikuttu' (Silk AAB), (e)'Alu Kesel' (ABB), (f) (Milani *et al*., 2016). The fibres of the banana structure are formed when several bundles of elementary cells overlap and bond together by lignin. The nodes were observed at irregular distances along the fibres which is identified as bast fibres (Alwani *et al*, 2015).

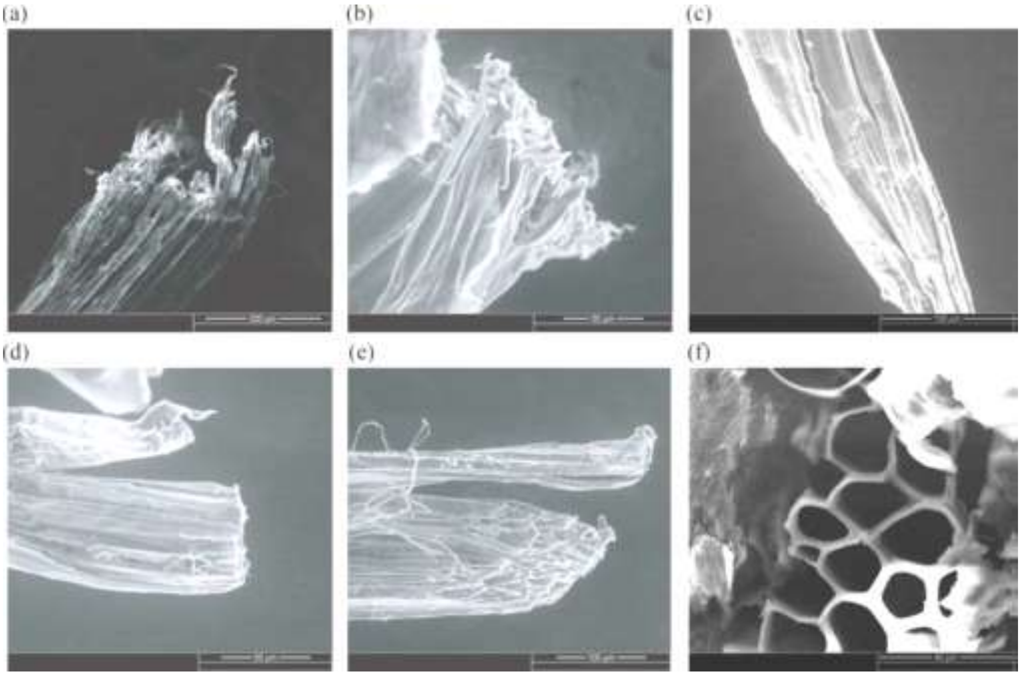


Figure 2-10 SEM microscopy of surface of banana fibres

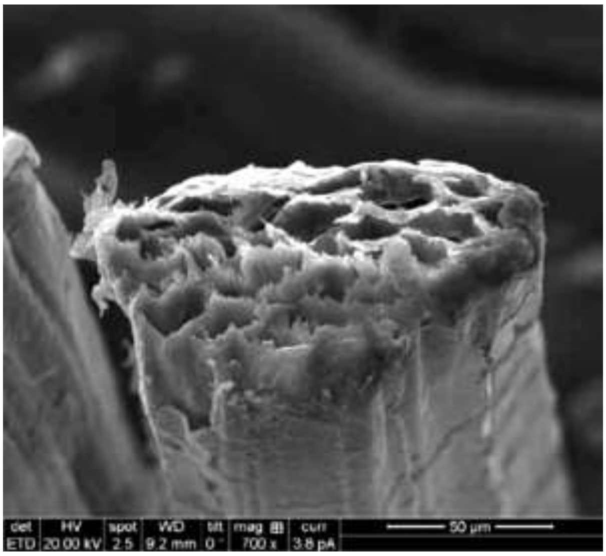


Figure 2-11 SEM microscopy of cross section of banana fibre

Several studies have looked in to the chemical composition of banana fibres. Cellulose, hemicellulose, and lignin are three main organic compounds of plants cell walls (Chen, 2014) and therefore has a huge effect on the properties of the banana fibre properties, which in turn influence the its fibre characteristics (Kumar *et al*., 2013). Cellulose is the largest chemical in the banana fibre and provides strength and resistance to the plant cell walls. Banana plant fibre contains around 16% of hemicellulose component.

Hemicellulose is lightly cross-linked and normally functions as liner among cellulose and lignin (Doshi & Anjali, 2016).

Table 2-3 Chemical composition of banana fibres

Cellulose (%)	60 -65
Hemi cellulose (%)	6 -19
Lignin (%)	5 -10
Pectin (%)	3 – 5
Ash (%)	1 – 3
Extractives (%)	3 – 6

Source :Gupta *et al*., (2015) and Jagadeesh,et al.,(2015)

Table 2-3 shows the chemical composition of the banana fibre (Jagadeesh *et al*., 2015 and Gupta *et al*., 2015). Lignin is the more hydrophobic component. The properties of lignin are usually characterised by the content of methoxyl, carboxyl, hydroxyl and carbonyl groups. The lignin component affects the construction, characteristics, morphology, and flexibility of the banana fibre (Doshi & Anjali, 2016 : Kumar *et al*., 2013).

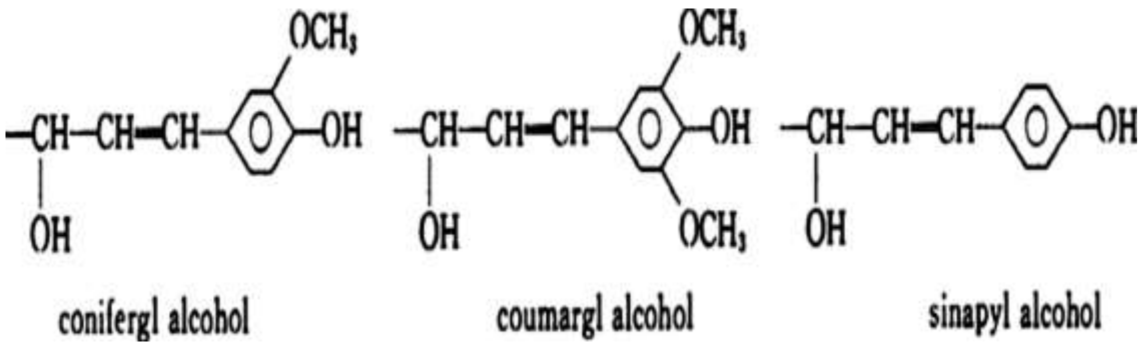


Figure 2-12 Basic structural unit of lignin

The mechanical properties depend on cellulose content along with micro fibril-angle. Mechanical properties of banana fibres are determined by low micro-fibril angle and high cellulose content (Kulkarni *et al*., 1983). The crystalline cellulose of the banana fibre is arranged in a helix at an angle of 11^0 to 12^0 and has a diameter of 100 to 200µm (Kulkarni *et al*., 1983).

Presence of both crystalline and amorphous regions in all five different banana varieties (Ambun, Ambul, Kolikuttu, Seenikesel, Alu Kesel) found in Sri Lanka was studied by Milani *et al*., (2016). X-ray powder diffraction patterns are observed in banana fibre powder that supports the presence of both crystalline and amorphous regions. Milani *et al*., (2016) reported mainly the cellulose structure with the intensity peak at 2Θ = 22° and a shoulder in the region 2Θ = 18°–20°. Mohiuddin *et al.,* (2014) explained that banana fibres contain lignocelluloses and comprising of helically twisted cellulose small-scale fibrils in amorphous matrix of lignin and hemicelluloses. Independent studies of the composition of the fibre by two investigators have established the same results.

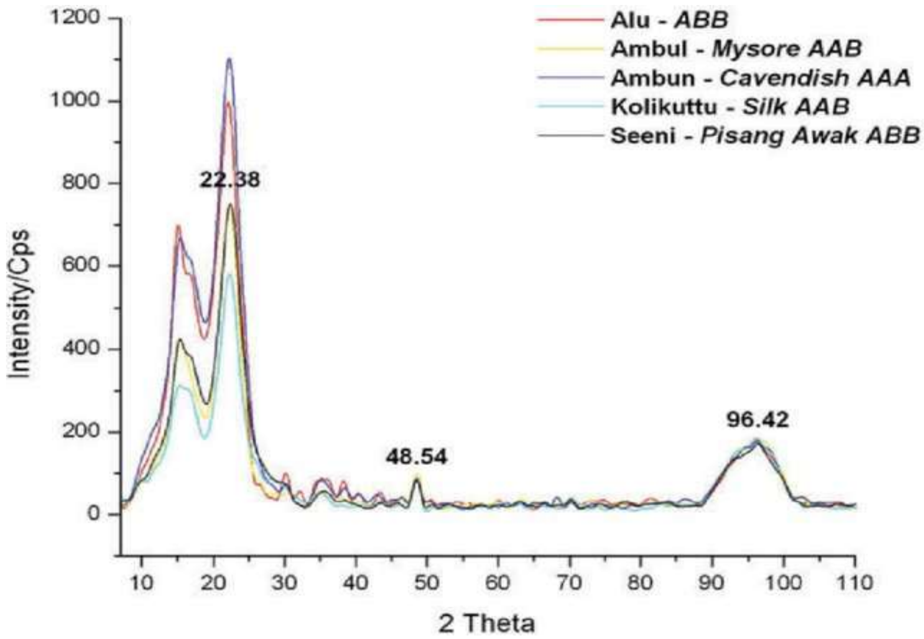


Figure 2-13 X - ray diffraction of banana varieties

Cellulosic fibres contain micro fibrils in an amorphous matrix of lignin and hemicellulose. These fibres consist of several fibrils that run all along the length of the fibre. The strength and stiffness of the fibres are achieved by hydrogen bonds and other linkage (Amir *et al*., 2017). The amorphous structure of the cellulose fibres has confirmed the FTIR and XRD analysis. The analysis through FTIR and X-Ray diffraction confirms that the chemical composition of the banana fibre as Cellulose, hemicellulose, pectin and lignin (Peets *et al.,* 2019).

Jagadeesh *et al*., (2015) reveals that the FTIR spectrum for raw banana fibre absorption band is at 3326 cm^{-1} as allocated for hydroxyl groups. Raw banana fibre has impurity and it spectrum depicts C=0 at 2273 cm^{-1}. FTIR spectrum found that, O-H stretching, C-H stretching, C-O stretching =O stretching, C–O–C stretching, C–O stretch and C-C aromatic bond types are found in banana fibres and that banana fibres are cellulose and lignin grounded materials. FTIR results (Figure 2-14) of 'Ambun' (Cavendish AAA), 'Ambul' (Mysore AAB), 'Kolikuttu' (Silk AAB), 'Seenikesel' (PisangAwak ABB), 'Alu Kesel' (ABB) showed similar absorption wave lengths (Milani *et al*., 2016).

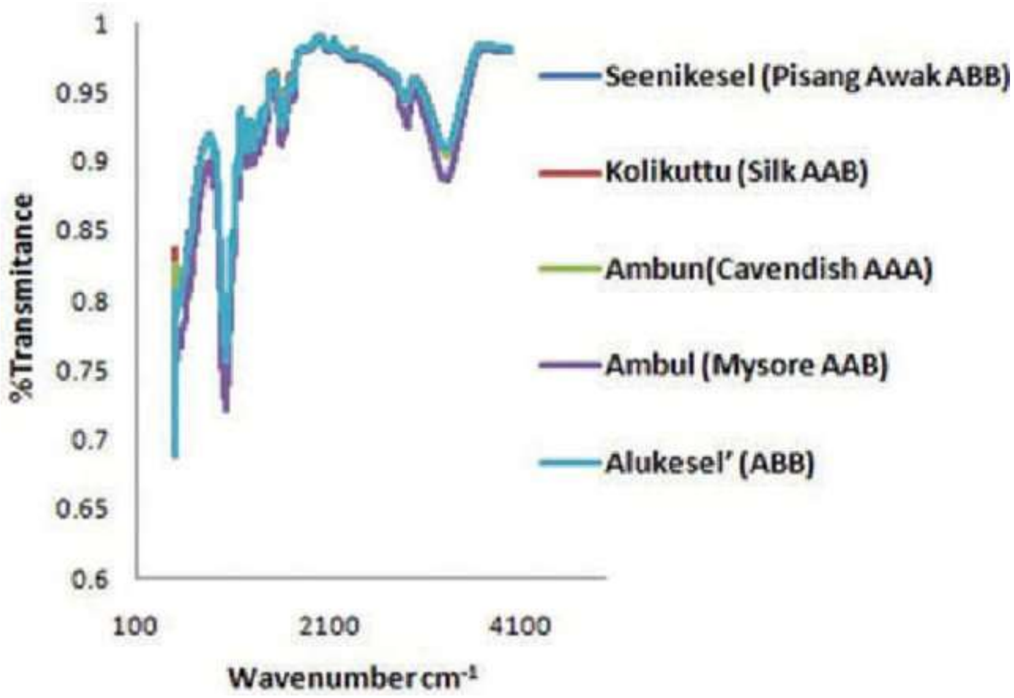


Figure 2-14 FTIR analyis of banana varieties

Banana fibres show high variability along the length and between the fibres of the banana pseudostem (Mukhopadhyay *et al*., 2008). The length of the banana fibre varies on the specific method of its extraction. For example, manual extraction method, extraction machine type, treatment of the fibre during fibre extraction changes the length of the fibre (Temesgen & Sahu, 2014). The importance of the length of the fibre lies in its processing, especially spinning, where generally the longer a fibre is, the easier it is to process. Strength of the banana fibre is measured in tension when the fibre is loaded along with long axis and designated as tensile strength. A universal tensile tester is used to measure the strength of the single fibre. The strength of the fibres is normally expressed as ‘tenacity’, meaning the maximum force (Newtons) required to break the fibres is divided by the linear density(tex) at the point of rupture. The tenacity of the banana fibre is measured as the breaking strength. Sarma & Deka, 2016 reported that the tensile strength of the raw banana fibre is 30.6 cN/tex.

Chauhan & Sharma (2014) defines fibre fineness as the size of the cross-sectional dimensions of the fibres and Liyanage *et al*., 1998 study showed that, fibre fineness means the measure of the cross-sectional measurements of the filaments.

Chauhan & Sharma (2014) describes fibre linear density of the fibre as the frequently used testing method of fineness. Temesgen and Sahu (2014) is of the view that the banana and jute fibre fineness are determined by microscope and torsion balance. The fineness of the banana fibre linear density is around 6.77 Tex. Subsequently, the fineness of the banana fibre contrasted with that of the jute fibre revealed that the banana fibre is coarser.

Aseer *et al*., (2013) demonstrates that the diameter of the banana fibre has a range of around 0.03 to 0.36 mm. Ray *et al*., 2012 reported that the fineness of the mechanically extracted banana fibre is 24μm. Shroff and Karelia’s, (2015) study shows that the fineness of the mechanically extracted fibre was 130 deniers. However, Subagyo and Chafidz's, (2016) report revealed that the mechanically extracted fibre diameter was about 80 - 250 µm. But the fibre diameter of the top ten banana varieties used in the current research vraied from 78.02 µm to 214.4 µm indicating that it is of a similar value to finidings in Subagyo and Chafidz, (2016) study. Mohiuddin *et al*., (2014) mentioned that caustic soda treatment improves the fibre fineness to produce fine yarn.

The raw banana fibre has a very low moisture-holding ability (Temesgen & Sahu, 2014) because of the presence of hydroxyl groups (Shah *et al*., 2013). Shroff and Karolia, (2015) reported that the raw banana moisture regain was at 8.63%.

Banana fibre is a cellulosic fibre and strongly hydrophilic components with many hydroxyl groups (–OH) in the structure of the fibres. The hydrophilic nature of banana generates the water uptake by these lignocellulose components, due to the formation of hydrogen bonds between fibre and water molecules. (Shah *et al*., 2013)

2.10 Applications of Banana Fibre

The banana fibre has the potential for industrial applications in the manufacturing of paper, rope, mat industries and production of other composite materials for vehicles (Padam *et al*., 2014). Soni & Patel (2016) found that the banana fibre can be used to produce car mats by mixing a yarn with jute, cotton and banana fibre to make a nonwoven fabric.

Banana fibres are a cellulose substitute for high-quality paper making and reinforced composites (Ray *et al*., 2012). Mohiuddin *et al*., (2014) highlights how the Philippines, Malaysia, Japan, and Korean countries use banana fibre as blended material in their textile industry. European countries were found to make socks and gloves using banana fibres (Mohiuddin *et al*., 2014). Mohapatra *et al*., (2010) mentioned that banana fibres can be used as environmentally degradable bag (eco-bag), hard paper, and as card boards.

Figure 2-15 Handicraft from banana fibres

2.11 Studies related to banana fibre extraction and treatment methods

The banana fibres can be extracted from the pesudostem by mechanical extraction and biological, chemical extraction or degumming and treatment methods (Vellaichamy & Gaonkar, 2017) : Ray *et al*., 2013).

Mechanical and biological extraction methods help to eliminate the adhesive substance from the surface of the fibre bundle (Doshi & Anjali, 2016). Furthermore, the chemical extraction procedure causes natural pollution and creates more ecological issues compared with the other two methods (Hoondal *et al*., 2002).

2.11.1 Mechanical extraction methods

The fibres from the pesudostem could be extracted by hand as well as by a decorticator.This section will examines the two methods that Beam's (2013) study identified to mechanically extract banana fibres, namely: Manual stripping and decorticator extration methods.

Manual stripping

The banana fibre is arranged on the outer surface of the sheath which enables it to be peeled-off in pieces of 5-8 cm wide and 2-4 mm thick along the entire length of the sheath. The stripping strategy is known as tuxying and the strips are called "tuxies".

Bacnis method and Loenit method are used for tuxying in Philippines (Ray *et al*., 2012). A manual stripping method is used in the Philippines and India, which is another tropical country similar to Sri Lanka.

The Philippines has a large natural fibre manufacturing market and Sri Lanka can learn from the techniques used in these countries. Figure 2-16 illustrates the banana stem stripping process.

Figure 2-16 Banana fibre stripping process steps

a. Bacnis method

The outer sheaths of banana pseudostem are tightly covered by layers of fibre, which is approximately four per cent of its weight (Drews and Noorden, 2014). The fibre is located primarily adjacent to the outer surface of the sheaths and can be peeled-off in ribbon strips of 5 to 8 cm wide and 2 - 4 mm thick, in the entire length of sheath. Bacnis hand stripping process is widely followed in Philippines and India.

The fibre that is stripped clean is then air dried and made up into bundles for subsequent grading and bailing. This way the trunks are pulled and separated from the sheath. Then the trunks are levelled, and the fibre is stripped from the stem by tuxying (stripped) the thick part and pulled from the tuxy (ribbons).

b. Loenit method

Loenit method is a semi-mechanical extraction method where the ribbon strips (tuxy) are extracted using a knife or any sharp pointed tool. Ribbons are cut from one sheath at a time and then the fibres are dried and washed in the water.

Kumar *et al*., (2013) explains that in India, the stem is cut into small pieces to ease the scrapping process. The stem layers are scrapped using comb-like scrapper. Then scraped fibres are hung in the shade to dry. This kind of scrapping process demands considerable skill and patience. Research on this kind of hand extraction processes pave the way to create minimum a cost in the production of extracted fibres.

Decorticating machine extraction method

Studies have been carried out on the yield and the quality of fibre extracted from pseudostems using the decortication extraction method (Ray *et al*., 2013). Fibres are extracted using a decorticator machine (Mukhopadhyay, 2009).

The decoatication machine consists of a rotating drum mounted shaft. As the drive rotates, the strips cut from the banana stems were fed between the drum. By using decorticator crushing action the pulp was removed. After the extraction, excess pith of the fibres were removed thuough gentle combing. The the fibres are then immersed in a large centrifugal washing machine to wash and then allowed to dry.

The flow chart in Figure 2-14 illustrates fibre decorticating steps in the production of banana fibres.

References are found in the literature regarding the development of automatic and semi - automatic decorticating machines to extract fibres from pesudostem in an attempt to improve the production rates (Vigneswaran, 2015 : Das *et al.,* 2010).

Figure 2 14- Banana fibre extraction process

On the other hand, there are eco-techniques for the extraction of fibre (Bavan, 2011). Here the decorticating machines are used for mechanical separation of fibres. Drews and Noorden, (2014) explains how the machines that cut stems are used to cut banana stems into sections of 120 to 180 cm in length. This layer of the stems layers crushed between rolls (decortication method). The pulpy tissues are scraped away from the fibres, which are then oven dried, graded and baled.

Mechanical operations for the extraction of the banana fibre simplifies the fibre separation to a certain extent. However, there is a heavy damage to the fibre in mechanical separation along with higher level of material wastage.

There are more mechanisms for the extraction of the banana fibres. For example, Pitimaneeyakul (2009) employed a made-up motor-driven machine as an extraction tool for banana pseudostem. Manohar (2016) found a slotted-barrel rotating machine to extract the banana fibres. Here the decortication machine has a single roller with 27 horizontal stainless steel blades and blunt edges. Compared to manual process, this decortication method increases fibre production and reduces the labour work. Stems of banana plants layers are crushed between two drum rollers and the pulpy part is removed and finally fibre is achieved (Vadivel *et al.,* 2017). The line diagram of a decorticator shown in Figure 2-15.

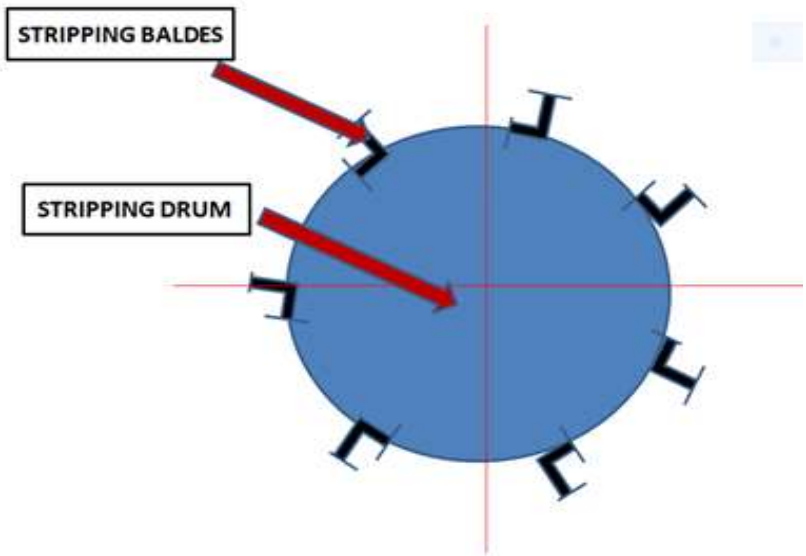


Figure 2-15 Decorticator semi – automatic

Ray *et al*., (2012) highlights how the decortication method is a simple and user-friendly method that enables a clean working environment, produces more fineness fibres and has a low maintenance cost.

The decortication method extracts 15 kg of fibre in 8 hours. This method provides fibre with superior quality in terms of length, softness, strength, and colour (Vadivel *et al.*, 2017).

In 2016, Suhaib and Awate, published a report on a modern machine for the decortication process. This method, derived from attempts to improve the production rates, can produce quality fibres with fibres that are uniform in size and free from pulpy materials. This machine is power operated using 700 rpm.

After comparing different mechanical fibre extraction methods, the decortications method was selected for the use of this study. Based on the practical experience gained from this study, it can be stated that the stripping method is not suitable in the extracting of long fibres like banana fibre. The percentage of fibre breakage is high in the stripping method and it is difficult to extract large quantity of fibres. Furthermore, the stripping method reduces the fineness of the fibres which is necessary for producing quality textile.

Compared to the stripping process, the decortication fibre extraction method was found to reduce the labour work, gives higher efficiency and increases the quality of the fibre since the fibres that are split using machine decortication are also coarser. However, it is surprising to note that inventors have not utilised this machine for the extraction of fine banana fibres, given its advantages as mentioned in this section.

References are found in the literature regarding development of automatic and semi – automatic decorticating machines for banana fibres. In this research study, the automatic decorticating machine is used to improve the production rates and to extract fine fibres. This method can save time and minimise the wastage. This research study aims to investigate the effect of the decorticator extraction parameters on fibre properties.

2.11.2 Biological extraction or degumming of the banana fibres

In the biological extraction method, strips of banana stems were cut and treated with a different type of enzymes at varying levels of temperature and duration of treatments. Enzymes that were generally used cellulases and pectinases enzymes. Pectinase enzymes are used in retting or degumming treatments for bast fibres, such as flax, hemp, kenaf, jute and banana fibres (Ryszard, 2012). Under this method, banana stems are immersed with pectinase enzyme and kept under standard atmospheric condition. Treated stems are extracted by hand or machines. The chapter will now look at the biological banana fibre extraction methods that are identified in this study and examine each method:

In the study conducted by Chauhan & Sharma (2014) on the biological method for banana fibre extraction, they found that when the banana stem was treated with 0.5% concentration of pectinase enzyme for 36 hours at 40°C in the retting method, the fibre fineness was improved by 93.2%.

The treated single fibre strength was about 258.3 gf. According to this report, it takes 36 hours to get the best fine fibre from banana pseudostem through biological extractions, which is a time consuming method.

Enzymatic extraction on the other hand reduces contamination and cause less harm to the fibre. Pectinolytic proteins have been connected to the degumming of other regular fibres such as jute, hemp, flax, ramie and coconut fibres. Pectinases are proteins that are gathered by an extensive number of microorganisms, including filamentous organisms. Sarma & Deka (2016) reported how Aspergillusnigerin is a greater source of pectinase (5.362IU/G) in contrast to Aspergillus as disinfects that deliver organisms with powerful degumming and in the extraction of the banana fibre. Fibres that were treated with Aspergillusniger for 22 days displayed a diameter ranged between 200-250 µm and had higher breaking strength (tenacity: 24.5 cN/tex). Sarma & Deka's, (2016) investigation revealed that the breaking strength of the fibre was affected by the diameter of the fibres. The results of the Maheshwari *et al*., (1994) study came to a similar conclusion.

The enzyme retting method gives banana fibres with an excellent quality, although comparatively the process takes a longer duration (6–7months) (Bavan & Kumar, 2011). In this extraction method, a longer time period exposed to enzyme treatment may decrease the strength of the fibres.

Although the biological extraction is time consuming, it is highly effective in removing specific components of lignocellulose and incurs minimum harm to the environment. The current research study was accompanied by subjecting the pseudostem to pectinase enzyme at different temperature and different duration. This research project was seeking to explore and investigate the influence of enzyme treated banana fibre parameters on fibre properties.

2.11.3 Chemical extraction or degumming of the banana fibre

Under the chemical extraction process, part of the banana stems is treated with different types of chemicals. The banana stems are immersed with chemicals in the bath and kept under specific conditions. Chemically treated stems are then extracted by hand or machines.

Parkash (2013) analysed a chemical method for the extraction of the banana fibre where the pieces of the banana stem were dunked into 2% NaOH solution for 24 hours at room temperature. The NaOH solution was prepared by dissolving 20 g of NaOH in 1000 ml of refined water at room temperature. This process removes lignin from pseudo stem fibres. This NaOH treatment reduces the roughness of the fibres.

In Kumar's (2011) study, the banana stems were squeezed to remove the juice and cut into 3.0 cm lengths and then the chips were air dried. The chemical composition of a representative sample is treated with Formic/Acetic Acid process, urea/NaOH process, soda process, Soda anthraquinonoid process and Kraft process with $NaOH/Na_2S$. Pulping the banana fibre with NaOH, H_2O_2 and $NaClO_2$ gives it a good strength and a textile grade fibre. The main advantage of this chemical separation is that it did not effected the length of the fibre.

Shinde *et al*., (2018) reported that an alkali treatment (NaOH) was effective in reducing the fineness of the fibre, and greatly improved the quality of the fibre produced. Chemical extraction takes up to 35-40 days, thus giving it another added advantage.

Subagyo and Chafidz (2016) study reveals that the residual components of the banana fibre from the chemical extraction method, which are soluble in the alkaline solutions. The surface morphology of the fibres that were treated with a 5% NaOH solution were not much different from the raw fibres, and once the impurities were removed, the surface seemed clearer. The debris of the fibres are not clearly visible, but fibrils were clearly visible when the fibres were treated with a 10% NaOH solution. Chemical concentration, temperature, duration and presence of antioxidants are factors that were considered while conducting the current research for chemical extraction while and investigating how these parameters affect the fibre fineness and strength.

2.11.4 Biological treatments of banana fibres

Enzymes play a major role in the study of natural fibres, such as bast fibrous plants. The enzymes improve the fibre parameters in the processing and finsihing of bast fibres (Chauhan & Sharma, 2014). Enzyme are used to degumming the plants as well as improve the cleanliness, hompgeneity, fineness and softness of the natural fibres (Ryszard, 2012). In the biological treatments of fibre, mechanically extracted or hand stripped fibres are treated with different concentrations of different enzymes.

Pectinase enzyme were found to be very suitable in the separation of fibre bundles since pectin was removed from the sheath. Fibre that were treated using the pectinase enzyme had a linear density of 9.73 tex and a tenacity of 56.32 g/tex (Brindha *et al*., 2017).

In Vardhini & Murugan's (2016) study, banana fibres were treated with three different concentrations of Laccase and Xylanase enzyme solutions at 10%, 15%, and 20% separately at a temperature of 60°C. Material to liquor ratio (MLR) was 1:40 and the treatment time was 3 hours for both Laccase and Xylanase enzymes. The pH was maintained at 5 and 7 for Laccase and Xylanase enzymes, respectively (Vardhini & Murugan, 2016). Under this method, the percentage of lignin that was removed using laccase enzyme was at 29.9% and the cellulose content was increased by 6%. The percentage of lignin that was removed using xylanase enzyme was at 27% and the cellulose content increased by 17% . When treated by laccase enzyme, the diameter if the fibre was at 92 µm and under the xylanase enzyme treatment, the diameter was 34 µm. This revealed that the pectinase enzyme treatment has reduced diameter from 213.2 µm to 90.6 µm which is about 57.5%.

Doshi & Anjali (2016) discovered that the banana fibre can be softened by treating it with laccase enzyme for 45 minutes. Afterwards, the fibres are washed and treated with hemicellulase for 60 minutes. Then the treated fibres are washed and treated with cellulase enzyme for 30 minutes. Lastly the treated fibres are washed and treated with pectinase enzyme for further15 minutes. This specific order of enzyme treatment gave a better fineness to the banana fibres. Under this treatment, the linear density of the banana fibres was reduced from 14.4 tex to 11.5 tex. However, the cost of this method were high due to the high price of enzymes and the process itself was quiet complicated (Doshi & Anjali, 2016). It will be difficult to find enzymes in Sri Lanka and most of the plant fibres are weak under acidic conditions.

Another method of biologically treating banana fibres sees the banana fibres that were gathered by hand stripping treated to crude pectinase obtained from Streptomyces lydicus and used (15 U protein/25 mg of fibre) for 90 min at 45 ^{0}C and 150 rpm in a turning shaker at pH 7.5. The treated samples were dried and fine fibres were achieved. Under this method the highest enzyme yield was reported at 72 h (Jacob *et al*., 2008). When treated thus, the fibre tensile strength is 2.35N and diameter is 0.15mm (Jacob *et al*., 2008).

During this extraction process the tensile strength of the fibre bundles decrease against the increasing enzyme solution. However, it was revealed that this process has a longer duration and therefore, it is a disadvantage.

In Shroff and Karolia's, 2015 study, two grams of banana fibres were treated with various enzyme concentrations (10 and 12% owf) and 3 different time intervals (8, 12, and 14 hours) were maintained. The pH level was maintained at 5 and the temperature was at 50-55°C, while the M: L ratio was 1:60. The banana fibres were treated with hemicellulase, pectinase and cellulase enzymes by varying its concentration and time. Fibres were treated with these enzymes were measured for weight loss, strength loss and whiteness index of the fibre. A SEM analyses were carried out and the fibre with the most softness was selected for nonwovens through the needle punch method. The banana fibres that were treated using cellulose and pectinase enzymes were softer when more impurities were removed. The best results were obtained when a concentration of 12% enzyme solution were used for 12 hours for the treatment of the fibre. When analysing the above results it was revealed that as the fibre finesse increased, the weight of the fibre reduced. Furthermore, hemicellulase catalyst expels hemicellulose from the fibre, pectinase enzyme influences pectin and cellulase enzyme affects the cellulose and makes the surface soften. Pectinase enzyme is best for removing more impurities from the banana fibre, making the fibre soft (Shroff and Karolia, 2015).

Vellaichamy & Gaonkar, (2017) carried out a study on banana fibre softening treatment using enzymes that were extract from aspergillusniger. The reaction in enzyme of polygalactouronase and lignin peroxidise was found to be 25 and 0.153 U/ ml respectively. This biological method of softening was practiced though enzyme treatment (2 and 4 hours), culture treatment (48 and 72 hours) and anaerobic treatment (72 and 168 hours). The diameter of the fibre treated using crude enzyme ranged from 121 to 131µm. Fibres produced using culture enzyme had a diameter that ranged from 158 to 180µm. These treatments improve fibre fineness and their mechanical properties.

Ortega *et al*., (2016) study looks in to the production of banana fibre yarns for technical textile. According to this study, mechanically extracted fibres were treated with 20 % concentrations of pectinase at 45^0C of temperature for 6 hours and stirring at 200 rpm. The pH was controlled 3.5 to 4.5 for the enzyme treatment process, and a bath renewal after three hours. This enzyme treatment produced fibres that had a reduced tensile strength of 17 % and fibre linear density of 360 cN/tex. However, it was found that a 50/50 blend of banana and cotton fibres and a blend of 70% banana and 30% wool blends performed better as a yarn. The spinning machinery should be modified to produce these kind of high linear density (high stiffness) fibres. This is a major disadvantage for this method.

High concentration of enzymes and time parameters weakened the fibres that were produced using enzyme treatments. The period of pectinase enzyme treatment was revealed to produce fibres with the highest grade (Chauhan & Sharma, 2014). Non - cellulosic constituents like pectic substances were removed during the pectinase enzyme treatment.

Pectic substances are the primary components of the plant kingdom of the middle lamella. A thin layer of adhesive extracellular material is between the primary cell walls of adjacent young plant cells. The main chain of pectin is partially methyl-esterified-1,4-D- galacturonan. A pectic substance such as pectin and pectic acid may depend on the source, degree, and type of branching. The pectinases enzymes hydrolyzing pectin and pectic acid. This enzyme supports efficient interference of the matrix to achieve good water absorbance without the negative side effect of cellulose destruction (Hoondal *et al*., 2002). The optimum activity determine for the pectinase enzyme is at pH 4.5 and 40°C. Histidine and glutamic acid are used to maintain the pH level of the treatment (the active site of the enzyme) (Buga *et al.*, 2010).

Alkaline pectinases are commonly used in the textile processing and degumming process of the plant fibres. In the degumming process, Pectinases are used to remove heavily coated, non-cellulosic gummy material from the cellulosic part of plant fibres such as ramie, hemp, and flax (Hoondal *et al*., 2002).

Nevertheless, there is a limited number of research material available on the use of the pectinase enzymes for the extraction of fibre from banana pseudostem. Chemical processes cause environmental side effects. Enzymatic treatments are environmentally friendly and has a low percentage of fibres. Enzymes treatments help to remove the non-cellulosic components from the fibres, thus making them softer (Shroff & Karolia, 2015).

The major problem when using enzymes is the selection of ta suitable enzyme, proper enzymes conditions and the cost of enzyme applications. The current research study was carried out to investigate the opportunities of improving the fineness and strength of banana fibre through the biological treatment of banana fibres using pectinase.

2.11.5 Chemical treatments of banana fibres

In chemical treatments, mechanically extracted or hand stripped fibres are treated with varying concentrations of different chemicals. Sodium hydroxide is a commonly used chemical for all-natural fibre treatments (Bavan, 2011).

Fibres treated using NaOH solution were shown to have improved their strength and had an increase in cellulose percentage compared to the fibres that were mechanically extracted (Jagadeesh *et al*., 2015). But it was also found that an increase in NaOH chemical and time duration increases the strength of the fibre (Jagadeesh *et al*., 2015). Jagadeesh *et al*., 2015 study demonstrates how alkali treatments increases the strength of banana, how it absorbs more water into the fibre, and how easier it is to remove the impurities on the fibre surface. Alkali treatments were also found to expand surface harshness (Ebisike *et al*., 2013).

Onyedum *et al*., (2015) study investigated how the banana strands were hacked to three different lengths, 10mm, 30mm, and 50mm and the results of the filaments when treated with 2% of NaOH, for an hour under constant blending. Strands were then dried outside for 6-7 days. The objective of this treatment was to remove the moisture content and to increase the tensile strength by 30% in the fibre.

Temesgen and Sahu (2014) investigated the properties of banana fibres that were treated using caustic soda, bleaching agent (H_2O_2), vegetable oil and aloe vera gel. The research revealed that the vegetable oil and aloe vera gel treated banana fibres were obtain superb moisture content and softness as compared to the raw banana fibre. A 2.5% - 5% NaOH concentration obtained a better fineness without affecting the fibre strength. Next the study examined the banana fibres that are treated with H_2O_2 (4%), NaOH (2%), Na_2CO_3 (1.5%), Na_2SiO_4 (1.5%), $MgSO_4$ (1.5%), and a few droplets of wetting agent, at a temperature of 60^oC- 90^oC for one hour. The average of the fineness of these fibres was found to be 5.8 Tex and elongation at break (%) average 2.8. The banana fibres that were treated with H_2O_2 and NaOH had a crystalline component of cellulose that became amorphous and the cylindrical shape of the fibre turned into a convoluted shape. The researchers reported that the spin ability was improved under this treatment.

Vardhini *et al*., (2016) study looked at fibres treated with NaOH concentration of 11g/L, treatment time 150 min and temperature at 90 ºC which was an optimum condition for lignin decomposition. There was a 20% increase in the botanical compositions of cellulose, but the botanical compositions of hemicelluloses were reduced under this treatment. However, the single fibre quality and the crystallinity of the fibre were superior.

Ahad *et al*., (2009) investigated fibres that were treated with a concentration of 5%, 10% and 15% NaOH solution for 3 hours at room temperature. SEM was used to investigate the surface morphology of the fibre under this treatment. It was found here that a15% NaOH chemical solution eliminates impurities, improved surface roughness, enhance fibre-matrix interaction and a superior fibre strength can be achieved using a 5% NaOH chemical solution.

Zin *et al*., (2018) report looked at how the alkali treatment removed fibre impurities and how the increment in surface roughness can be observed using scanning electron microscope (SEM) results. The results of this research study stipulated that a 6% NaOH treatment (4 hours) with a two-hour immersion time gives the highest tensile strength and increase the surface roughness. The diameter of this treated fibres averaged at 0.11 ± 0.0088mm. This alkali treated fibre exhibit 25% reduction in diameter compared to mechanically extracted fibre.

Githinji *et al*., (2015) studied the separated banana stem, where 20 grams of fibres were treated at 100 ^{0}c with four different concentration of sodium hydroxide (NaOH) with arrangements such as 0.75M, 1M, 1.25M and 1.5M. This treatment ran for 120 minutes and the liquor ratio was 1:25. It was found fibres treated with a 1M concentration of NaOH at 100°C for 120 minutes had an improved breaking extension (20%) compared to other treatments. The results further showed that non - cellulosic materials are partially removed when the temperature is increased.

The chemical treatment of an alkali concentration of 1M at 90°C for 90 minutes provides the best breaking tenacity and the breaking extensions of the banana fibre (Githinji *et al*., 2015). The banana fibres were treated with a concentration of NaOH

11g/L, and at temperature of 90 ^{0}C for 2.5 hours. This alkali treatment reduced the higher percentage (40%) of lignin (Vardhini *et al*., 2016).

The studies showed that the alkali treatment increases the surface roughness and these treated fibres have sufficient strength. The available literature also showed that these alkali treatments produce the finest fibre with a minimum reduction in tenacity. However, these treatments were found to increase the single fibre strength and improve the crystallinity of the fibres.

Heckadka *et al*., (2020) investigates the properties of Areca, banana, and flax fibres when treated with a 10% volume of sodium bicarbonate solution for 24 hours, 72 hours, and 96 hours at room temperature. Another batch of these fibres were separately treated with a 2% volume of sodium hydroxide for 1 hour, then treated with a 2% volume of potassium permanganate solution for 10 min, (both at room temperature) and then treated with a 2% volume of sodium hydroxide solution at room temperature for about 1hour. The diameter of the Chromium sulphate treated fibres increased. The density of the Sodium bicarbonate treated fibre decreased with increased duration of treatment, whereas the density of the potassium permanganate treated fibre was found to have decreased. The SEM images of the Potassium permanganate treated fibre exhibited clear cell ridges. However, these experiments highlighted that the use of sodium bicarbonate, potassium permanganate, and chromium sulphate have promising results with natural fibres such as sisal and coir, but not with banana fibres.

The combined treatment of NaOH, H_2O_2 and Na_2CO_3 increased the fineness (5.8 tex) of the banana fibres and the single yarn strength and tensile strength were decreased by increasing the concentration of the chemicals (Tholkappiyan, 2017). Hypochlorite bleaching treatment reduce 6.44% weight loss of the banana fibre and peroxide bleaching treatment reduce 5.37% weight loss of banana fibre (Joshi *et al*., 2018).

Sheng (2014) study states that the NaOH, sodium silicate and hydrogen peroxide solution of bleaching processes eliminated the maximum amount of the residual gum and lignin component of banana fibres.

The chemical treatments affected several factors such as the type of chemicals, treatment duration, and temperature. Several chemical treatment methods such as alkali bleaching, softening, and acid treatments were used to improve the properties for their suitability as a textile fibre. It was found that the bleaching treatment resulted in changing the chemical composition, fineness, surface morphology, and high moisture absorption properties of the banana fibre. To achieve the required fineness and strength, it is essential to supplement the actions of chemical treatments. Chemical treatment methods have proved to develop fineness and make the fibre surface free from non-cellulosic substances. This research study was seeking to explore and investigate the influence of different chemically treated banana fibre parameters on fibre properties.

2.12 Chapter Summary

This chapter examined the textile manufacturing in Sri Lanka, availability of the banana plant in Sri Lanka, and the useful properties of the pseudostem and banana plant in the extraction of banana fibre. The main focus of the chapter was on the different methods of banana fibre extractions that are currently available, the different treatment methods currently used in the global textile industry and the evaluation of these techniques for the benefits of the textile industry.

The analysis of the existing literature demonstrated that the mechanical extraction widely practiced in the industry gives a higher capacity and productivity of the fibre (Ray *et al*., 2013) : (Vadivel *et al*., 2017). Hence, this study was aimed at testing the effects on the banana fibres when using biological, chemical extraction, and these treatments compared to the banana fibres that are mechanically extracted.

The studies that examined alkali treatments attested to the fact that the surface roughness of the banana fibre increased and lignin of the fibre was reduced greatly when treated with alkali (Vardhini *et al*., 2016) : (Zin *et al*., 2018) : (Ahad *et al*., 2009): (Onyedum *et al*., 2015) : (Githinji *et al*., 2015). This was found to be unfavourable for manufacturing of textiles. The existing literature on the properties of Alkali treated fibres revealed varying results.

The authors, Joshi *et al*., (2018) and Sheng (2014) investigative work highlighted how chemical treatments can remove maximum amount of lignin. However, these researchers did not analyze the mechanical properties of these treated fibres.

The effects of the fibre extraction and treatment methods on the fibre yield and quality were also studied. Jacob *et al*., (2008) reported that an unrefined catalyst was utilized for banana fibre treatment of crude enzyme (pectinase).

The combined treatment of NaOH, H_2O_2 and Na_2CO_3 increased the fineness (5.8 tex) of the banana fibres and the single yarn strength and tensile strength were decreased by increasing the concentration of the chemicals. Combined treatments achieved sufficient fineness of 5.8 tex value for spin ability (Tholkappiyan, 2016). Treatments using a combination of NaOH, H_2O_2 and Na_2CO_3 are known in the literature to provide quality treated fibres that can be used for spinning (Tholkappiyan, 2016). The results from this study showed that there is a continuous reduction in non- cellulose content and linear density of the fibres. However, enzyme and chemical combined treatment effect on fibre properties were not reported.

The current research study was carried out to investigate the possibilities of improving the fineness and strength of banana fibre through the enzyme and chemical combined treatment of banana fibres using pectinase and NaOH, H_2O_2 and Na_2CO_3 chemicals.

3 METHODOLOGY OF STUDY

3.1 Introduction

The purpose of this chapter is to explain in detail the research design and the methodology implemented in the investigation of the different techniques used for the extraction and treatment of banana fibres. A survey of the existing literature on the current research processes helped design this methodology. The chapter will present the research philosophy, research design, sampling strategies, sampling area and sample size chosen for this study, followed by a detail description of the research instruments, data collection and the method of data analysis used.

3.2 Research Philosophy and Strategies

Mechanical, biological and chemical extraction and treatment methods were used in this study to characterize the interfacial behaviour and physical and chemical properties of the banana fibre. The results from each extraction and treatment technique is analysed by using quantitative methods.

3.3 Research Design

In an attempt to explore the systemic connection between experimental observation and mathematical expression of the research, the research is focused on producing quantifiable observations of the various methods currently used in the extraction and treatment of banana fibres. Previous research studies have tended to focus on the statistical analysis to describe the fineness of the fibre and other outcomes when employing various methods to extract fibres (Tholkappiyan, 2017 : Chauhan *et al*., 2014).

The main sampling area used for this study is the dry, intermediate and wet zones areas of Sri Lanka. These areas are known to be popular for the cultivation of vegetables and bananas (Hathurusinghe, 2012). Different varieties of banana stems are obtained from selected geographical areas in Sri Lanka that cultivate the banana plant.

3.3.1 Population and Sample

The top ten varieties of banana cultivars in Sri Lanka, namely Embul, or Ambul (Mysore type, AAB group), Kolikuttu (AAB), and from the Cavendish subgroup: Anamalu (AAA), Rathambala/ Rath kehel (AAA) and Ambon, or Amban (AAA).

Ambun, Atamuru, Seeni, Alu kehel, Poowalu and Suwandel were selected for this research study.

The ten varieties of banana fibre stem and leave samples are showed in Figure 3-1.

(1) Kolikuttu (AAB) (2) Seeni, (3) Embul, or Ambul (Mysore type, AAB group), 4) Atamuru, (5) Ambun (6) Suwandel, (7) Poowalu, (8) Rathambala /Rath kehel (AAA) (from the Cavendish subgroup), (9) Alu kehel, and (10) Anamalu (AAA).

Kolikuttu (AAB)

Seeni(AAA)

Ambul (Mysore type, AAB group)

Atamuru(AAA)

Ambun(AAA)

Swandel(AAA)

Poowalu(AAA)

Rathkehel(AAA)

	
Alu kehel(AAA)	**Anamaalu(AAA)**

Figure 3-1 Banana varieties stem sample

Zoning technique were used for the banana fibre sampling method. Banana fibre samples consists of less than 5Kg of loose fibre, spreaded it out in an even layer. The samples were obtained at random a minimum of 100 tufts of apporoximately equal size. The total mass sufficient to give a laboratory test samples of required size. Fifty (50) samples of equal size banana fibre samples were tested in every treatment methods.

3.3.2 Research Methodology

To formulate the research design, a literature survey was carried out on the existing techniques of banana fibre extraction or degumming and treatment methods. By examining these methods, the literature survey helped to identify how the properties of each method impacted the behaviour of the textile fibre. In order to examine the physical and mechanical properties of the fibres, the 10 varieties of the selected banana fibres that were mechanically extracted were examined further. Among the ten banana varieties identified in this research, the five best varieties, namely Ambun, Ambul, Atamuru, Puwalu and Kolikuttu, were then selected to determine the finer fibre and strong single fibre strengths of the banana fibres.

These five banana varieties were subjected to mechanical, biological, chemical extraction or degumming methods (Table 3–2). Different types of extracted fibre samples (Mechanical method, biological and chemical extraction or degumming) were washed in cool water and dried in the oven and tested as per the standard methods of testing. Finally, Ambun (genome AAA) was selected for further analysis due to its low fibre fineness compared with all other fibre varieties. The mechanically extracted fibres of the middle layers of the Ambun pseudostem were put through an enzyme and chemical treatment (Table 3-3 and 3–4). Samples of banana fibres (middle layer: Figure 3-4) that were treated using different chemical and enzyme concentrations were washed in cool water, dried in the oven and tested as per the standard methods of testing.

Scanning electron microscopy and fibre linear density were used to observe and determine the fineness of the enzyme and chemically extracted and treated banana fibres.

The mechanical strength of the untreated and treated banana fibres were obtained by using a universal tensile tester machine.

Fourier Transform Infrared spectrophotometer (FTIR) was used to determine the spectrum of each of the treated and untreated sample of banana fibres and it also helped determine the chemical components of untreated and treated fibre samples.

The spectrophotometer measured the samples of untreated banana fibre (raw banana fibre), the reflectance factor of the treated banana fibres and evaluated the color deviations of ΔE^* values obtained by CIELab (L^*, a^*, b^*, c^*, and h) from the color system. The data from these experiments were then collected and analysed to determine whether the different extraction methods and different treatment techniques have an impact on the fibre fineness and strength of the banana fibres.

The results demonstrated that the banana fibres were suitable for the process of dyeing. Then the colour properties of the dyed banana fibres are compared against dyed cotton fibres. Reactive dyes are used in the dyeing of cotton fibre due to their wide colour range and good wet fastness properties. Reactive dyes are also suitable when used with cellulosic fibre like cotton fibres. Therefore, cotton fibres were selected for this comparison study. The effects of dye concentration on the colorimetric (CIELAB) and washing fastness properties were also studied.

Table 3-1 shows methodology of the research and listed enzyme and chemicals used for this experimental work.

Table 3-1 Methodology of the research

Overall study design	**Quantitative study**
Research Type	Experimental Method
Research Method	Quantitative analysis
Data Analysis	Statistical analysis with SPSS
Methods of data collection	Measurements -: The investigation of the fibre fineness, fibre linear density and strength will be guided by ASTM International and AATCC (American Association of Textile Chemists and Colorists) standards. FT-IR analysis of banana fibres was carried out in order to study the components. Dye ability test on banana fibres. FT-IR analysis (ASTM E168, E1252), XRD analysis, Water absorbency (AATCC Test Method-79-2007) of banana fibres was done to study the components.
Target Population	Sri Lankan banana varieties
Study Population	Ambul (AAB group), Kolikuttu (AAB), Anamalu (AAA), Rath kehel(AAA) and Ambun (AAA), Atamuru, Seenikesel(ABB), Alu Kesel (ABB) and Poowalu(AB), Suwandel(AB)
Sampling Method	Convenience sampling : Zoning technique
Fibre extraction method	Decortication extraction Biological extraction or degumming Chemical extraction or degumming
Types of treatments	Biological treatment Chemical treatment Enzyme and chemical combined treatment
Enzyme type	Pectinase enzyme
Auxiliaries / Chemicals	Hydrogen peroxide (H_2O_2), Sodium Hydroxide (NaOH), Sodium sulphide, Commercial softeners, Wetting agent, Detergent, Acetic acid, Sulphuric acid (H_2SO_4), Turkey red oil, Glycerin and Aloe vera

3.3.3 Flow chart of Research Methodology

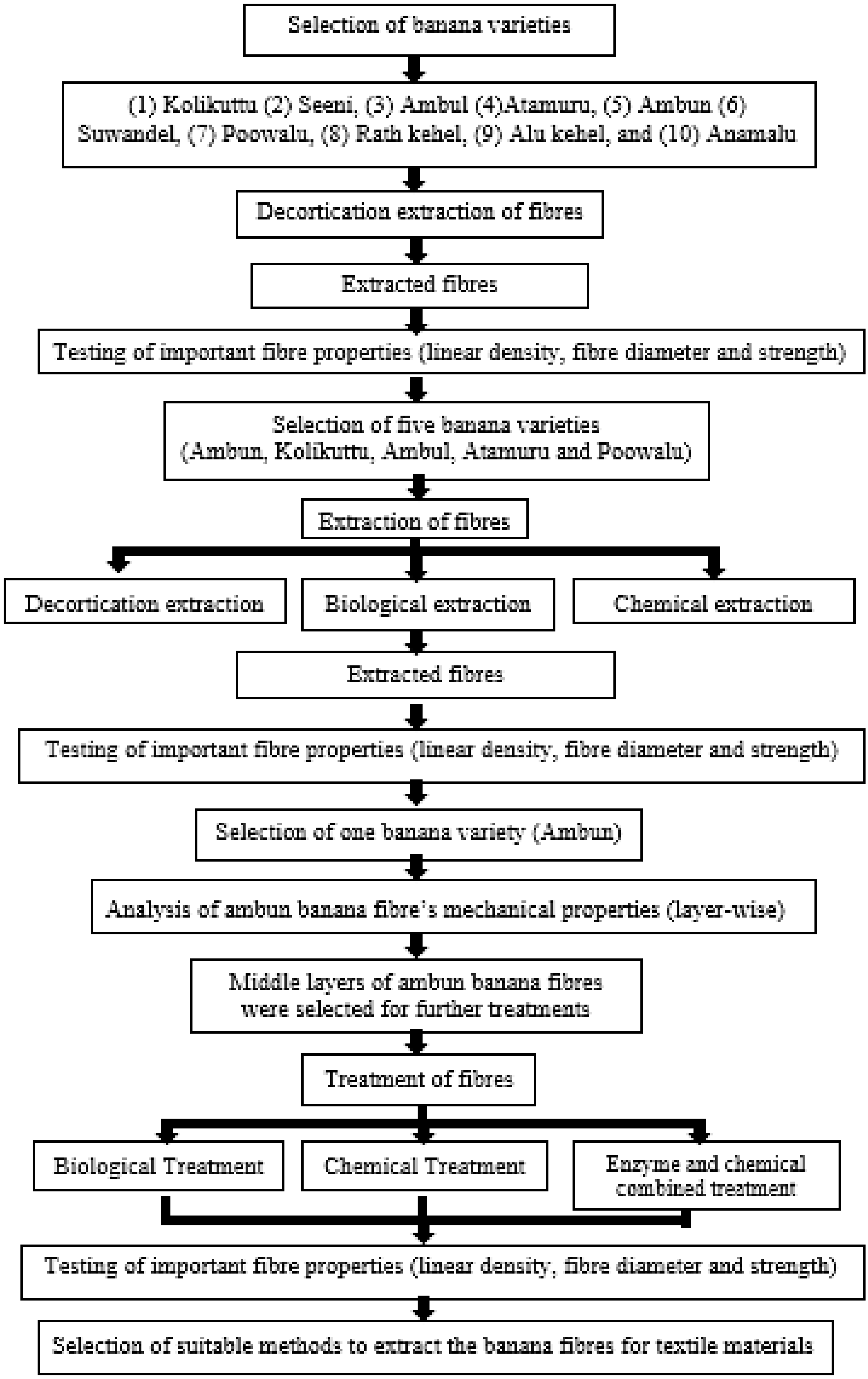
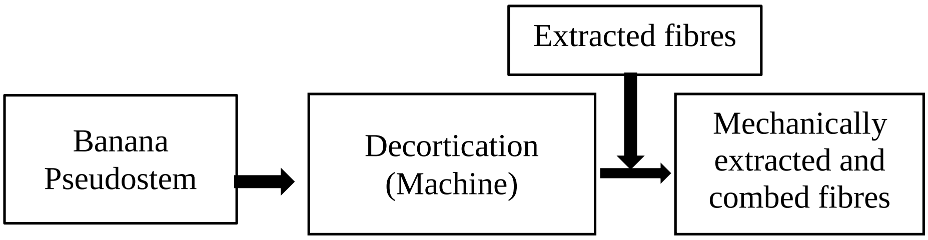
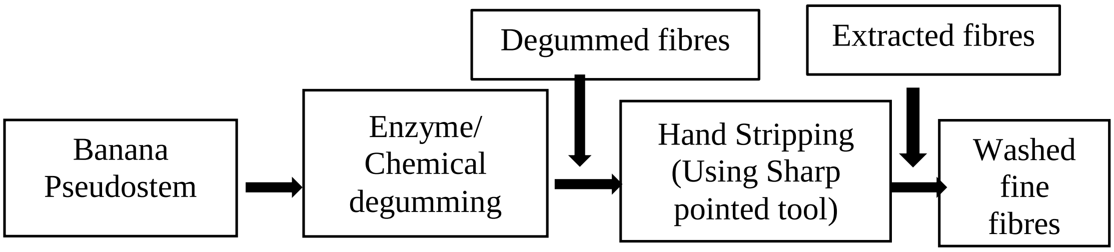


Figure 3-2 Flow diagram of experimental procedure

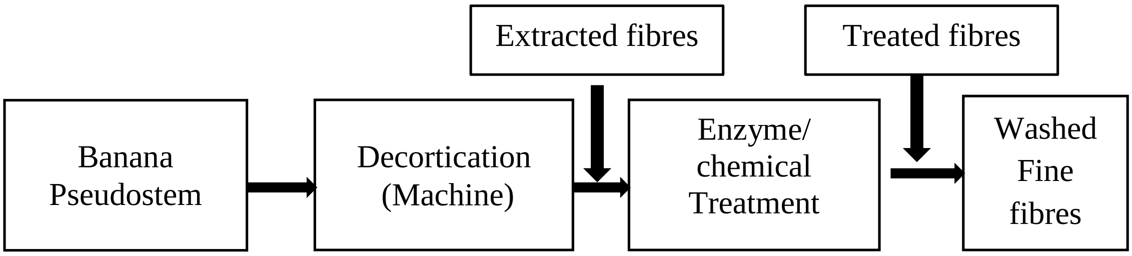
3.3.3.1 Experimental procedures (Conceptual diagram of Extraction and treatment methods)



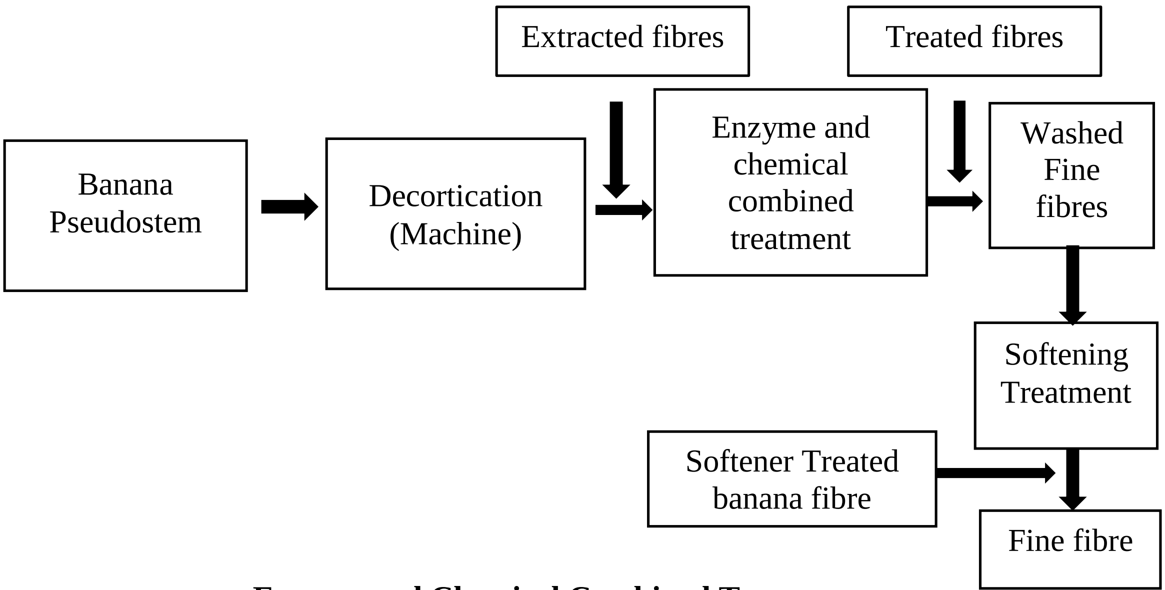
Mechanical Extraction



Biological and Chemical Degumming or Extraction



Biological and Chemical Treatment



Enzyme and Chemical Combined Treatment

Figure 3-3 Schematic diagram of Extraction and Treatment

The controlled variables of this research study are chemical and enzyme concentration, temperature, and treatment time. The dependent variables of this study were the banana varieties, the structural features, the morphological characteristics of the fibres, the tensile properties of the fibres, fineness of the fibre, the absorbency of the fibres, bleaching, and dyeability properties of the fibres.

3.3.4 Extraction of banana fibre

Preparation of stems

This research investigates the factors that influence the quality of the fibre inside the banana pseudostem to determine which layers are suitable for delivering fine banana fibres by identifying the banana pseudostem layer-wise properties.

The banana pseudostem that were collected for fibre extraction were taken from the waste pseudostem of the banana plant, cleaned and cut to 20 inches in length. Each sample was cleaned by water till all the surface debris were removed.

The external layer of the outer sheath is removed so that the external layer can be easily broken during extraction, to avoid difficulties in extracting fibres samples. The core of the pesudostem is not a sheath and therefore it was not utilizing for this study. The layers of the banana pseudostem were selected based on their location in the pseudostem.

Figure 3-4 illustrates the inner part of the stem which is identified as the first layer. The outer layers of the stem are identified as the fourth layer. The two sets of middle layers are selected starting from the inner to the outer layer and named as the second and third layers.

Generally, the banana fibre is situated near to the outer surface of the sheath and can be peeled-off easily in ribbons of strips. Thus, the banana stem is prepared for the extraction or degumming of the banana fibres.

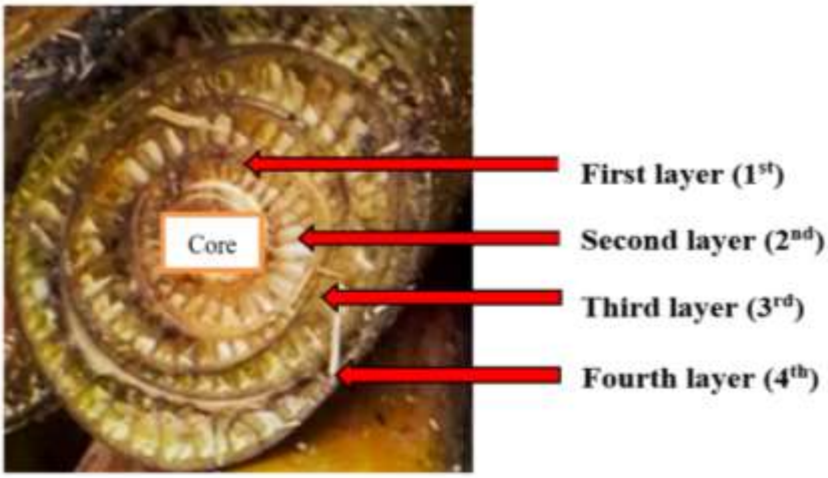


Figure 3-4 Layer of banana pseudostem

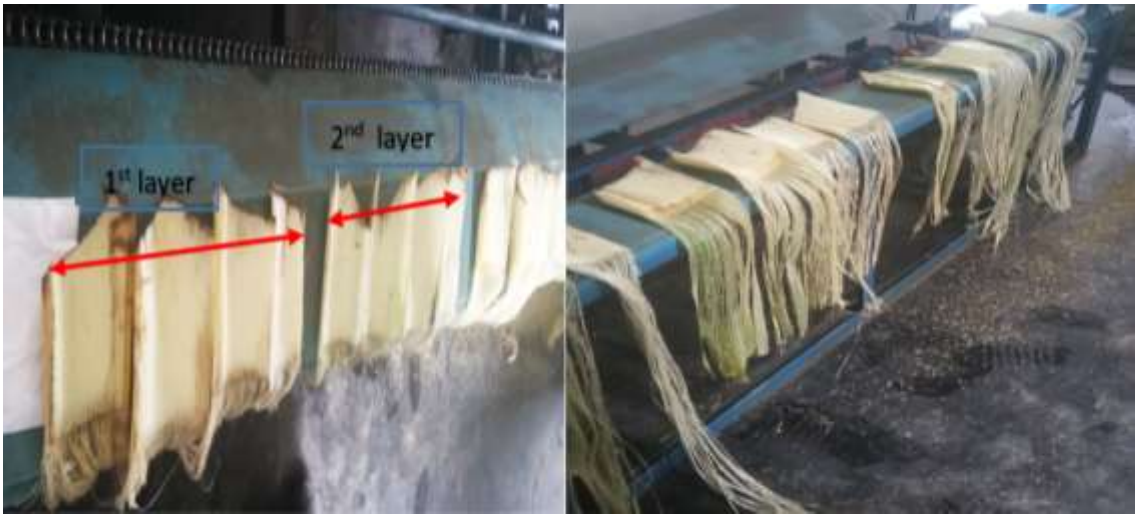


Figure 3-5 Separated layer of pseudostem

Methods of extracting the banana fibres

This study identified the following methods for extracting the banana fibres:

1) Mechanical or decortication extraction

2) Biological extraction (Enzyme treated stem used for the fibre extraction)

3) Chemical extraction methods (Chemical treated stem used for the fibre extraction)

1) Mechanical extraction method - Decortication method

Due to its higher capacity and productivity, fibre extractors commonly use the decorticator extraction methods in the fibre industry (Vellaichamy & Gaonkar, 2017). The banana fibres were extracted from the waste pesudostem of the banana plant by using the decorticator extraction machine and the stem cutter machines. In this research mechanical extraction follows the experimental work of Vellaichamy & Gaonkar (2017) and Jagadeesh *et al*., (2015). Certain aspects of the extraction machine, such as its roller speed, feeding angle and clearance, affects the quality and production of the fibre. However, this extraction machine can produce a larger quantity of banana fibres compared to that of the manual extraction methods. Figure 3-6 and 3-7 display the extraction machine and stem cutter machines.

Figure 3-6 Banana stem cutter Machine

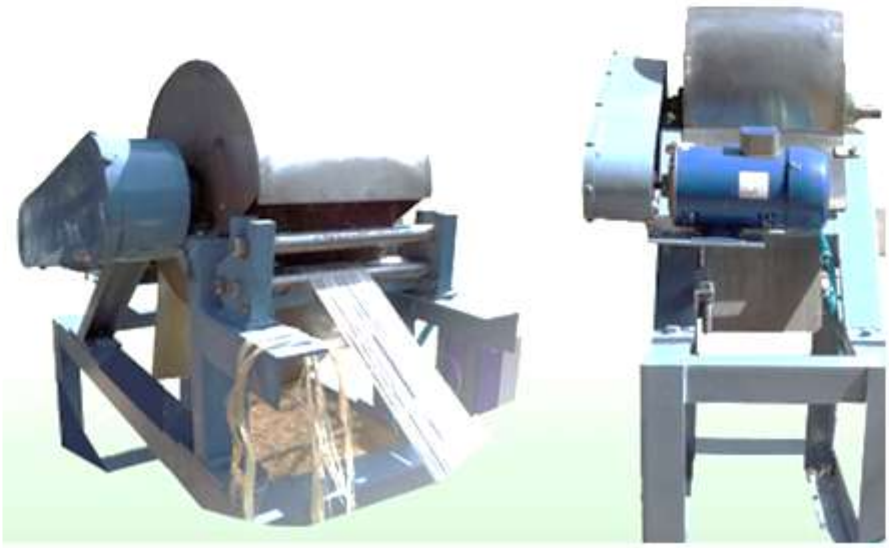


Figure 3-7 Banana Fibre Extraction Machine

The decorticating machine consists of a rotating drum mounted on a shaft. Twenty-seven blades are mounted on the circumference of the drum which creates a beating action by means of an electric drive.

The pulpy material is created with this action is then removed by a crushing action. The fibres are then thoroughly washed and dried under a sunshade. The extracted fibres are in the form of long strands in a slightly dull yellowish colour.

2) Biological extraction method

The banana pseudostem are cut to a length of 20 inches and further cleaned by water. The cleaned pseudostem is treated under biological methods (degumming). This biological extraction method is based on the experiments carried out by Shroff & Karolia, (2015) and Jacob *et al*., (2008). Table 3 - 2 shows the details of the experiments conducted in a lab using this biological extraction method.

In the biological degumming or extraction, the pectinase enzyme was selected (Shroff & Karolia, 2015) and the biological extraction method was performed using 1%, 2.5%, 5%, 8% and 10% concentration of the pectinase enzyme (Jacob *et al*., 2008). 20cm piece of banana stems were immersed in the enzyme bath and subjected to the enzyme treatment condition (temperature). At first, the banana pseudostem were retting in concentrations of 1%, 2.5%, 5%, 8% and 10% pectinase. The treatment liquor ratio was 1:50 and pH was maintained at 4.5 to catalyse the enzyme treatment (Buga *et al.*, 2010).

The duration of the enzyme treatment was based on the study conducted by Chauhan & Sharma, (2014). The banana fibres that were treated with an enzyme concentration of 5% were collected at different intervals, namely 12 hours, 24 hours, 36 hours, and 48 hours.

3) Chemical extraction method

The chemical extraction method was performed using Sodium hydroxide ($NaOH$). 20cm piece of banana stems were immersed in a bath of 2% , 5% and 10% $NaOH$ solution under 90^0C (Subagyo and Chafidz, 2016). Table 3.2 shows the details of the experiment carried out using this chemical extraction method in the lab.

Table 3-2 Biological and chemical extraction method

Extraction method	**Enzyme type**	**Concentration (%)**	**Temperature**	**Duration**
Biological and chemical extraction	Pseudostem treated with pectinase wetting agent and acetic acid (pH: 4.5)	5%	55^0c	2 hours, 12 hours, 1day, 36 hours, 3 days
	Pseudostem treated with caustic soda	5% & 10%	90^0c	2 hours

In both treatments (Enzyme degumming and chemical degumming), the pseudostem was extracted using the stripping method after the degumming. The linear density, the diameter and the tensile strength of these treated fibre samples were further tested and analysed. The purpose of this is to investigate the effects of banana fibre extraction parameters on fibre fineness and establish suitable methods to reduce the fineness that enable banana fibres to be used as textile materials.

3.3.5 Banana fibre treatment methods

After mechanical extraction process, the extracted fibres were treated with enzymes and chemicals.

Banana fibres were treated by following methods:

1) Enzyme treatment

2) Chemical treatment

3) Biological and chemical combined treatment

1) Biological treatment of banana fibre

The banana pseudostem, in lengths of 20 inches, were collected, cleaned and then taken for experimentation in this study. The pseudostem samples were weighed using an electronic scale. Using the stem cutting machines, the banana stems were separate into two parts. The samples of pseudostem were extracted using the decorticator machine and these extracted fibres were then cut into 15 cm in length. Treatment parameters, such as fibre immersion time, temperature, pH value and the concentration of each enzyme were selected from experiment carried out by (Shroff & Karolia, 2015: Buga et al., 2010 : Jacob *et al*., 2008).

Under the biological treatment process, the pectinase enzyme was selected to soften the banana fibres (Shroff & Karolia, 2015 : Jacob *et al*., 2008). This crude pectinase enzyme obtained from Streptomyces lydicus. The extracted fibres were then treated with four different concentration of the pectinase enzyme: 1%, 2.5%, 3%, 5%, 8% and 10% concentration, at 45 to 55^0c of temperature (Buga *et al*., 2010). The pH was maintained at 4.5 for the enzyme treatment (Ortega *et al*., 2016). Histidine and glutamic acid are used to maintain the pH (4.5) of the biological treatment (the active site of the enzyme) (Buga *et al*., 2010). The bath liquor ratio was at 1:50. Treated banana fibre samples were then thoroughly washed using running water and dried in an oven. This biological treatment method is detailed in Table 3.3.

Table 3- 3 Biological treatment method

Type of treatment	**Treatments No**	**Enzyme type**	**Concentration (%)**	**Temperature**	**Time**
Biological Treatment	01	Pectinase, wetting agent and acetic acid (pH: 4.5)	1%	55^0c	2 hours, 12 hours, 1 day, 36 hours, 3 days
	02		2.5%		
	03		3%		
	04		5%		
	05		8%		
	06		10%		

This pectinase enzyme treatment was treated with different concentrations of enzymes and then the optimized percentage of enzyme concentration was selected. The selected concentration of the enzyme was at different time intervals and at an ideal optimized period.

The banana fibres treated with a concentration of 5% enzymes were collected at an interval of 12 hours, 24 hours, 36 hours, and 48 hours (Chauhan & Sharma, 2014). The treated banana fibre samples were then thoroughly washed using running water and dried in an oven for further the testing.

2) Chemical treatment of banana fibre

Banana pseudostem in lengths of 20 inches were collected, cleaned and taken for experiments in this study. The stem was cut using the stem cutting machine. The banana pseudostem fibres were extracted using a decorticator machine. Once the pseudostem was inserted into the decorticator machines, it crushed the pseudostem and extracted the fibres. After the extraction, the fibres were allowed to dry. Gentle combing was performed to remove excess pith of the fibres. After combing, the fibres were washed by immersing the fibres in the large centrifugal washing machine and allowed to dry.

The extracted fibres were cut into 15 cm in length. Fibre immersion time and concentration of chemical treatment parameters were selected from previous experiments. Mechanically extracted banana fibres were treated with different concentration of Sodium hydroxide (Subagyo and Chafidz, 2016) and (Osorio, César, Baracaldo, Florez, & Jairo, 2012), Sodium sulphide (Subagyo and Chafidz, 2016), commercial softeners, Hydrogen peroxide (Subagyo and Chafidz, 2016), Turkey red oil and Glycerine, while maintaining a constant temperature and duration (Vellaichamy & Gaonkar, 2017). Twelve types of chemicals were used in this study with concentrations ranging from 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% concentrations. This study also carried out experiments using treatments that combined enzymes and chemicals. Several trials of chemicals and combined treatments were performed to determine the fineness and the strength of the fibres. The treatment methods that yielded the banana fibres with the best properties were selected for the dyeing process. Table 3-4 presents details of the treatment that uses a chemical treatment.

The following steps were conducted under the chemical treatments:

1) Raw banana fibres were treated with 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% concentration of Caustic soda, Sodium sulphide and Bleaching agent (H_2O_2) and Sodium Hydroxide (NaOH) solutions, at a temperature of 55 ^{0}C and 95^{o}C for 2 hours. The treatments liquor ratio is 1:50 (Temesgen and Sahu 2014).

2) Raw banana fibres were treated with 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% concentration of silicone softener at a temperature of 85^0C for 20 minutes (Temesgen & Sahu, 2014). The treatments liquor ratio is 1:50 and the pH was maintained between 4.5 – 5.5.

3) Raw banana fibres were treated with 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% concentration of amylase enzyme at a temperature of 80^0C for 2 hours. The treatments liquor ratio is 1:50 and the pH was maintained between 8 - 8.5.

4) Raw banana fibres were treated with 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% of permanganate -acetone solution (Imoisili *et al*, 2017), glycerine, Acetic acid, Aloe vera gel, castor oil or turkey red oil at room temperature for overnight (Temesgen & Sahu, 2014). The treatments liquor ratio is 1:50.

5) The samples of the treated banana fibres were thoroughly washed using running water and dried in an oven.

Table 3-4 Chemical treatment method details

Type of treatment	**Treatment**	**Chemical or Enzyme type**	**Concentration (%)**	**Temperature**	**Time**
Chemical Treatment	01	Sodium Hydroxide (NaOH)	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	55 ^{0}c	2 hours
	02		1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	95^0c	2 hours
	03	Sodium sulphide	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	55 ^{0}c	2 hours
	04		1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	95^0c	2 hours
	05	Glycerine	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	RT	Over Night
	06	Turkey red oil	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	RT	Over Night
	07	Silicone softener	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	85^0c	20 Minutes

		till the pH is 4.5 – 5.5			
	08	Bleaching agent(H_2O_2) and Sodium Hydroxide (NaOH),	1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	55 ^{0}c	2 hours
	09		1%,2%,3%,4%,5%,6%,7%,8%, 9% and 10%	95^{0}c	2 hours
	10	Acetic acid	1%,2%, ,4%,5%, ,8% and 10%	95^{0}c	2 hours
	11	Amylase enzyme(pH: 8 -8.5)	1%,2%, ,4%,5%, ,8% and 10%	80^{0}C	2 hours

(*RT – Room temperature)

3)Biological and chemical combined treatment

Mechanically extracted fibres were treated with 5% concentrations of the pectinase enzyme at a temperature of 45 to 55^0 c and the pH was controlled at 4.5 (Buga *et al*., 2010). The liquor ratio of 1:50 was used for the treatment. The treated banana fibre samples were thoroughly washed using running water and dried in an oven. After the enzyme treatment, the samples that were treated with a 2.5% and 5% concentration were further subjected to a concentration of 6% Hydrogen peroxide, 2% sodium silicate, 3% caustic soda and 0.2% wetting agent at the temperature of 95^{o}C for 2 hours. The liquor ratio of 1:50 was used for the above treatment.

These fibre samples that were treated with a combination of enzymes were also washed using running water. Afterwards, these washed fibres were treated with 1% softener for 2 hours and dried in the oven.

Table 3-5 presents details of the treatment that uses a combined treatment of Enzymes and chemicals.

Table 3-5 Enzyme and chemical combined treatment

Type of treatment	Chemical or Enzyme type	Concentration (%)	Temperature	Time
Enzyme and chemical combined treatment	Enzyme treatment and Bleaching agent (H_2O_2) with Sodium Hydroxide (NaOH)	2.5% enzyme, 6% H_2O_2 and 3% NaOH	55^0c and 95^0 C	Enzyme treatment :2 hours and chemical treatment :2 hours
	Enzyme treatment and Bleaching agent (H_2O_2) with Sodium Hydroxide (NaOH)	5% enzyme, 6% H_2O_2 and 3% NaOH	55^0c and 95^0 C	Enzyme treatment :2 hours and chemical treatment :2 hours

3.4 Testing methods of banana fibre

3.4.1 Testing of banana fibre length

The distribution of the fibre length of the plant fibres need to be gauged for quality control purposes. This is carried out by classifying the data gathered in to a graph or into a table format.

The two properties that are generally used to measure the amount of fibres from a pseudostem are (1) the number of fibres in each length category and, (2) the mass of fibre in each length category. The synthesized distribution of 100 fibres were used for the experiments of the current research.

Test method: The Shirley comb sorter Method

Conditioning

All test specimens (treated and raw banana fibre) were subjected to the standard atmosphere for testing: 20 ± 2°C and 65 ± 2 % relative humidity.

Procedure

Banana pseudostem were collected with lengths of 20 inches, then they were cleaned and dried for the investigations. Initially the pseudostem weights were measured using an electronic scale. The measured dry weights were observed and recorded. Duration of time taken to extract (decortication method) the fibres in each sample lot was recorded. Extracted fibres were subjected to the standard atmospheric condition for 24 hours.

The banana fibre samples were then taken, and the individual fibre length was measured. The fibres were straightened out on the table (flat black background) and the individual length of fibres (around 1000) were measured. Length of fibres were measured by a steel meter rule. The length of each of the 1000 fibres were grouped and the values were catalogued as shown in table 4-2. A histogram of the frequency distribution was presented in chapter four.

The results are accordingly arranged, and the mean, standard deviation and coefficient of variation is calculated and tabulated herewith to value quality control.

3.4.2 Microscopic appearance

Optical microscope is used to study the surface of the samples. However, this microscope can display a magnification of only 1000 – 2000 times.

Test method: The standard test method of **AATCC** 20A methods

Conditioning: All test specimens (banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Procedure:

Raw and treated banana fibres were treated under the standard atmosphere (temperature is 20 ± 2°C and 65 ± 2 % relative humidity) for testing. Then conditioned fibres were cut in to 1 cm length. Afterwards the 1 cm samples were placed on the glass slide by using a mounting medium to test the samples under both light microscope and SEM microscope. They were then examined under the longitudinal view using a microscope, which assisted in identifying the fibre characteristics of the samples.

Total Magnification: 40x, 100x, 400x, 1000x.

3.4.3 Measuring the diameter of the banana fibre

The fineness of textile fibres is expressed as either fibre diameter or linear density (Cook, 2001). Scanning electron microscope was used to test the diameter of the banana fibres. This microscope images are able to examine the internal structure of the banana fibre. The microscope can show a magnification of 1500 magnification. This type of electron microscope is capable of viewing the three dimensional external shape of the banana fibre. Scanning electron microscopy (SEM) was used to analyse the exterior properties of fibres.

Test method : - The standard test method of AATCC 20- 2007

Test Specimens: - 20 number of fibre specimens were randomly selected for the testing.

Conditioning:

All test specimens (banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Procedure:

The fibre diameter was assessed using the SEM microscope. Five fibre diameter measurements were taken at different location of the fibre to calculate the average fibre diameter.

Scanning electron microscopy (SEM) was used to observe the diameter results to evaluate the fineness of the fibre. It was analysed by calculating fibre thickness (diameter) at five different places with a magnification factor of 1500X.

This research assumes that the cross section of banana fibre is approximately circular based on the finding reported in Mukhopadhyay *et al*., (2016).

Results calculation

The mean, standard deviation and coefficient of variation of banana fibre diameter are calculated. The fibre diameter was observed under SEM microscope as the average of five diameter measurements taken at different locations along the treated and extracted fibre.

3.4.4 Testing of single fibre strength

Test method : The standard test method of ASTM0701 (2007)

Test Specimens: 25 number of fibre specimens were randomly selected for the testing.

Conditioning: Untreated and treated banana fibres were subjected to the standard atmosphere for testing, which is 20 ± 2°C (70 ± 2°F) temperature and 65 ± 2 % relative humidity.

Specimen Preparation

Using a paper cutter, sufficient number of cardboard squares with 25 mm by 25 mm dimensions were cut. In the centre of each cardboard squares, 14 mm (0.55 in.) diameter holes were cut out. A piece of poster board was placed on the flat table to view specimens conveniently during the preparation of the specimens. In the meantime, bonding resin was prepared and cardboard squares were placed on the poster board, in turn, under the magnifying glass which was light.

This magnification provides easy viewing of the fibre when the resin is mounted on to the cardboard square. A small amount of bonding resin was applied centrally to each of the required die-cut squares at two opposite locations, beginning at the inside edge and extending outward to the outer edge. The fibre clamps used in tensile testing can affect the apparent fibre properties.

The customary method of determining specimen elongation, by measuring clamp separation, assumes that the stresses applied to the specimen during the test are confined by the clamps to the original specimen length. Most fibre clamps do not completely conform to the stresses, and therefore, an erroneously high elongation may be observed from the result that were based on a nominal gauge length, which is shorter than the effective gauge length.

Procedure

The specimen that was tested was carefully mounted in the jaws of the clamps in order to remove slack. The specimen must lay straight within the jaws under extreme care to ensure alignment of the fibre specimen, with line of action between the force-measuring device and the point where the fibre leaves the moving face of the jaw. Any misalignment can produce transverse motion of the clamps and jaws can produce errors in measurements of elongation. Thus, misalignment may contribute to premature fibre failure.

Calculation

Breaking Force

Using the machine that tests tension, the breaking force of individual specimens were recorded in three significant digits and measured in cN (gf).

Breaking Tenacity

Breaking tenacity of individual specimens were calculated up to three significant digits

Strength and Extension at break

Breaking tenacity of individual specimens were calculated up to three significant digits. The banana fibre samples that were previously treated mechanically, biologically and chemically were placed in standard atmospheric conditions. Specimens were taken using the standard methods and for the ease of handling the sample, each fibre were separated and a standard test method of ASTM- D- 2256, was used to determine the tensile properties.

A universal tensile testing machine (Instron) was used to measure the breaking strength and the extension of the fibres that break. The machine was set at 15 cm and at a strain rate of 100 mm/min and different banana fibres varieties were tested.

Instrument - Tensile Strength machine

The Electro Mechanical Instron universal tensile tester machine was also used in this experiment. The fibre sample was cut in to desired dimension for mechanical testing. This test method measures covers the strength of the single fibre samples.

Single fibre strength (N) can recorded in three digits of the breaking force of individual specimens and it can be read directly from the tension testing machine and the results measured in cN (gf). The extension (mm) can calculated three digits of the breaking tenacity of individual specimens.

3.4.5 Testing of banana fibre linear density

The simplest method to test the linear density is to measure the length of a fibre, determine its mass by weighing, and repeat this for each fibre samples. The banana fibre specimens were prepared based on ASTM D1907 standard method to measure the fibre linear density. This method of testing provides the average linear density of banana fibres.

Test method: The standard test method of ASTM D1907

Conditioning

All test specimens (treated and raw banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Test procedures

The banana fibre specimens were in a standard atmosphere for 24 hours. These conditioned banana fibres were cut at a measured length.

Weight of the banana fibre specimen was measured using the weight balance (to the nearest 0.005 mg) and the number of fibres in the bundle were counted.

Calculation

The average single fibre linear density in an untreated bundle and treated bundle were calculated based on the mass and the length of the specimen bundle. The number of fibres in the specimen bundle also has an impact on the average fibre linear density (Equation 1). The single fibres in a bundle are calculated from the measurements of the mass and length of the untreated and treated bundle. The average fibre linear density was calculated using equation one (1):

$$Td = 1000\ W(L \times N) \quad \text{……………………………... Equation 1}$$

T = average fibre linear density, dtex,

D = average fibre linear density, denier,

W = mass of bundle specimen, mg,

L= length of bundle specimen, mm, and

N= number of fibres in the bundle specimen

The mean average linear density, standard deviation and coefficient of variation were calculated for each treated and raw banana fibre samples. Linear density of Banana fibres was measured in ‘Tex’.

3.4.6 FT-IR Analysis of banana fibre

Fourier Transform Infrared Bruker TENSOR 27 spectrophotometer was used to determine the spectrum of each treated and untreated samples. Chemical components of fibres were investigated by using FTIR Machine. If infra-red light is passed through a sample of organic compound, some of the frequencies are absorbed while other frequencies are transmitted through the fibre samples.

The FTIR spectrum was analysed for plotting the percentage of absorbance or percentage of transmittance values against frequencies. Spectra recording was obtained from potassium bromide (KBr) disc technique. Spectrum results show the appearance and relative intensities of the absorption peaks due to number of functional groups.

This spectrum is capable of giving indirect, but very valuable qualitative and quantitative structural information on polymer to evaluate the structural order and compositions of polymers and crystallinity. The transmission range of mode of the testing was 4000–600 cm^{-1}.

FT-IR analysis of banana fibres was done to study the components and its spectrum depicts O – H stretch, free hydroxyl, O- H stretch, H- bond, - CH2 - CH2 -, -C≡ C – and C- H alkenes compound gatherings that are available in the untreated banana fibre.

Conditioning: All test specimens (treated and raw banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Instruments: Infra-red spectroscopy or FTIR Machine (Fourier Transform Infrared spectra -photometer)

3.4.7 X-ray diffraction testing method

The micro structure of the bbanana fibre was analyzed using X-ray diffractometer. The data gathered from the diffractometer presented the crystallinity, crystallite size and lattice distortion of the banana fibre.

Instruments: X-ray Diffractometer

3.4.8 Testing the moisture content of the banana fibre

The specimens for moisture content test were made in accordance with JIS 1096:1990, DBA standard test method. The moisture regains of the mechanically extracted and treated fibres were examined using a moisture testing oven. Weight of the water content in a banana fibre is measured as a percentage of oven dry weight of the banana fibre.

Test method: The standard test method of JIS 1096:1990, DBA

Conditioning

All test specimens (treated and raw banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Test procedures

The banana fibre specimens were conditioned under standard atmosphere for 24 hours. Conditioned banana fibres were cut at measured lengths. Weight of the banana fibre specimens were measured using their weight balance.

Calculation

The mass of the oven-dry treated and untreated fibre specimens was used for this method. The fibre mass after the specimen has been dried in an oven is controlled at 105 ± 2^{o}. The moisture content of an oven dry weight bundle was calculated from the mass of untreated and treated bundle. The average moisture content was calculated using equation (2).

$$MC(\%) = 100W/D$$

Equation 2

Oven dry weight = D

Weight of water(W) = Original weight- oven dry weight

Moisture Content = MC

The mean average of the moisture content, standard deviation and coefficient of variation were calculated for each treated and raw banana fibre samples.

3.4.9 Water absorbency of banana fibres

Absorbency characteristic of textile material is one of the specific factors that influence the textile processing. Good absorbency property is essential for efficient preparatory processes, dyeing and finishing processes. Wet-ability and absorbency characteristics of a textile material can influence the uniformity of dyeing.

The practical test consists of measuring the time of absorption of a drop of water that was allowed to remain in contact with the textile material (AATCC Test Method-79-2007).

Test method: The standard test method of AATCC Test Method-79-2007

Conditioning

All test specimens (treated and raw banana fibre) were subjected to the standard atmosphere for testing, which is 20 ± 2°C and 65 ± 2 % relative humidity.

Test procedures

The specimens of the banana fibre were conditioned under standard atmosphere for 24 hrs. Convenience sampling method is used for selecting banana fibre samples. The specimen that had 5g of loose fibre bundle was placed in 9.5±1mm below the tip of the burette.

A drop of distilled water was allowed to fall on the surface of the mechanically extracted banana fibre bundle. The time required to disappear was measured using a stop watch and it was recorded as the wetting time. The test was repeated for five samples of each raw fibre samples.

3.4.10 Testing of fibre oil content

Banana fibre specimens were prepared based on JIS 1096:1990 standard method to measure the oil content and tested according to the test method.

3.4.11 Fibre grading system

The fibre grading systems are recognized as essential for both customers and the manufacturers of natural fibres. Identification or grading of fibre content in textiles in the fibre industry has become extremely challenging even for experienced parties in the field. This is mainly due to increase in the variety of fibres and blending techniques used in the industry. Consequently, laboratory tests are very important for grading and verification.

This research focuses on observing the surface structure of the banana pseudostem fibres under the light microscope and scanning electron microscope to determine the fineness, strength, chemical solubility, burning behaviours, and grading of different banana varieties. Fibres and fibre bundles were inspected visually and tested. One focus of this research was to produce quantifiable observations. So the quantitative method can lead to exploring the systemic connection between experimental observation and mathematical expression for the grading of banana fibres.

Based on the results, a novel grading system was introduced for different banana fibres varieties (Sri Lankan cultivar). The banana grading system was designed using five grading parameters: strength, fineness or coarser, colour, lustre and contamination of impurities, and four corresponding grading points: one (1), two (2), three (3) and four (4). The quality banana fibre grading system is presented in Table 3- 6.

Table 3-6: Banana fibre grading system

Grading points	**Quality**	**Parameters**
1	High quality: Very good	Golden yellow colour and lustre, Slightly soft, Fine fibre. Low contamination of impurities. Diameter range:≥75 to 85 µm. Tensile strength range: ≥ 2.5N
2	Medium quality :Good	Golden yellow colour and lustre, Slightly soft. Medium fine fibre, Medium contamination of impurities. Diameter range:≤ 85 to 87 µm. Tensile strength range: ≥ 2.4 to 1N
3	Ordinary: Medium quality	Dark in colour, lustre, Medium coarser, Medium contamination of impurities. Diameter range: ≤87 to 110 µm. Tensile strength range: ≥ 2.4 to 1N
4	Low quality: Bad	Dark in colour, No lustre. Coarser fibre, High contamination of impurities. Diameter range: ≤ 111 µm ≤ . Tensile strength range: ≤ 1N

3.5 Pre-Treatment of banana fibres

3.5.1 Enzyme and chemical combined treatment

The extracted fibres were in the form of long strands and slightly dull yellowish in colour. Extracted fibres were cut to 15 cm in length. Fibre samples were weighed at 5 gram using an electronic scale.

Under the enzyme treatment process, the mechanically extracted banana fibres were treated with a 5% of pectinase enzyme with wetting agent, while maintaining a bath liquor ratio of 1:50. The pH was controlled between 2.5 to 3.5 in the enzyme treatment. The fibres treated with an enzyme under the chemical treatment process were subjected to a temperature of 90^0C with a concentration of 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH (chemicals).

This investigation studied the effects of bleaching on the reflectance value and yellowness or colour difference of banana fibres.

The banana fibres samples that were treated using this combination was thoroughly washed and dried as per the usual process. The banana fibres that were treated with peroxide bleaching had an increased whiteness to their colour and it was also observed that their lignin components were removed (Wang *et al.*, 2003: Balakrishnan *et al.*, 2019).

The banana fibre is a cellulose fibre. It comprises of micro-fibrils in an amorphous matrix of lignin and hemicellulose. After the lignin components are removed, the dyeing process is done using reactive dyes (Chinta & Vijaykumar, 2013). These treated banana fibre samples were then dyed using reactive type of (red, blue and yellow colours: three standard colours) dyes.

3.6 Dyeability of banana fibres

3.6.1 Dyeing recipe and conditions

Both enzymes treated and combined scoured and bleached banana fibres were selected for dyeing processes (Wang *et al*., 2003 : Balakrishnan *et al*., 2019).

3.6.2 Selection of chemicals and dyes

Enzyme and chemically pre – treated fibres were selected for the dyeing process. Reactive dyes (Red, blue and yellow) were used for the banana dyeing process.

Reactive dyes react with cellulose to establish covalent bond and these dyes are water soluble (Chinta & Vijaykumar, 2013). Structure of red, blue and yellow reactive dyes are shown in Figure 3-7, 3-8 and 3-9.

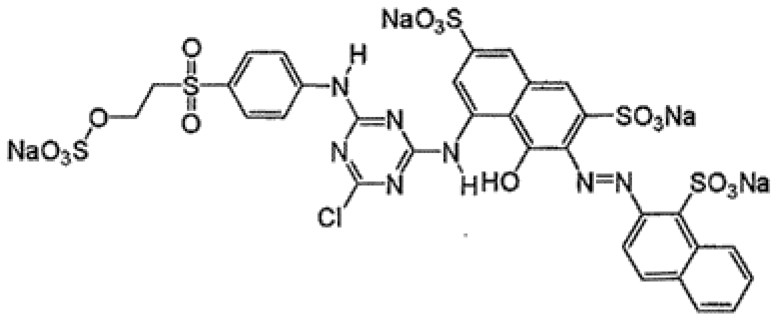


Figure 3-7 Reactive red 250

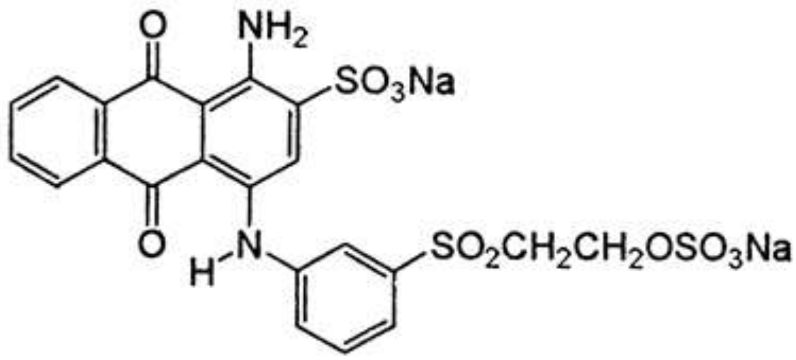


Figure 3-8 Reactive blue 19

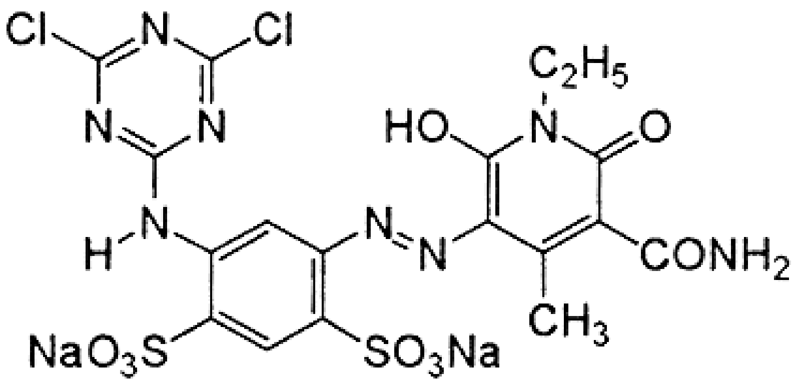


Figure 3-9 Reactive yellow 86

Colour properties of dyed banana fibre samples were compared with reactive dyed cotton fibre samples (red, blue and yellow colours). The dyeing recipe of banana fibre is detailed in Table 3-7. This reactive dyeing based on the following experimental procedure on the work of Irfan *et al*., (2018).

Table 3-7 Dyeing recipe of reactive dye

Type of dye	Colours	Fibre type	Dye – bath ratio	Concentration (%)	Temperature	Time
Reactive dye	Reactive red 250, Reactive blue 19 and Reactive yellow 86	Banana fibre (15g)	1:50	0.25, 1, 4 and 6	60^0c	90 min
Reactive dye	Reactive red 250, Reactive blue 19 and Reactive yellow 86	Cotton fibre (15g)	1:50	0.25, 1, 4 and 6	60^0c	90 min

Reactive dyeing experiments were performed in a dye-bath ratio of 1:50 using exhaustion method (Chinta & Vijaykumar, 2013). Oven dry weight of 15g each banana fibres and cotton fibres were used in each dye bath.

Primary colours of red, blue and yellow of “Cibacron” dyes (commercial brand) were used to dye the banana fibres.

Pre – treated banana fibre (15g) and combined scoured and bleached cotton fibre (15g) (on the basis of oven-dry fibre samples) were dyed with three standard colours (Red, blue and yellow) each with four concentrations (0.25, 1, 4 and 6).

Reactive red 250, reactive blue 19 and reactive yellow 86 types were used and maintained the concentration of salt at 18 g/l, concentration of soda ash at 3.6g/l, concentration of wetting agent at 2g/l. Initially the dyeing temperature was kept at 45 °C then the temperature was gradually raised to 60^0c for 90 min.

After the dyeing procedure, both cotton and banana dyed samples were soap washed to remove the chemicals and un-fixed dyes. This step improves the wash fastness properties of the samples (Raza Miah *et al*., 2017).

Dyeing of banana fibre using the following dyeing cycle

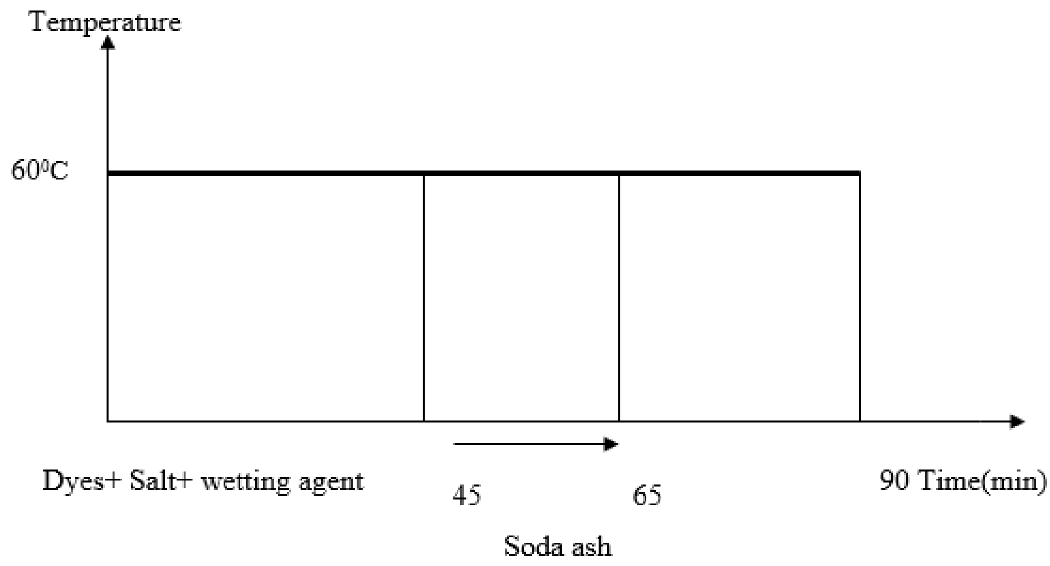


Figure 3-8 Reactive dyeing cycle

Figure 3-10 shows that reactive dyeing cycle for banana fibres. This dyeing cycle mentioned the dyeing temperature and time period (Ali *et al*., 2015 (Irfan *et al*., 2018).

3.6.3 Washing Procedure

Dyed banana and cotton samples were rinsed in cold water (10 min). Then the fibres were rinsed with 2g/l non-ionic detergent at 60°C for 15 min and followed by hot water rinse at 95°C for 10 min (Ali *et al*., 2015).

Again the banana and cotton dyed sample was rinsed in cold water for another10 min (Ali *et al*., 2015). Finally, the samples were oven dried to assess the colour properties.

3.6.4 Dye ability test on banana fibres

After scouring, bleaching and dyeing process, the colour values were obtained by using spectrophotometer. CIE L* a*b* colour values and hue of the dyed samples were measured using spectrophotometer (Datacolor 600).

The spectrophotometer measured raw banana fibre, dyed fibre and cotton fibre samples reflectance factor and the colours deviations of ΔE* values obtained by CIELab (L*, a*, b*, c* and h) colours system.

Spectrophotometer is a hybrid instrument and it gives colorimetric information, for example, X, Y, Z or CIEL*a*b* values for different standard illuminates.

Spectrophotometers vary from colorimeters in that measure reflectance, transmittance, or absorbance for different wavelengths in the range. On account of reflectance estimation, the amount estimated is named Reflectance factor and is characterized as the reflectance of the example at a given wavelength contrasted with the reflectance of the ideal diffuse white estimated under accurately the same.

Light source, method of spectral separation or dispersion, and a detection system are four main key parts of Spectrophotometers. Wavelength Range is generally somewhere between 360-750nm, with 400-700 most common (Randall, 1954).

Colour measurement of banana fibre was performed by Datacolor 600 spectrophotometer. Before using spectrophotometer colour measurement, the long strand fibres were consistently wound on a piece of cardboard. Then colour differences were expressed in CIE L*a*b* units. Lightness demonstrates L*, a* indicates the red/green coordinate, and the yellow/blue coordinate b*. Deltas for L* (ΔL*), a* (Δa*) and b* (Δb*) may be positive (+) or negative (-). The total difference Delta E (ΔE*) is always positive (Konica, 2016).

- ΔL* (L* sample minus L* standard) = difference in lightness and darkness (+ =lighter, - = darker)
- Δa* (a* sample minus a* standard) = difference in red and green (+ = redder, - = greener)
- Δb* (b* sample minus b* standard) = difference in yellow and blue (+ = yellower, - = bluer)
- ΔC* (C* sample minus C* standard) = difference in Chroma (+ = brighter, - = duller)
- ΔH* (H* sample minus H* standard) = difference in hue

3.6.5 Colour fastness to washing

Loose banana fibre and cotton samples were tested by compressing them into pad and sewing it between multifibre strip and maintained low liquor ratio. The change in colour and staining of un-dyed adjacent fabrics are assessed as fastness rating.

Test method: Washing fastness of the samples were tested according to ISO 105-C06 A2S :1994 standards (AATCC).

Instrument: The instrument used in this method is called launder – ometer

Banana fibre specimen in contact with adjacent fabrics was mechanically agitated under particularized conditions of time (40 minutes) and temperature (40^0C), soap with soda solution, then rinsed and dried. Banana fibres was dried by hanging in the air at a temperature of 60^OC (Sachan & Kapoor, 2007).

The variations in colour of the dyed samples were compared with the original specimen. The staining of the adjacent fabrics was evaluated with the reference specimen. These two-colour changes were measured by using grayscale for colour change and staining. The difference in the colour change is given a numerical value ranging from 5 to 1. This numerical values were described in the quantitative terms as following:

Class 5: Excellent

Class 4: Very good

Class 3: Good

Class 2: Fair

Class 1: Poor

Normally, class of 2 and 1 are not acceptable.

3.7 Data Analysis Procedure

The data collected from the sequence of experiments carried out in this research was further investigated utilizing IBM Statistical Package for Social Sciences (SPSS). This section analysed the maximum, minimum, mean, standard deviation and coefficient of variation of the variables.

Especially the mean value of the variable was analysed. Statistical method at 95% confidence interval level was used in the data analysis. This results are compared to observe the variation in the data and where that variation is found. After analysing the data, the results are presented in a separate chapter (Data analysis and Discussion) using statistical tables and graphs in order to give a graphical interpretation.

3.8 Chapter Summary

This chapter outlines the methodology of the extraction and treatments, testing methods, test samples and experimental equipment employed to study the effect it has on the extraction of banana fibres. The banana fibre treatment methods (Biological treatment, chemical treatment and enzyme and chemical combined treatment) and extraction methods (Biological and chemical extraction) were examined in detailed, followed by an explanation of the fibre linear density, strength, diameter, FTIR, X-ray diffraction testing methods and its effect on the quality of the extracted banana fibres.

This study will be focusing on the feasibility of Banana fibre as a textile. A major constraint of the study was limited to the most popular ten Sri Lankan varieties of banana plants. Scanning electron microscopic analysis of banana fibres was done to study the fineness (diameter) of banana fibres. A preliminary study conducted on the banana fibre extraction methods available in the literature review.

The goal of this investigation is to bring textile feasible fibre properties such as fibre fineness and strength. A literature survey will be conducted related to international research and their finding about banana fibre extraction methods. The biological treatment shows higher strength values (19%) than the other treatments, even though biological and chemical treatments gave moderate improvement in fibre fineness. Results shows that biological treatment reduces fibre fineness (from 168.4 mm to 101.45 mm) and linear density (from 25 tex to 21 tex) compared to mechanical extraction. Chemical treatment resulted in 64% reduction in fibre diameter and 10% increase in fibre strength compared to mechanically extracted fibres. Enzyme and chemical treated fibre presented 71% reduction in fibre diameter and 9% increase in fibre strength compared to mechanically extracted fibres. However, fibre strength decreased with an increase of chemical concentration.

4 DATA ANALYSIS AND DISCUSSION

4.1 Introduction

The objective of this chapter is to present the key findings of banana fibre extracted and treated fibre properties were analysed in this research. This section details different extracted fibres such as (1) mechanically extracted fibre (2) biologically extracted fibre and (3) chemically extracted fibre physical and chemical properties were discussed.

This section was investigating the different treated fibres such as (1) biological treated fibre (2) chemical treated fibre and (3) chemical and enzyme combined treated fibre properties were analysed.

Further, this chapter compares applicability of using each method and treatments for banana fibre. Finally, this chapter concludes with suitable banana varieties for fibre extraction and treatments after analysing its fibre strength, fineness (Fibre linear density and Diameter), absorbency and dye absorption rate.

4.1.1 Estimation of mechanically (Decortication method) extractable fibre quantity in Sri Lanka per year

The table 4-1 represents information on the extractable amounts of banana fibres from a selected six districts. In this table shows the availability of banana fibres source in our country. In table 4-1, the extractable amount of the banana fibres from a single banana pseudostem was calculated and practicing the decortication extraction method in this research study.

Land used for cultivation (hectare) and No of plants per hectare details were collected from Department of Census and Statistics. According to available statistical data around 53,246 ha of land is used to banana cultivation in 2019 throughout the country. About 825 banana plants can be grown in one (1) hectare (Advisory circular no.c5 by Coconut research institute of Sri Lanka) and around 260g of fibres can be extracted from a banana stem (Report on Banana fibre by Manoji Allagedara, The National Crafts Assembly, Rathnapura District). Assuming rate of effective plants is 0.5. The weight of fibres in each pesudostem was weighed using an electronic scale in the same standard conditioned. The same test was repeated for ten times and the results are presented below.

The amount of fibres that is required to extract one pesudostem (Extractable amount of fibre from a single plant)

= the mean value of banana fibre weight

= 260 grams,

with the standard deviation of 150.68

The extractable amounts of banana fibres in Sri Lanka the are presented in Table 4-1. The average extractable amounts of banana fibre were calculated using an equation one (1),

$$Land\ used\ for\ cultivation\ \times No.of\ plants\ per\ hectare \times 260 \times 0.5$$

Equation -1

Table 4-1 Extractable amount of banana fibres in Sri Lanka

	Kurunegala	**Badulla**	**Monaragala**	**Kandy**	**Gampaha**	**Rathnapura**	**Total**
Land used for cultivation (ha)	6981	2464	6962	3166	2709	7471	29753
No of plants per hectare	825	825	825	825	825	825	4950
Extractable amount of fibre from a single plant	260g	260g	260g	260g	260g	260g	260g
Assuming rate of effective plants	0.5	0.5	0.5	0.5	0.5	0.5	3
Extractable amount fibres (Kg)	**748712**	**264264**	**746674**	**339553**	**290540**	**801264**	**3191009**
Extractable amount fibres (ton)	**749**	**264**	**7467**	**339**	**291**	**802**	**319**
Revenue generation from banana fibre	16284491	5747742	16240170	7385288	6319250	17427508	69,404,451

4.2 Properties of banana fibres

4.2.2 Optical Microscopic Structure

a) <u>Mechanically extracted fibres</u>

Ten varieties of banana fibres were used in this study, which are following (1) Kolikuttu (AAB) (2) Seeni, (3) Embul, or Ambul, 4) Atamuru, (5) Ambun (6) Suwandel, (7) Poowalu, (8) Rathambala (AAA) (9) Alu kehel, and (10) Anamalu (AAA). Initially these ten varieties of banana fibres are microscopically examined under two different microscopes (light microscope and scanning electron microscope). However, there is no different in surface morphology (light microscope) amongst banana varieties (Table 4-2).

Table 4-2 Microscopic structure of top ten banana cultivars

Banana fibre variety		Magnification of microscope	
		20X	40X
01	Ambun (AAA)		
02	Embul (AAB)		
03	Kolikuttu (AAB)		
04	Poowalu (AB)		
05	Seeni (AAB)		
06	Anamalu (AAA)		

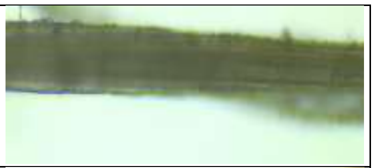
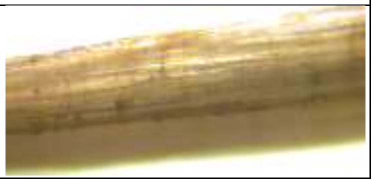
07	Rath kehel (AB)		
08	Atamuru (ABB)		
09	Suwandel (AB)		
10	Alu kehel (ABB)		

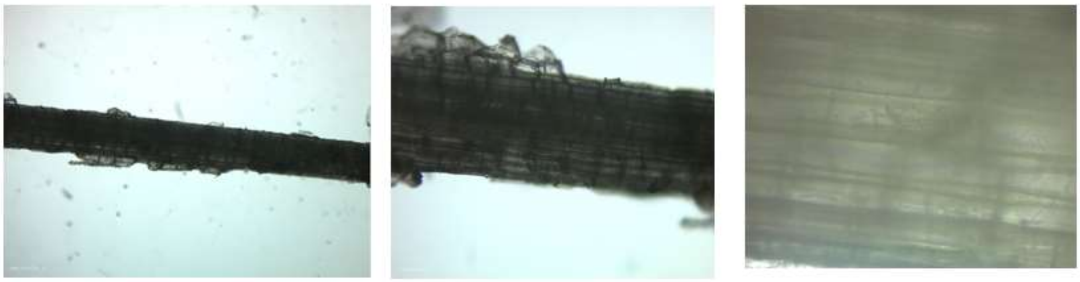
Table 4-2 show that presence of irregular lines, lustrous, straight rigid and obvious slubs in banana fibres. The mechanically extracted banana fibres appearance is much rough, because of the roughness of banana fibre, the microscopy images are cloudy and imprecise.

The non- fibrous materials were observed in fibre surfaces in all varieties and this non cellulose materials were covered around the fibre bundles. Lignin, hemicellulose pectin and pentason are some of non-cellulosic components (Jagadeesh *et al.*, 2015). There are no elementary fibres observed in the microscopic images (Table 4-2).

Each variety of pseudo stem was further cut into four different layers. Inner pseudo stem layers are labelled as first layer and external pseudo stem layers is labelled as fourth layer. After that, Banana single fibre samples longitudinal view were observed from different layers in the ambun banana stem.

Figure 4-1 to Figure 4-4 display microscopic appearance of single layer wise fibres (Ambun banana stem layers wise obtained fibres). Figure 4-1 to Figure 4-4 show that presence of irregular lines, lustrous, straight rigid and obvious slubs, and the length of joint distance in banana fibres. Thus, banana fibre has similar physical properties like flax fibre (Das *et al.*, 2010).

The mechanically extracted banana fibres appearance is much rough compared to other treated fibres. Because of the roughness of banana fibre, the layer-wise microscopy images are cloudy and imprecise. Splitting up of fibrous strands was observed on the surface of all layers of Ambun fibres. This bundle structure consisting of several fibrils. Fourth layer and first layer of Ambun fibre clearly shown broken parts, entangled micro fibrils, multicellular and bundle structure.



4 X 10X 40X

Figure 4-1 Microscopic view of the first two layers

4X 10X 40X

Figure 4-2 Microscopic view of the second two layers

4X 10X 40X

Figure 4-3 Microscopic view of the third two layers

4X 10X 40X

Figure 4-4 Microscopic view of the fourth two layers

The average diameter of a cell in the raw fibre is approximately 93 µm. Banana fibre samples were examined from different layers in the banana stem. However, there is no different in surface morphology amongst layers and visibility of the surface is not much clean surface due to the presence of bonding or pulpy materials on the surface.

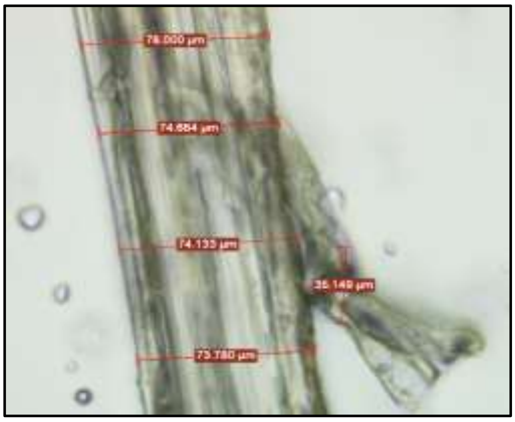


Figure 4-5 Mechanically extracted banana fibre(Middle layer) (40X)

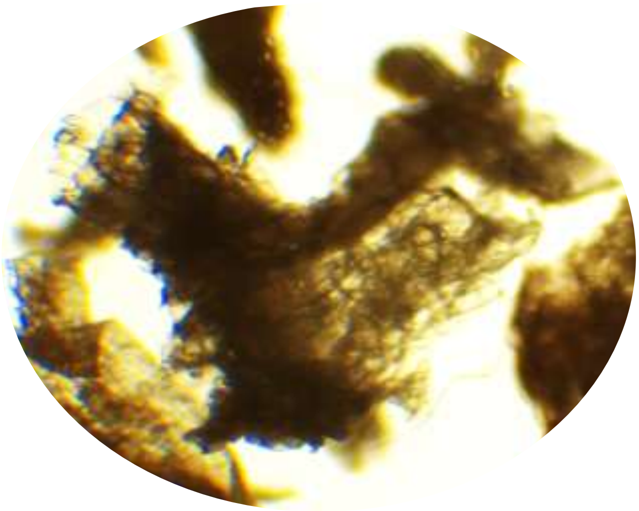


Figure 4-6 Cross section view of raw banana fibre(10x)

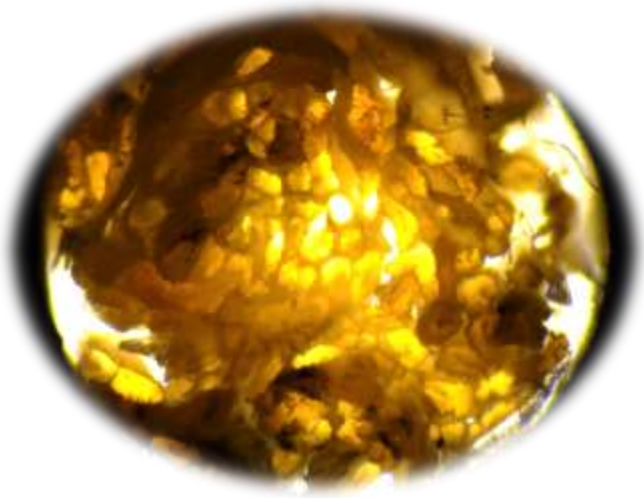


Figure 4-7 Cross section view of raw banana fibre(40x)

Figure 4- 6 and 4-7 display cross sectional view of untreated banana fibre. Cross section view of raw banana fibre is not much distinct and irregularly in shape. The ultimate fibres and their fibrils are not clearly visible in the cross section image. The transverse section of banana fibre revealed in Figure 4-6 conforms the multi cellular structure.

In the cross section of the mechanically extracted banana fibre seen in hollow structures effects. (Figure 4-7). Figure 4- 6 and 4 -7 shows that one technical fibre consists of several smaller fibres bundled into one. The individual fibre consists of several technical fibres. The hollow structure of the fibre supports the sufficient insulation and better absorbance properties (Subagyo and Chafidz, 2018).

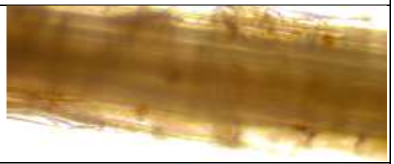
The fibre bundles frequently show a series of peculiar, thick, strongly silicified plates. It is difficult to separate fibre cells from technical fibres as the fibres seem to be compact and tightly bound.

a) Acetic acid treatment for banana fibres

Table 4-3 presents the microscopic view of different concentrations of acetic acid-treated fibres. These micrograph images illustrate the difference in their surface morphology after the acetic acid treatment.

This treatment removes certain impurities (lignin and hemicellulose) present on the fibre surface (Mlayah & Delmas 2005). The acetic acid-treated fibre has a rougher surface compared to the mechanically extracted fibre surface.

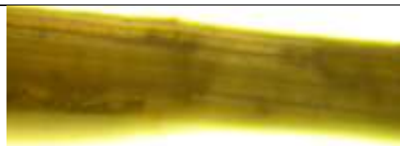
Table 4-3 Microscopic view of acetic acid treated banana fibres

Concentration of Acetic acid	Magnification of microscope	
	10x	40x
2%		
4%		
6%		
8%		
10%		

b) Castor oil treatment for banana fibres

Table 4-4 shows microscopic image of castor oil treated banana fibre. This fibre surface was irregular and contain impurities. Castor oil treated fibres were found to be soft and little lustrous.

Table 4-4 Microscopic view of castor oil treated banana fibres

Concentration of Caster oil	Magnification of microscope	
	10x	40x
2%		

4%		
8%		

c) Glycerin treatment for banana fibres

The morphological characteristics mentioned in Table 4-5 shows for different concentration of glycerine treated banana fibres. Glycerin treated fibres are not much clear due to removal of some pulpy materials. The pulpy materials are clearly visible when fibres are treated with 6% and 8% glycerine.

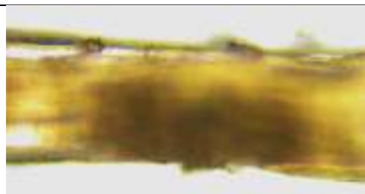
Table 4-5 Microscopic view of glycerine treated banana fibres

Concentration of glycerine	Magnification of microscope	
	10x	40x
2%		
4%		
6%		
8%		

d) Permanganate treatment for banana fibres

The microscopically view of permanganate treated fibre images are given in Table 4-6. The 2% and 4% permanganate treated fibres are not much different in surface morphology from the mechanically extracted fibres. The different concentration of permanganate treated fibres images confirms the tie- marks on the surface and it convey the bundle structure of the fibres. Permanganate treatment revealed the fibre becomes rough. The concentration of 4% ,6%, and 8% permanganate treated fibres showed uniform surface roughness because of the effective oxidation of the fibre surface and the removal of a considerable amount of lignin, waxy plastic along with the impurities from the fibre. The microscopic image of 10% permanganate treated fibres are becoming rough and started to fibrillated.

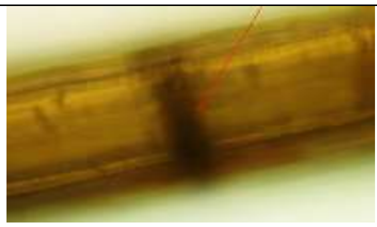
Table 4-6Microscopic view of Permanganate treated banana fibres

Concentration of Permanganate	Magnification of microscope	
	10x	40x
2%		
4%		
6%		
8%		
10%		

The tie- marks and multi- cellular structures are clearly visible when banana fibre treated with 2% permanganate and 5% sodium sulphide (Table 4-7).

These each bundle structure of the fibres consisting of several fibrils (Table 4-7).

Table 4-7 Microscopic view of multi-cellular structure

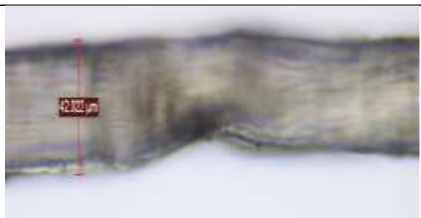
Magnification of microscope	2% Permanganate	5% Sodium sulphide
4x		
10x		
20x		

e) Sodium sulphide treatment for banana fibres

The horizontal marks on the fibre surface and multi- cellular structure are shown in Table 4-8. The 2% and 4% sodium sulphide treated fibres are not much different in surface morphology from the mechanically extracted fibres.

The 6% and 10% sodium sulphide treated fibres are shown structural differences and fibre bundles are completely individualized. Table 4-8 shows individual fibres were removal the cementing materials around the fibre bundles, after the 4% and 10% of sodium sulphite treatments.

Table 4-8 Microscopic view of Sodium sulphite treated banana fibres

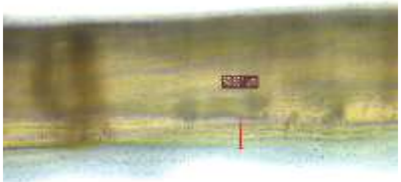
Concentration of Sodium sulphide	Magnification of microscope	
	10x	40x
2%		
4%		
6%		
10%		

f) Caustic soda treatment for banana fibres

The structural features of caustic soda treated fibre microscopic images are shown in Table 4-9. The caustic soda treated fibres are not much different in surface morphology from the mechanically extracted fibres. The surface is less clear, due to the removal of some impurities and debris.

Table 4-9 Microscopic view of caustic soda treated banana fibres

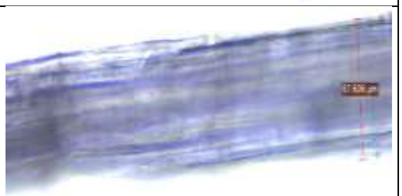
Caustic soda	Magnification of microscope	
	10X	40X
4%		

6%		
8%		
10%		

g) Hydrogen peroxide treatment for banana fibres

Hydrogen peroxide treatment imparted a white colour to the banana fibre and resultant fibre was found to be soft and lustrous (Table 4-10). Smoother surface features (6% and 8% H_2O_2) are observed in the bleached fibres as some of impurities were removed in the hydrogen peroxide treatment (Table 4-10).

Table 4-10 Microscopic view of Hydrogen peroxide treated banana fibres

Hydrogen peroxide	Magnification of microscope	
	10x	40x
2%		
4%		
6%		

8%		

h) Enzyme and chemical combined treatment for banana fibres

The ultimate fibres and their fibrils are clearly visible when banana fibres are treated with 6% combined chemicals (Table 4-11).

This treatment imparted a whiteness colour to the fibres and resultant fibre was found to be soft and lustrous. Banana fibres with 6% combined chemical treatment, fibrous bundles were well separated and fibrillation also started. There is a still better fibre separation and the ultimate fibres are visible (Table 4-11).

Table 4-11 Microscopic structure of Enzyme and chemical treated banana fibres

Combined treatment	Magnification of microscope	
	10x	40x
1%		
2%		
3%		

4%		
6%		
8%		

<u>Comparison of Enzyme, chemical treated and dyed banana fibre</u>

The enzyme and chemical treated banana fibre provides much clearer image than the raw banana fibres. The average cell diameter of enzyme and chemical treated banana fibre is approximately 59.76 μm.

Figure 4-8 to Figure 4-11 shows longitudinal view of treated fibres. Figure 4-9 shows longitudinal view of enzyme treated fibres.

Figure 4.9 presents longitudinal view image of combined scoured and bleached fibres and Figure 4.10 shows combined of enzyme, scoured and bleached treated fibre. Figure 4.11 shows the red colour dyed banana fibre.

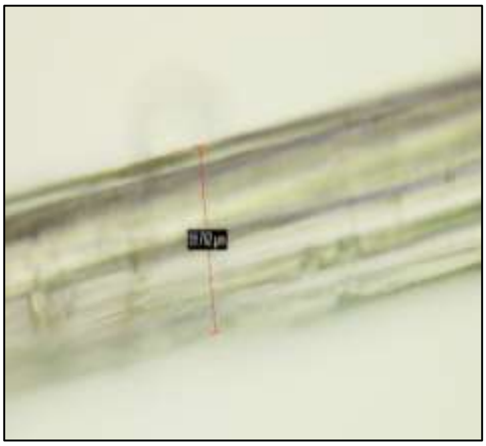


Figure 4-8 Enzyme treated fibre (40X)

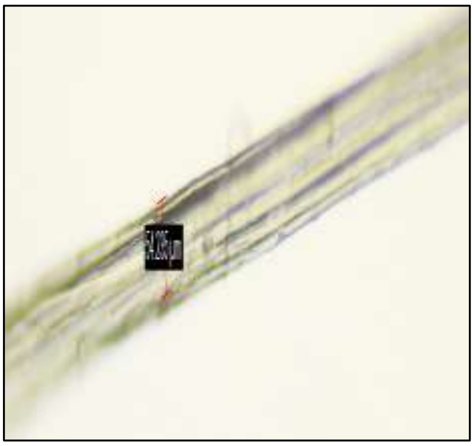


Figure 4-9 Scoured and bleached fibre(40X)

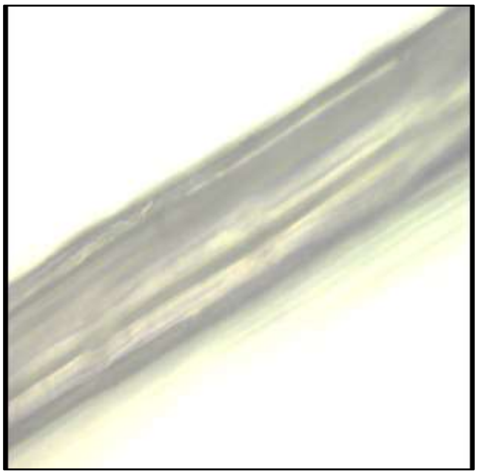


Figure 4-10 Enzyme treated and bleached fibre(40X)

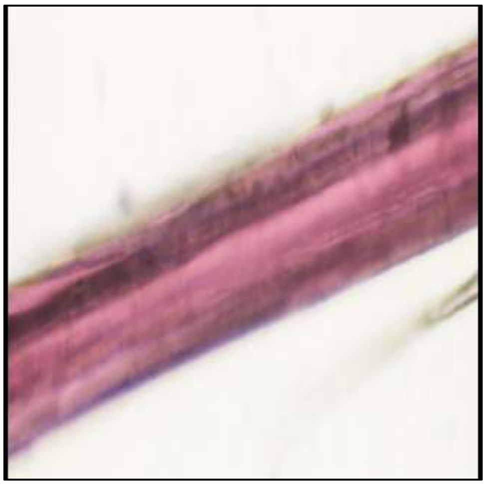


Figure 4-11 Dyed banana fibre(40X)

4.2.1 Banana fibre length

Compared to other common natural fibres banana fibres are extremely strong, lustrous and long length filament fibres. Generally, strengthens of spun yarns increases with lengthiness of staple fibres. Therefore, stronger spun yarns can be produced from banana fibres. Further, longer length of banana fibre can be produce a predetermined short length of fibres which can be efficiently blended with different fibres to produce blend spun yarns.

Banana fibres are very fine, off-white natural colour and lustrous. This natural lustre enhances the value of banana fibres. In the preliminary investigation, it is determined that the banana fibres have longer fibre length. The length of fibre may vary with the type of fibre extraction method. The length of mechanically extracted fibres was measured by a steel meter rule fixed on a table. Banana fibre distribution table showed 4-12, which is a synthesized distribution of 100 fibres and corresponding Figure 4-12.

Table 4-12 Banana fibre length distributions

Maximum Length of banana Fibre (inch) [x]	**Frequency [f]**	**Cumulative Frequency**	**[fx]**	**d =[x-24.85]**	**Square(d)**
11	0	0	0	-13.85	191.8225
12	3	3	36	-12.85	165.1225
13	4	7	52	-11.85	140.4225
14	6	13	84	-10.85	117.7225
15	15	28	225	-9.85	97.0225
16	20	48	320	-8.85	78.3225
17	26	74	442	-7.85	61.6225
18	35	109	630	-6.85	46.9225
19	44	153	836	-5.85	34.2225
20	63	216	1260	-4.85	23.5225
21	77	293	1617	-3.85	14.8225
22	97	390	2134	-2.85	8.1225
23	97	487	2231	-1.85	3.4225
24	92	579	2208	-0.85	0.7225
25	89	668	2225	0.15	0.0225
26	84	752	2184	1.15	1.3225
27	74	826	1998	2.15	4.6225
28	69	895	1932	3.15	9.9225
29	56	951	1624	4.15	17.2225
30	49	1000	1470	5.15	26.5225
TOTAL	1000		23508		1043.45

Length of thousands banana fibres were tested at room temperature and according to the length results, the following bar plot can be plotted (Figure 4-12). Results are simply obtained by accumulating the frequencies starting at zero for length 11inches.

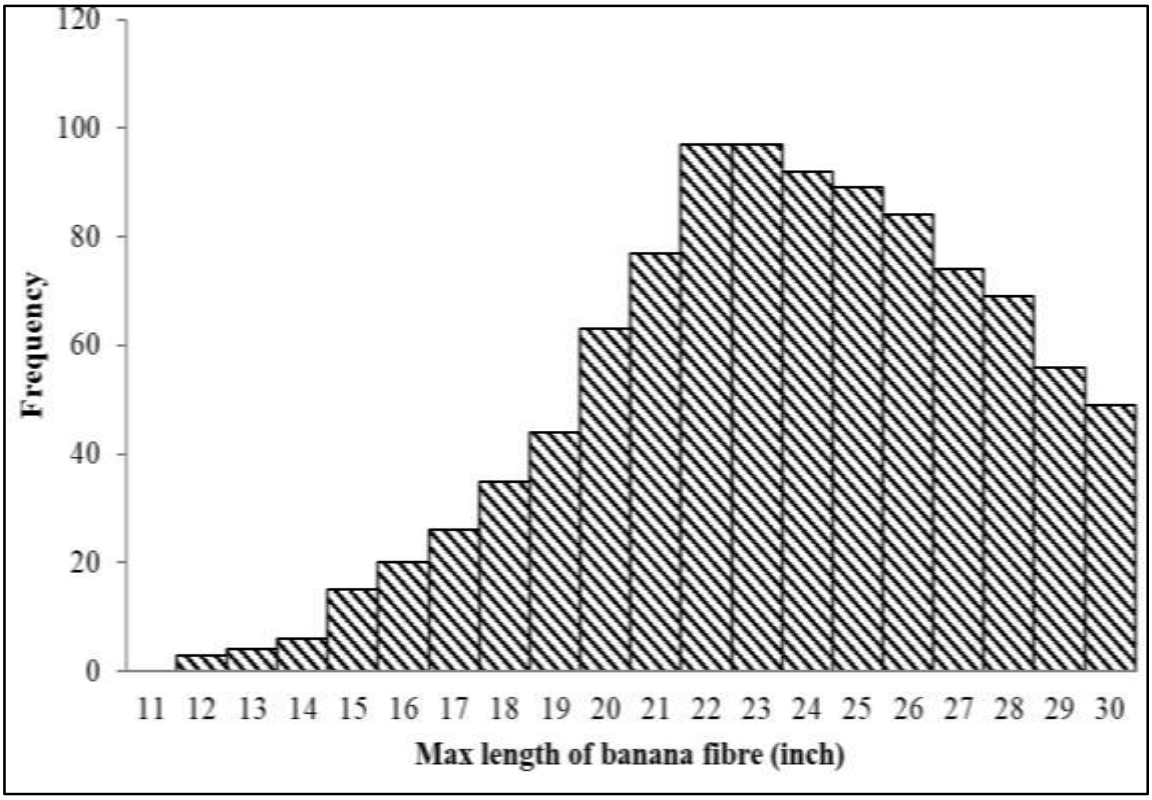


Figure 4-12 The distribution curve for the banana fibre length

Length of banana fibres readings are tabulated in a Figure 4-12. The mean value of the maximum length of fibres extracted from 8 feet pseudostem can be calculated as:

Mean = 23508 / 1000

= 23.50 inches,

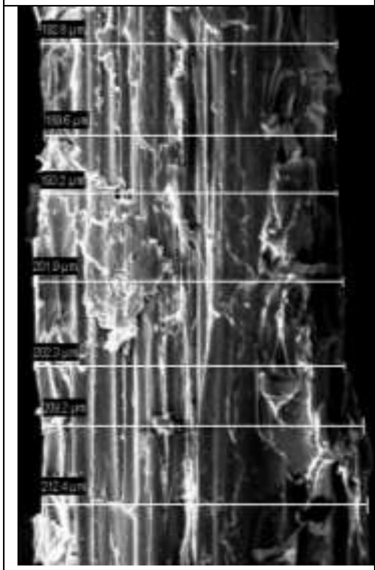
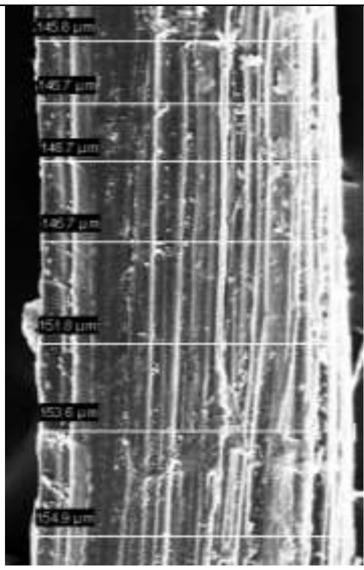
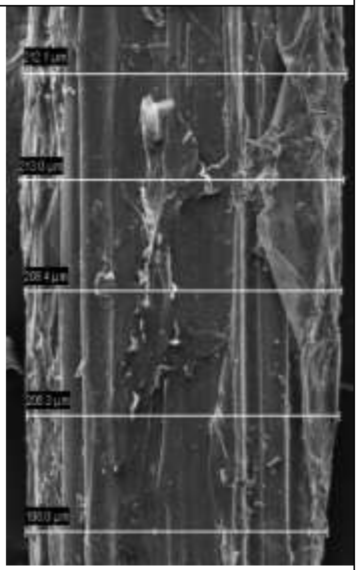
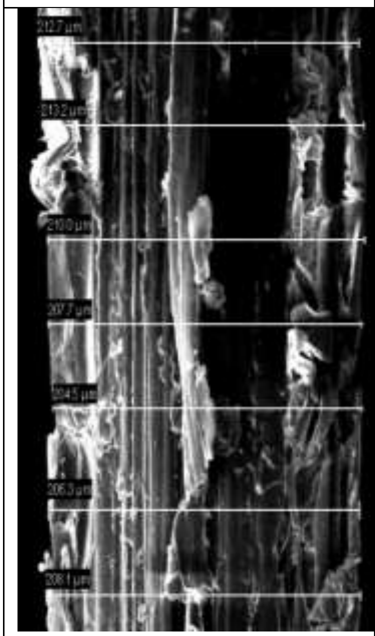
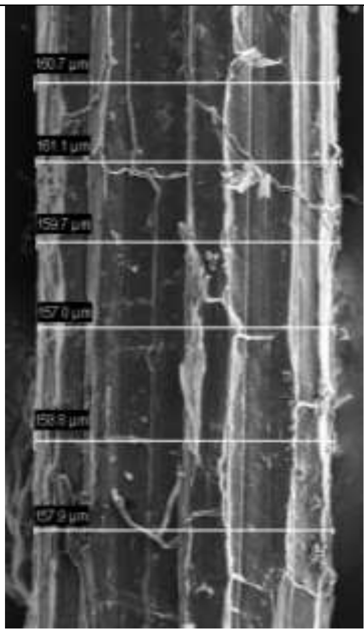
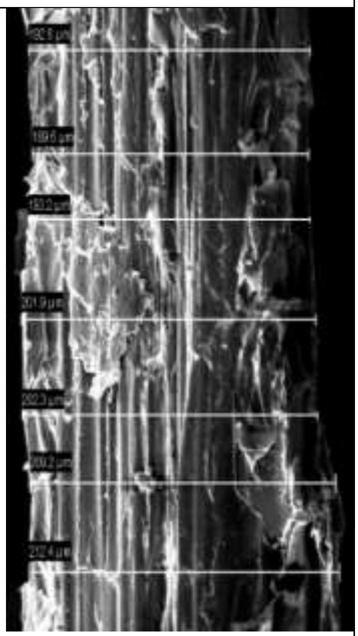
Standard deviation is 1.044, It can be assumed that the maximum value of 23 inches' length of fibres can be extracted from banana pseudostem.

4.2.3 Scanning Electron Microscopic (SEM) structure

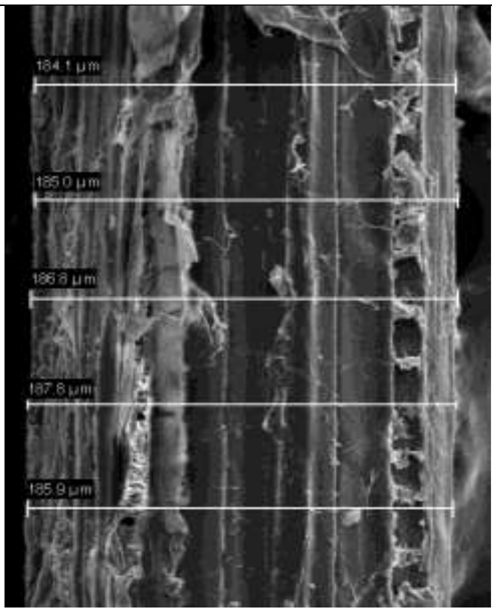
a) Mechanically extracted banana fibre

The structural features and fracture morphology of the banana varieties were analysed. Scanning electron microscopy image of ten selected banana varieties as shown in Table 4-13.

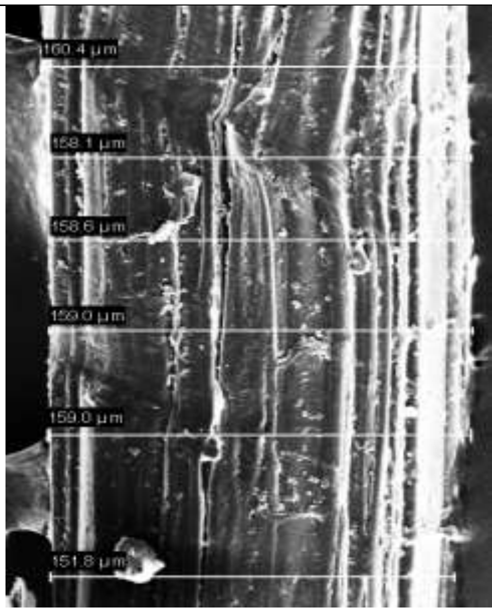
Table 4-13 SEM images of ten banana cultivars

SEM view of Rath kehel banana fibre	SEM view of Kolikuttu banana fibre	SEM view of Seeni banana fibre
		
SEM view of Anamalu banana fibre	SEM view of Ambun banana fibre	SEM view of Suwandel banana fibre
		

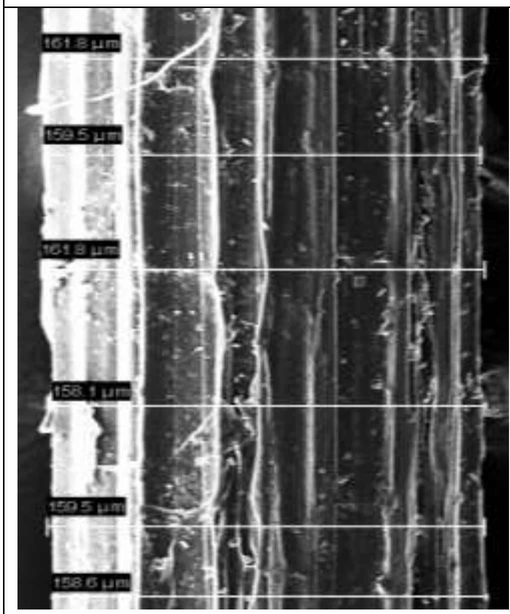
SEM view of Ambul banana fibre



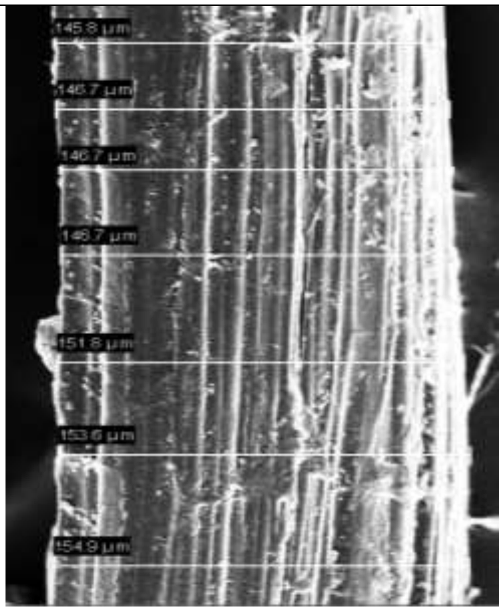
SEM view of Atamuru banana fibre



SEM view of Poowalu banana fibre



SEM view of Alu kehel banana fibre



This SEM images of all ten varieties fibres shown that fibre surface of morphology was rough and have impurities. Bonding substances or pulpy materials can be highly visible in extracted fibre images. The fibres have hollow nature and cellular in the structure. The transverse section of fibre shown in images confirms the multi – cellular structure. The different banana cultivars vary in fineness properties, the variation being of the order of 63% in terms of diameter (from maximum to minimum). As per the observation of SEM images of Table 4-13, mechanically extracted fibres have an irregular surface and contains impurities. In addition, mechanically extracted banana fibres have a higher diameter around 220 micrometres compared to chemical and biological method extracted fibres.

Table 4-14 SEM images of layer wise banana pseudostem

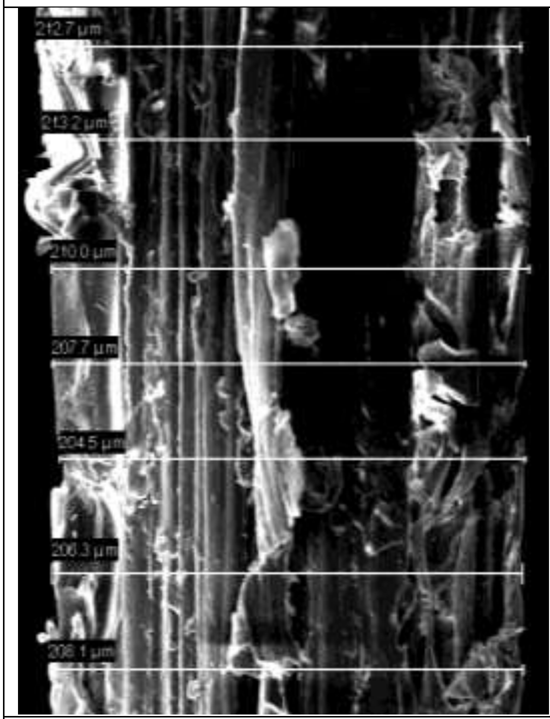
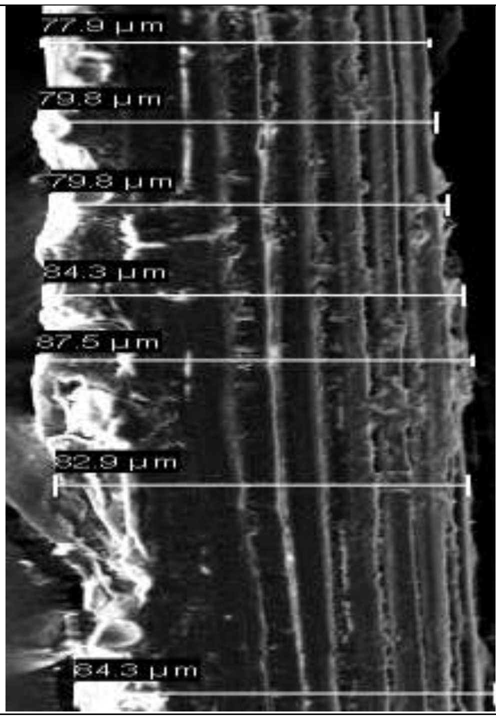
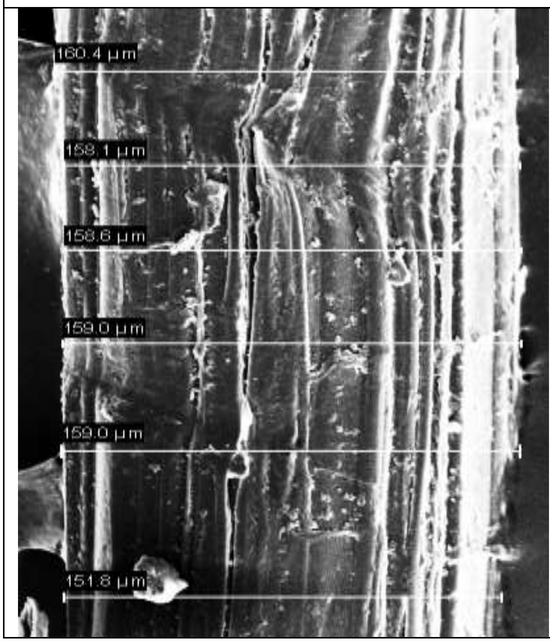
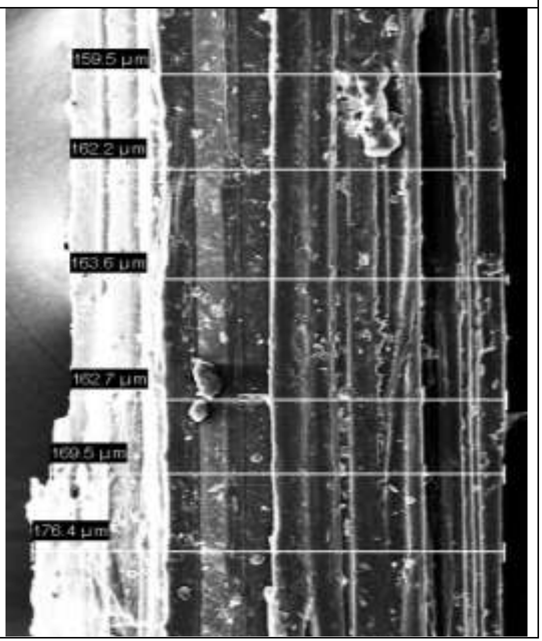
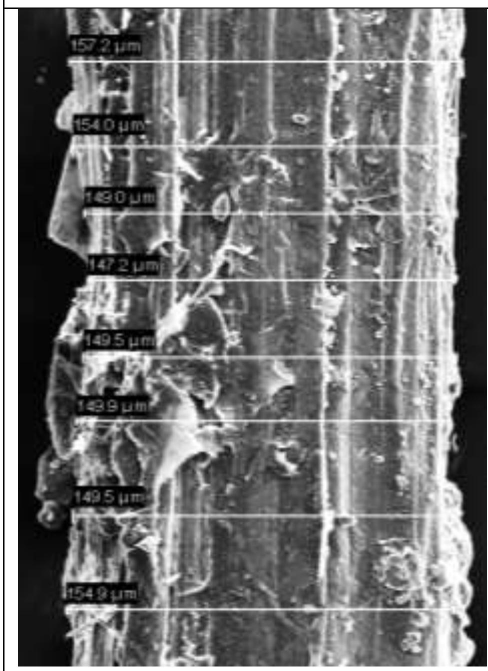
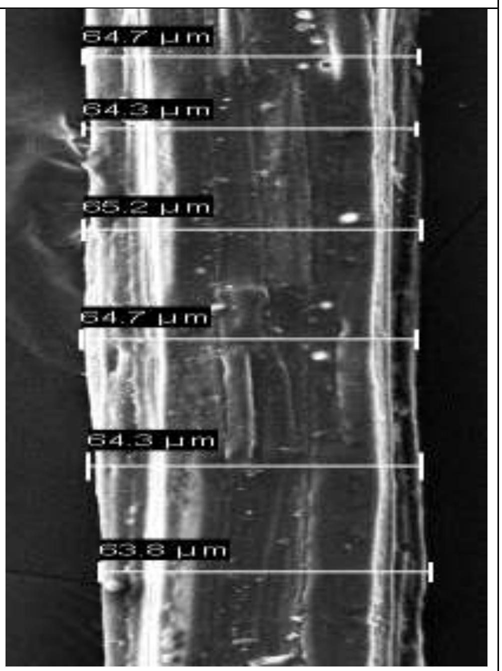
SEM microscopic view of first layer	SEM microscopic view of second layer
	
SEM microscopic view of third layer	SEM microscopic view of fourth layer
	

Table 4-14 shows the SEM images (1500X) of mechanically extracted layer of ambun banana fibre, which is shows damaged fibrils in the fibre surface. Mechanical method effect on properties of low micro-fibril angle and high cellulose content in the banana fibre (Mohiuddin *et al*., 2014). However, defibrillation does not happen in the enzyme treated fibres. Further, bonding substances can be highly visible in mechanically extracted fibre images. After machine decortication, splitting up of fibrous strands which are coarser due to the bonding substances or pulpy materials. Scanning electron microscopic examination have confirmed that bundle structure of Ambun fibre. Splitting up of fibrous strands, rough surface morphology and fragments were observed on the surface of fibre in all layers of Ambun and puwalu fibres. This bundle structure consisting of several fibrils. Fourth layer and first layer of Ambun fibre clearly shown broken parts, entangled micro fibrils, multicellular and bundle structure. Outer layers of fibres were coarser than middle layers. The order of Ambun fibre diameter differences was found as 2nd layer and 3rd layer < 1st layer < 4th layer.

b) Biologically and chemically extracted banana fibre

Table 4-15 SEM images of biologically extracted Ambun banana fibres

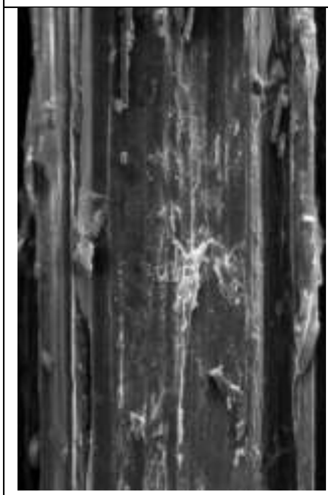
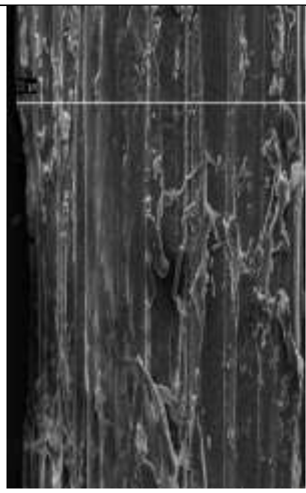
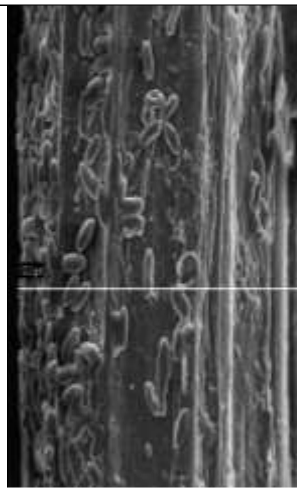
5% Enzyme treated fibre	5% Caustic soda treated fibre
	

Enzyme treated banana fibres SEM images show that fractured surfaces or longitudinal cracks on the banana fibre (Table 4.15).

Mechanically extracted Ambun banana fibre layer contains an irregular surface and impurities. This resulted the rough surface topography of mechanically treated Ambun (AAA Genome) fibre. However, this roughness of fibre can be improved by chemical and enzyme treatments. Since these methodologies will remove natural (lignin and hemicelluloses) and artificial impurities, however, these methods prevent defibrillation. The fractured surfaces of enzyme and chemical treated banana fibres of scanning electron microscopic (SEM) images signify that the crash or surface structure change as a result of the pull out of micro fibrils joined by tearing of cell dividers. This treatment indicates the removal of pulpy material, which is result in the reduction of diameter and the bundle strength was found to increase. The diameter reduction was mainly happened due to the removal of hemicellulose components.

c) Biologically treated banana fibres

Table 4-16 SEM images of enzyme treated Ambun banana fibres

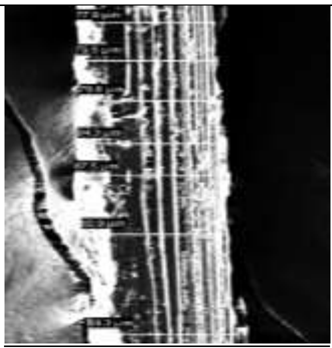
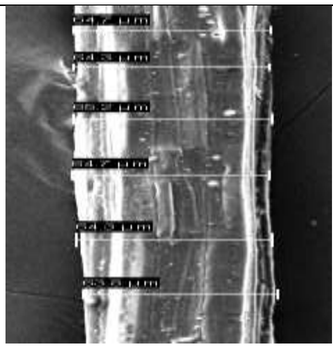
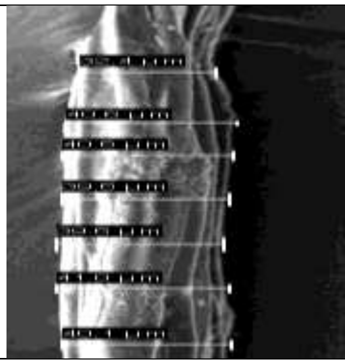
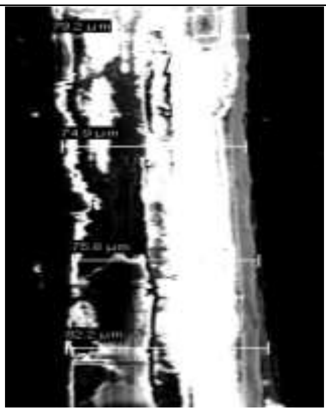
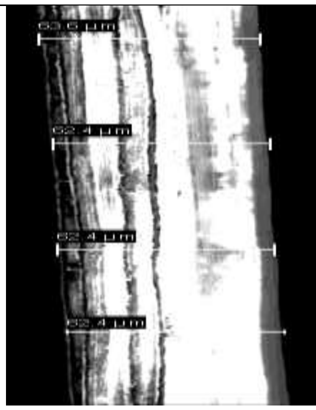
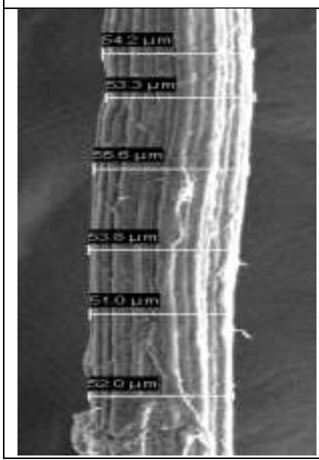
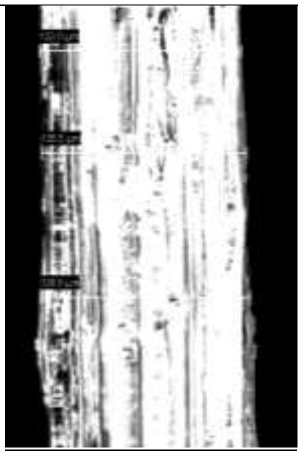
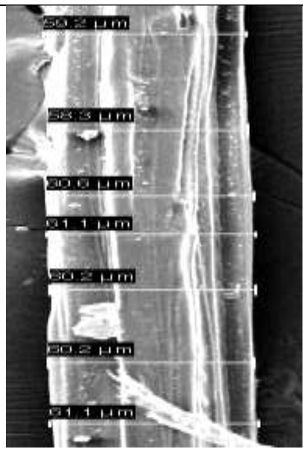
2.5% Enzyme treated banana fibres	5% Enzyme treated fibres	10% Enzyme treated fibre
		

The 2.5% enzyme treated banana fibres are not much different in surface morphology from mechanically extracted banana fibres. While treating fibres with 5% enzyme, the fibrils were well separated. However, fibrillation also started (Table 4-16). The SEM

images of enzyme treated fibres show that the diameter of the fibre is reduced due to the removal of binding material.

d) Chemical treated banana fibres

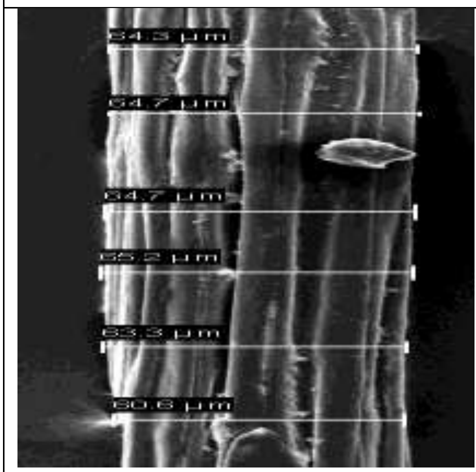
Table 4-17 SEM images of chemical treated Ambun fibres

5% Caustic soda and Hydrogen peroxide treated fibre	5% Caustic soda treated fibres	10% Caustic soda treated fibre
		
5% Commercial softeners treated banana fibre	5% Turkey red oil treated banana fibre	5% Glycerine treated banana fibre
		
5% Sodium sulfide treated banana fibre	5% Acetic acid treated banana fibres	5% Hydrogen peroxide treated banana fibre
		

The 5% acetic acid and glycerine treated fibres are not much different in surface morphology. Caustic soda treatment imparted a rough surface to the fibres. 5% Commercial softeners treatment imparted a cream colour to the fibres and the resultant fibre was found to be soft and lustrous. 5% Sodium sulphide treated banana fibre, 5% caustic soda and Hydrogen peroxide treated fibre and 5% hydrogen peroxide treated banana fibres has more clear surface, due to the removal of impurities.

e) Enzyme and chemical treated banana fibres

Table 4-18 SEM images of enzyme and chemical treated banana fibres

2.5% Enzyme, and chemical treated fibres (6% H_2O_2 and 3% NaOH)	5% Enzyme, and chemical treated fibres (6% H_2O_2 and 3% NaOH)
	

Both chemical and enzyme treatment methods remove the presence of natural (e.g. lignin and hemicelluloses) and artificial impurities. Higher removal occurs in chemical treatments, so chemical treatment fibre SEM image Table 4-18) shows the finer diameter than the other treatments fibres because chemical treatment removes the bonding agents (hemicellulose and lignin) between the micro fibrils. These bonding substances are highly visible mechanically extracted fibre images (refer the Table 4-18).

It determines the removal of cementing material of lignin, pentason, and others. The fractured surfaces of enzyme and chemical treated banana fibres of scanning electron microscopic (SEM) images signify that the crash or surface structure change as a result of the pull out of micro fibrils joined by tearing of cell dividers. Depth of the grooves were increased. The SEM images of enzyme and chemical treated fibres show that the diameter of the fibre is reduced due to the removal of binding material.

The optical microscopy investigation shows that banana fibre is a multicellular fibre as similar to other cellulose fibres such as cotton, flax, linen. Based on the SEM images analysis, mechanically extracted banana fibre contains irregular surface structure and impurities. Further mechanically extracted banana fibre’s average diameter is around 220 μm.

Comparing to other common natural fibres such as cotton, flax etc., banana fibre has a larger diameter value due to the higher chemical composition of Hemicellulose, lignin and pectin bonding substances can be observed third layer and fourth layer.

Chemical and enzyme treatments removed natural (lignin and hemicelluloses) and artificial impurities. Enzyme and chemical treated fibre SEM images shows that the fibrous bundles were well separated and achieved finer diameter then the other treatments**.** The biological and chemical treatments remove the binding material when binding materials is removed the bundle of fibres are separated. Therefore, the number of elementary fibres in the technical fibres are removed. Hence the diameter is reduced.

4.2.4 Fibre diameter

<u>a) Mechanically extracted banana fibre</u>

Figure 4-13 shows the results of mechanically extracted ten types of banana varieties fibre diameter values. The different banana cultivars vary in properties, the variation being of the order of 63% in terms of diameter (from maximum to minimum). Figure 4-13 gives the results of mechanically extracted top ten types of banana varieties fibre diameter values, it’s standard deviation and coefficient of variance of fibre diameter.

Low value of diameter value was obtained from Ambun (AAA) variety. High value of diameter was obtained from Rath kehel (AAA) fibre variety. Ambun fibre have an average diameter of about 78.02 μm and Rath kehel fibre have an average diameter of about 214.4 μm, which is about 63.6% reduction compared to Ambun fibre diameter. Fine fibres were obtained from Ambun (AAA) cultivars. However, the fineness of fibres varies from about 78.02 μm to 214.4 μm. The order of the diameter differences was found as Ambun < Kolikuttu < Puwalu < Atamuru < Seeni < Ambul < Suwandel < Alu kehel < Anamalu < Rath kehel.

The results reveal that Ambun banana (AAA Genome) of pseudostem has the least value of fineness while rathkehel fibre shows higher value of fineness among the testing types. In order to further testing for finer fibre testing, this research work was selected ambun, Kolikuttu, Ambul, Atamuru and puwalu varieties for further testing.

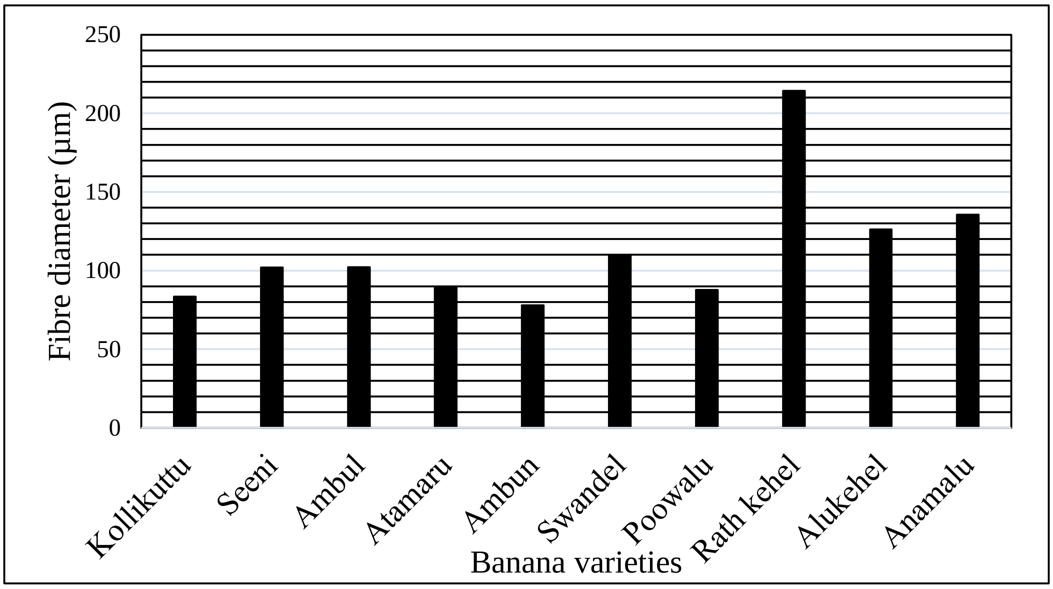


Figure 4-13 Diameter(µm) of mechanically extracted ten selected fibre varieties

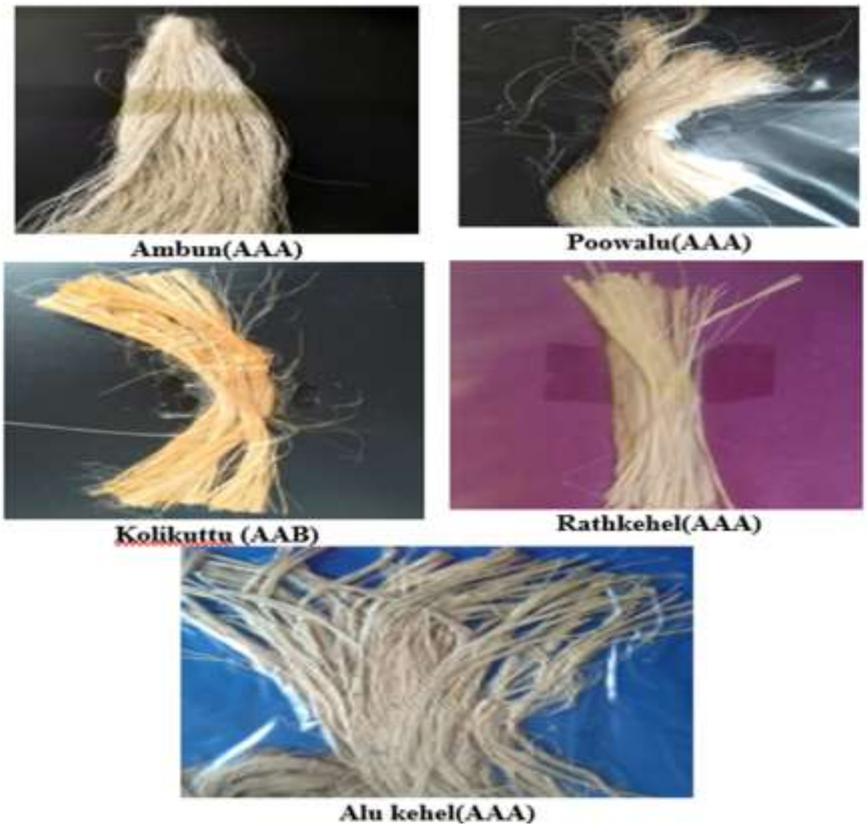


Figure 4-14 Mechanically extracted fiber samples

Figure 4-14 shows the some of mechanically extracted fiber varieties samples and these fiber shows variance in colour. Table 4-19 gives the standard deviation and coefficient of variance of fibre diameter from ten selected varieties of banana fibre diameter.

Table 4-19 Standard deviation and coefficient of variance of fibres diameter

Banana varieties	Kolikuttu	Seeni	Ambul	Atamuru	Ambun	Suwandel	Poowalu	Rath kehel	Alu kehel	Anamalu
Variance	8.22	1.82	2.97	0.98	8.38	2.18	14.57	8.91	6.97	4.44
Standard Deviation	2.86	1.35	1.72	0.99	2.89	1.47	3.81	2.98	2.64	2.10
Coefficient of variation (CV)	3.44	1.32	1.68	1.11	3.71	1.34	4.34	1.39	2.09	1.55

Table 4-19 shows that the standard deviation of ten varieties diameter. It has increased with an increase in the diameter of the fibres. It describes that courser fibres were more irregular.

Analysis of layer wise Ambun banana fibre diameter results

Table 4.20 shows fibre diameter results of Ambun banana fibres. It was observed that the fibre of the second and third layers of Ambun banana are finer than fibre of first and fourth layer. The result showed that the average fineness of the second layer is around 25 tex and the diameter value is around 79.8 µm. The test result showed the middle layers (second and third) to be the finest.

Table 4-20 Standard deviation and coefficient of variance of fibre diameter of Ambun

Test Method	**1st Layer**	**2nd Layer**	**3rd Layer**	**4th Layer**
Mean value of fibre diameter (µm)	206.3	79.8	78.02	159.6
Standard deviation	5.69	1.284	1.324	2.693
Coefficient of Variance(%)	2.758	1.609	1.69	1.687

Fibre flexibility is proportional to a negative power of fibre diameter or thickness. The handle, softness, and pliability of fabrics are all dependent on the bending properties of the fibres, so good fabric handle will require fibres of small diameter or linear density. Therefore, Ambun banana fibre was selected for further analysis because it had the lowest fibre fineness. The different layers of Ambun banana fibres vary in properties, the variation being of the order of 16% in terms of linear density (from maximum to minimum).

b) Biologically and chemically extracted banana fibre

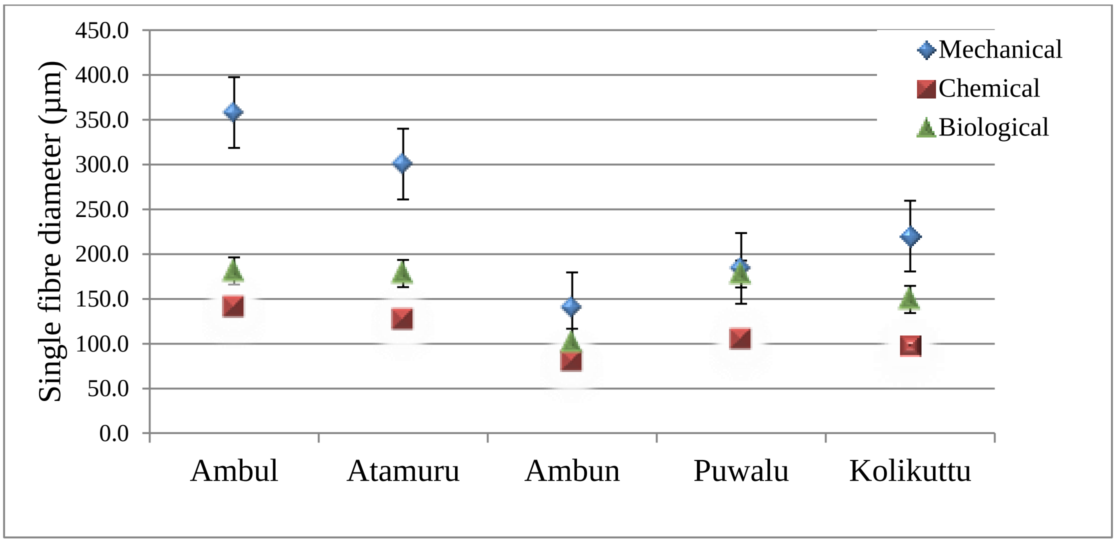


Figure 4-15 Fibre diameter of biological and chemical extracted banana fibre

Figure 4-15 shows that the diameter of biological and chemical extracted banana fibre results.

Biologically extracted Ambul fibre has a 49.4 % smaller fibre diameter compared to mechanically extracted fibre diameter value. Chemically extracted Ambul fibre has a 60.51% smaller fibre diameter compared to mechanically extracted fibre diameter value.

Biologically extracted Atamuru fibre has a 40.62 % smaller fibre diameter compared to mechanically extracted fibre diameter value. Chemically extracted Atamuru fibre has a 57.5 % smaller fibre diameter compared to mechanically extracted fibre diameter value.

Biologically extracted ambun fibre reduces the diameter from 357.9µm to 140.23 µm which is about 60.8% diameter reduction compared to mechanically extracted fibre diameter value. Chemically extracted ambun fibre reduces the diameter from 357.9µm to 80.59 µm which is about 77.4% diameter reduction compared to mechanically extracted fibre diameter value. Biologically extracted puwalu fibre has a 3% smaller fibre diameter compared to mechanically extracted fibre diameter value. Chemically extracted puwalu fibre has a 42.76 % smaller fibre diameter compared to mechanically extracted fibre diameter value. Biologically extracted Kolikuttu fibre has a 47.31% smaller fibre diameter compared to mechanically extracted fibre diameter value. Chemically extracted Kolikuttu fibre has a 55.5% smaller fibre diameter compared to mechanically extracted fibre diameter value.

However, Biological and chemical extraction method's fibre breakage percentages are very high. Biological and chemical extractions are a manual extraction and it's difficult to extract a large quantity of fibres.

c) Biologically treated Ambun banana fibres
Pectinase enzyme treatment has reduced diameter from 213.2 µm to 90.6 µm which is about 57.5% reduction compared to mechanically extracted untreated fibres (Figure 4-16 and 4-17). Biologically treated fibre diameters are lower than mechanically extracted fibre (untreated fibres) diameter.

This diameter reduction may be as a result of the fibre bundle leading to break down of the lignin components or gummy materials from the fibre. It was evident from the SEM image that the fibre surface was separated fine fibre after treatment as a result of pectinase enzyme. It also results in pectin decomposing in the fibre bundles, so that the bundles can be divided more easily and the fibre becomes more fine (Ryszard, 2012).

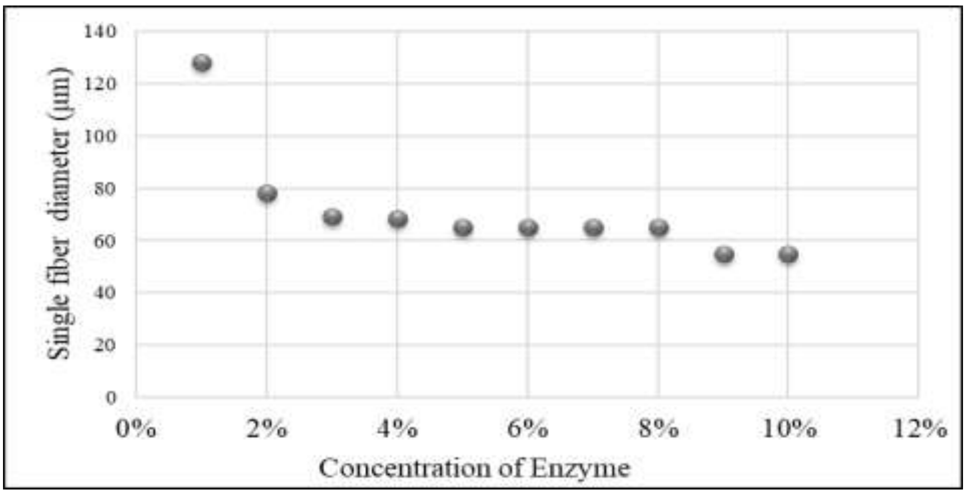


Figure 4-16 Effect of enzyme concentration on ambun banana fibre diameter

Figure 4-17 Enzyme treated ambun banana fibre

The fibre fineness varied with different periods of treatment (Table 4-21). It found banana fibre treatment of 72 hours could produce the best quality fibre from the mechanically extracted fibres. It found three days to be the best for immersing it in the enzyme solution because it resulted not only in the maximum fineness (73.44 µm or 16 tex) of fibre but also in the best strength value (162.3 gf) of fibre.

Table 4-21 Analysis of enzyme treated fibres collected from different time period

Time (Hours)	Fibre Fineness (µm)
2	177.75
12	209.3
24	101.6
36	95.2
48	90.6
72	73.44

The effectiveness of degumming was assessed in terms of fineness and fibre strength improvements. As the concentration of enzyme degumming bath increased the fibre strength was found to increase. As the concentration of enzyme treatment bath increased the fibre strength and fineness were found to decrease. On the whole enzyme degumming and treatment, the treatment with 5% enzyme treatment (72 hours) yielded the best fibre due to their strength (162.3 gf) and finest (73.44 µm). Therefore, the optimum parameters determined as 5% of enzyme concentration and treatment duration was 72 hours (3 days).

d) Chemical treated banana fibres

Figure 4-18 shows that caustic soda treatment has reduced diameter from 168.8 µm (untreated fibre diameter) to 70.65 µm (caustic soda treated fibre diameter) which is about 58.1% reduction compared to mechanically extracted untreated fibres. Caustic soda treated fibre diameters were comparatively lower than mechanically extracted untreated fibre diameter.

This diameter reduction may be as a result of deep penetration of caustic soda into the fibre bundle leading to break down the lignin components or gummy materials from the fibre. It was evident from the SEM image that surface roughness has increased due to the caustic soda treatment.

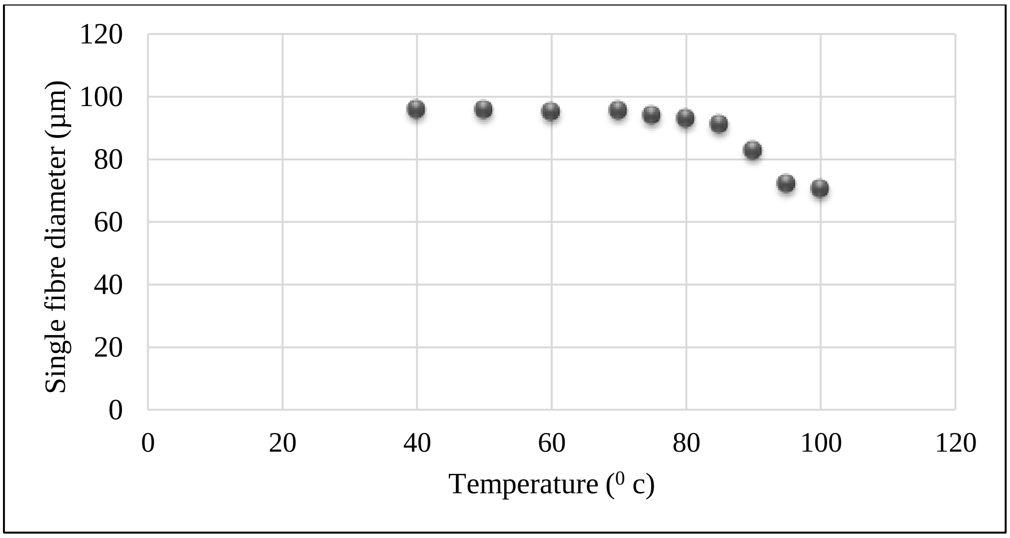


Figure 4-18 Effect of 5% caustic soda concentration on banana fibre fineness

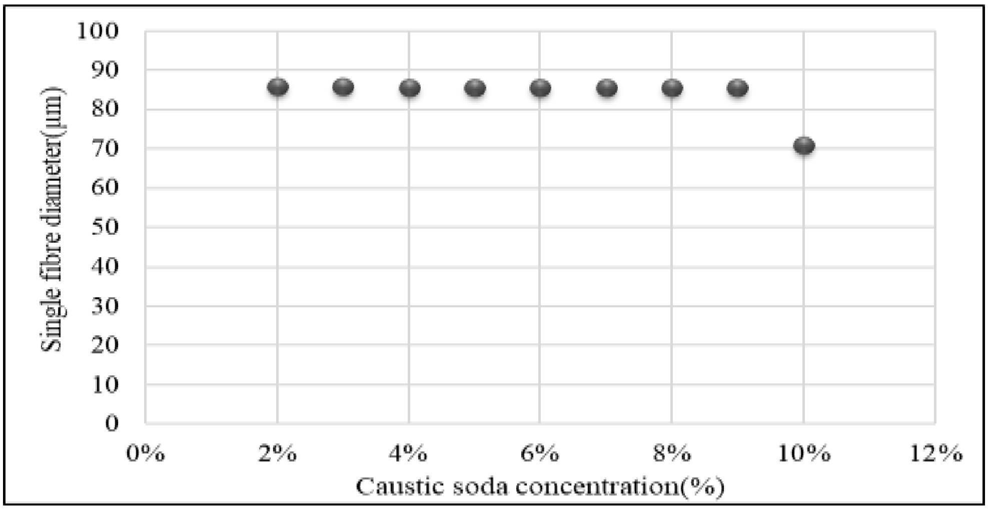


Figure 4-19 Effect of caustic soda concentration on banana fibre fineness

Figure 4-19 shows that different caustic soda concentration treatment has reduced fibre diameter from 168.8 µm to 84.8 µm which is about 49.7% reduction compared to untreated fibres. Caustic soda treated fibre diameters are higher than biological treated fibre and lower than mechanically extracted fibre (untreated fibres) diameter. Figure 4-20 shows that treated caustic soda banana fibres images.

Figure 4-20 Caustic soda treated banana fibres

This diameter reduction may be a result of caustic soda leading to break down of the lignin components from the fibre. It was evident from the SEM image that the increase in surface roughness.

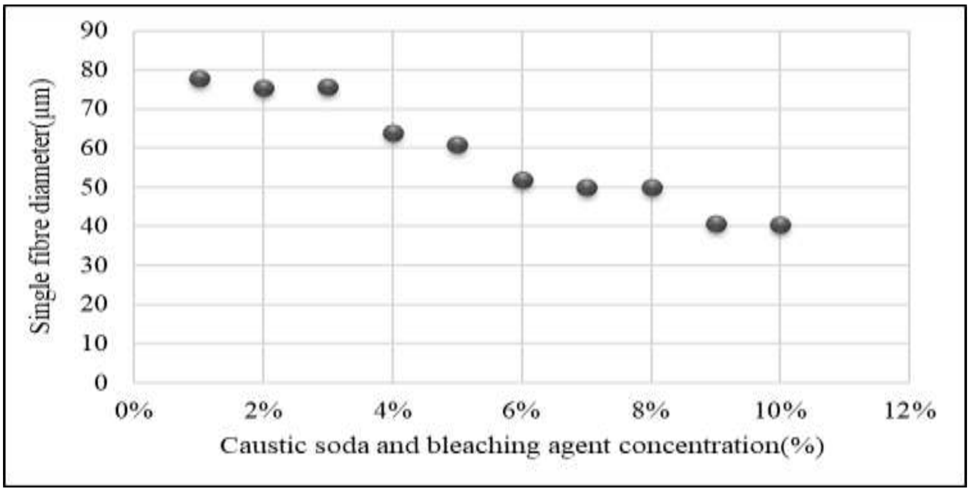


Figure 4-21 Effect of combined scouring and bleaching concentration on fibre diameter

Combined scouring and bleaching treated fibre has reduced diameter from 168.4 µm to 51.4 µm which is about 69.5% reduction compared to mechanical extracted (untreated) fibres

(Figure 4-21). This treatment improves the fibre surface adhesive characteristics by removing impurities which is confirmed in the SEM analysis. Figure 4-22 shows that combined scouring and bleaching treated banana fibres.

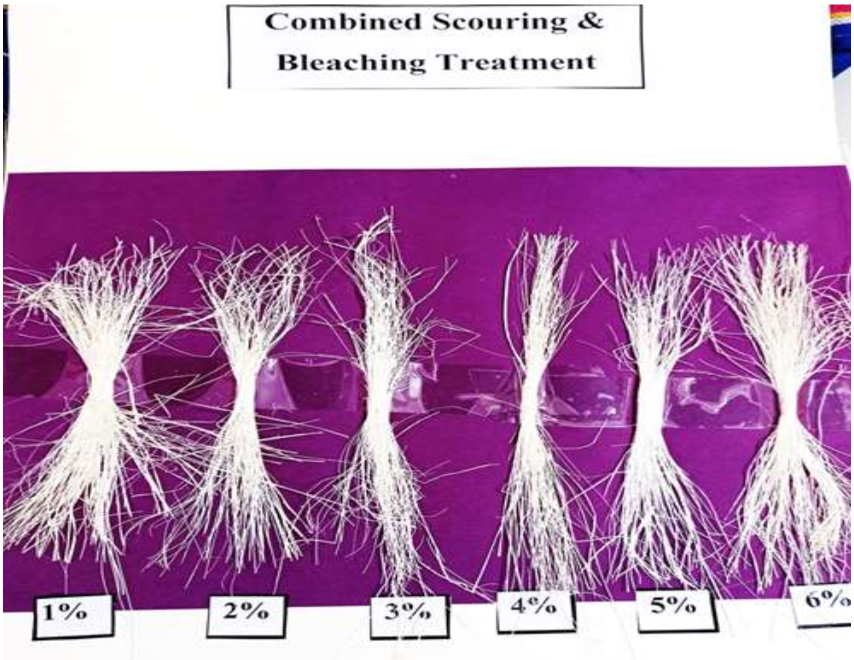


Figure 4-22 Combined scouring & bleaching treated banana fibres

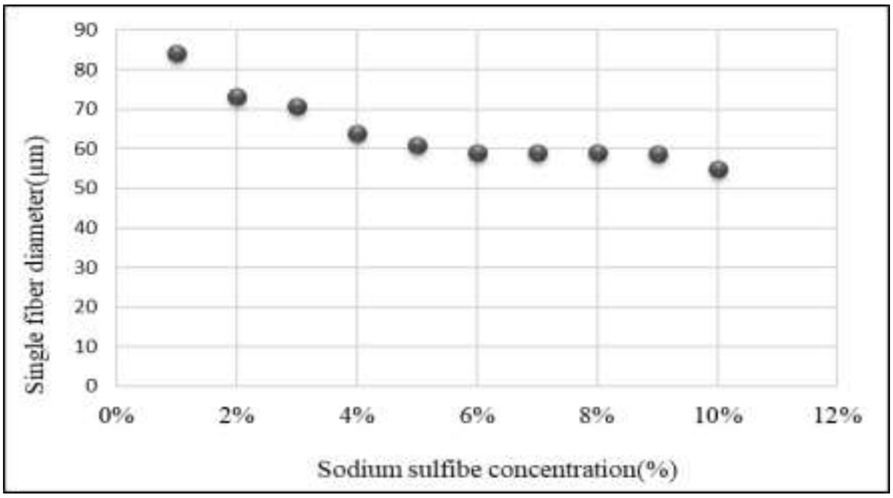


Figure 4-23 Effect of sodium sulphide concentration on banana fibre diameter

Sodium sulphide treatment has reduced diameter from 168.8 µm to 54.08 µm which is about 67.9% reduction compared to mechanically extracted untreated fibres. Figure 4-23 shows sodium sulphide treated banana fibres. Sodium sulphide treated fibre has diameters are comparatively lower than biological treated fibre and lower than mechanically extracted fibre (untreated) diameter. This diameter reduction may be a result of deep penetration of sodium sulphide into the fibre bundle leading to break down of gummy materials from the fibre.

Figure 4-24 Sodium sulphide treated banana fibres

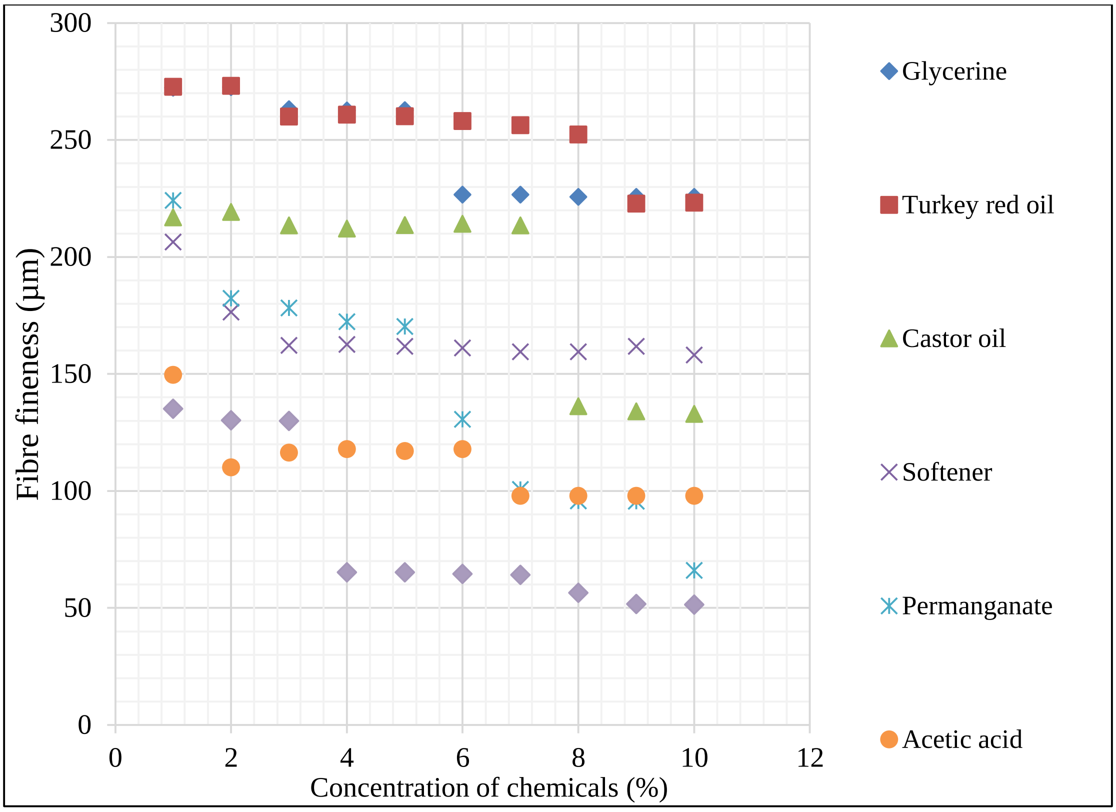


Figure 4-25 Fibre diameter of chemically treated fibres

Figure 4-25 and 4-26 shows that glycerine treated banana fibre has reduced diameter from 168.4µm to 114.2 µm which is about 32.3% reduction compared to mechanically extracted untreated fibres. According to figure 4-25, turkey red oil treated fibre has presented 1% increase in fibre diameter is contrast to mechanically extracted fibres. Figure 4-25 and 4-29 shows that acetic acid treated fibres has presented 48.4% increase in fibre diameter contrasted to mechanically extracted fibres.

According to figure 4-25 softener treated fibres has presented 6.3% increase in fibre diameter contrasted to mechanically extracted fibres. Hydrogen peroxide treatment has reduced diameter from 168.4µm to 60.2 µm which is about 64.3% reduction compared to mechanically extracted fibres (Figure 4-28).

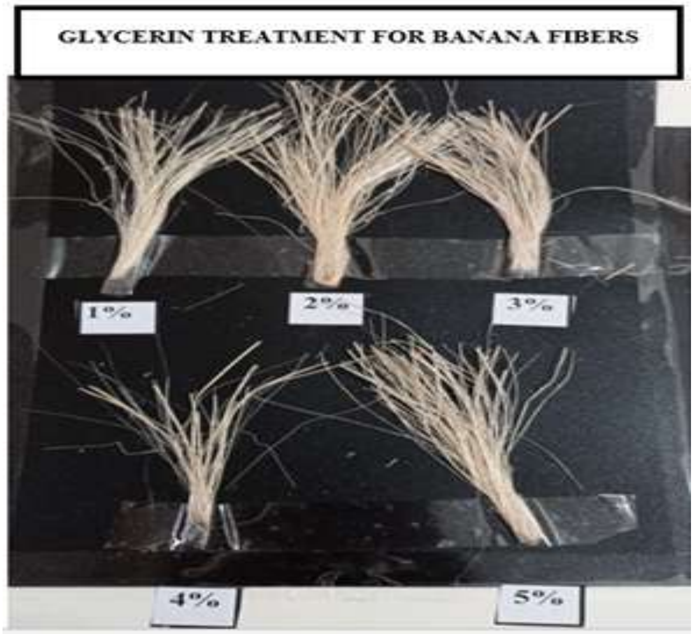


Figure 4-26 Glycerin treatment for banana fibers

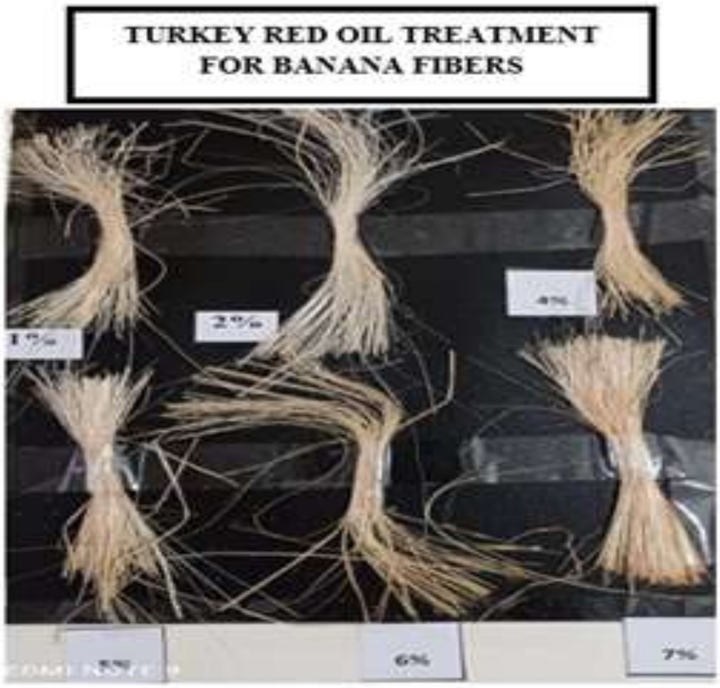


Figure 4-27 Turkey red oil treatment for banana fibers

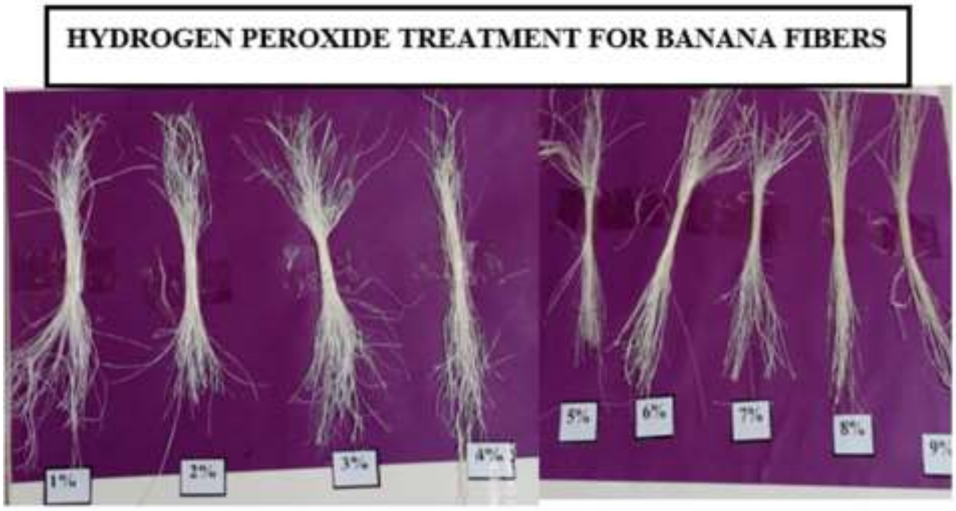


Figure 4-28 Hydrogen peroxide treatment for banana fibers

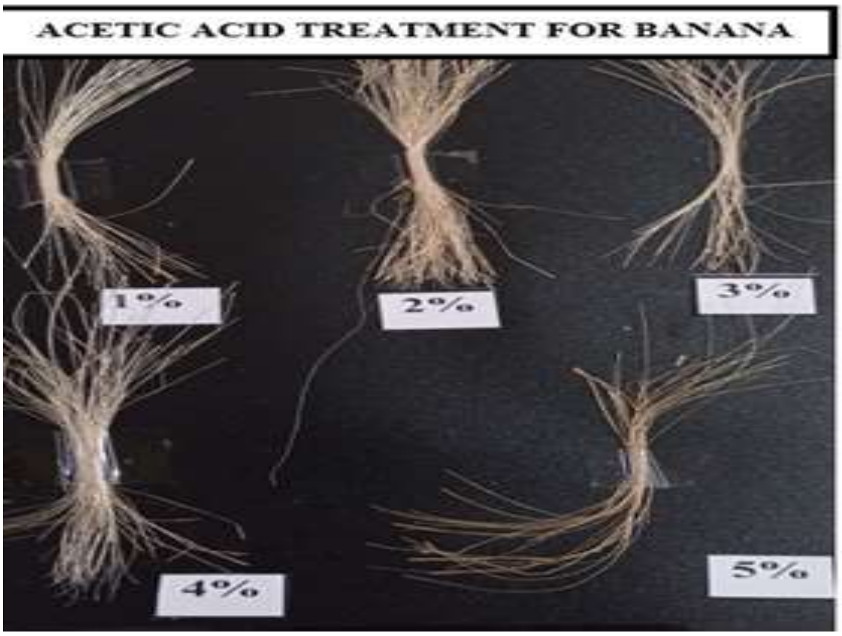


Figure 4-29 Acetic acid treatment for banana fibres

e) Enzyme and chemical treated Ambun banana fibres

Finally, the raw banana fibres were treated with enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH (Figure 4-30 and 4-31). Treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined treatment has reduced diameter of 48.8 µm and strength value is 2.931 N. Enzyme and chemical combined treatment has reduced the diameter from 140 µm to 48.86 µm which is about 71% diameter reduction compared to mechanically extracted fibre diameter value. From the experimental results, the raw banana fibres have been improved their fineness by approximately 71%.

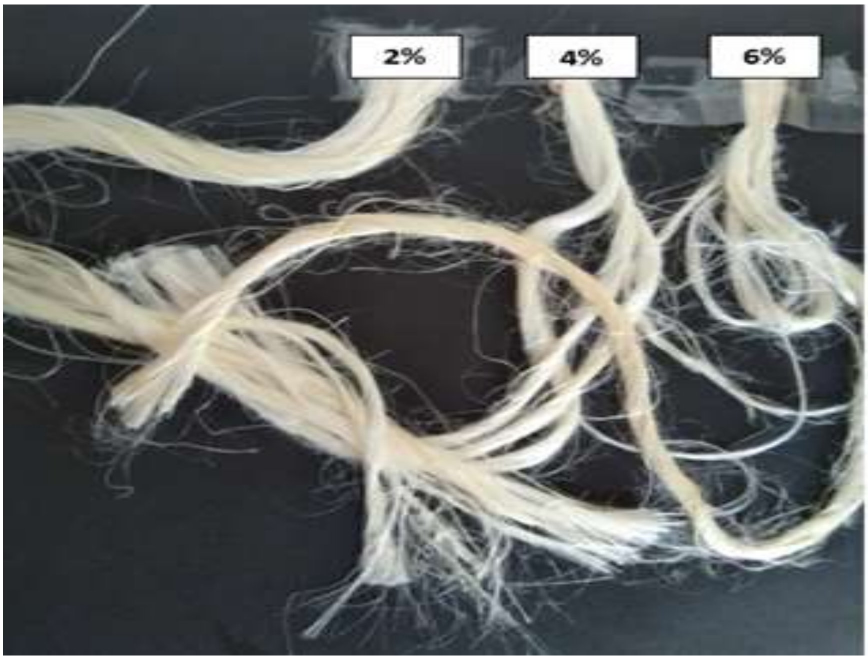


Figure 4-30 Enzyme and chemical treated fibres(2% to 6%)

Figure 4-31 Enzyme and chemical combined treated fibres (6%)

Treatment of enzyme and 7% H_2O_2, 2% Na_2SiO_3, 2.5% NaOH, combined treatment has reduced diameter of 49.7 µm and strength value has reduced 1.01 N. This treated fibres samples are breaking easily (Figure 4-32 and 4-33). The results indicate that the diameter and single fibre strength of fibres is affected after the enzyme and chemical combined treatment. This treatment removes the lignin impurities and reduces the impurities and result the reduction of diameter.

Figure 4-32 Enzyme and chemical treated fibres (7% to10%)

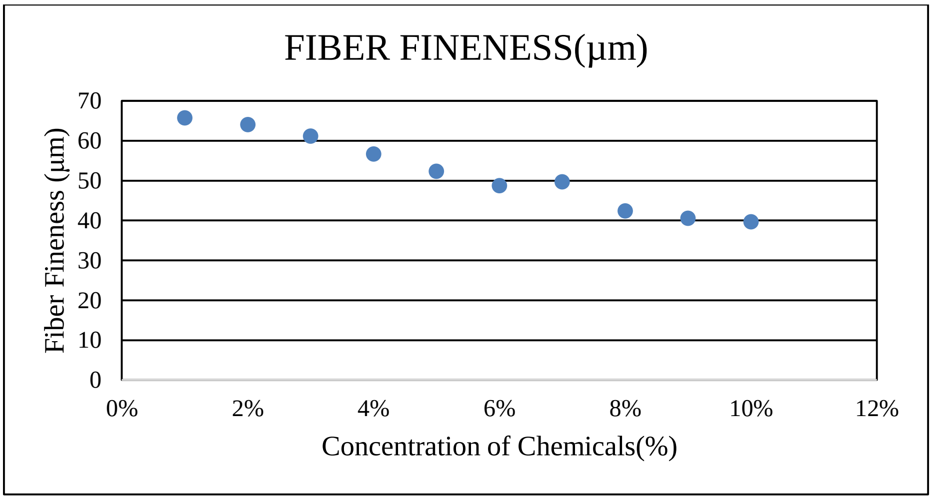


Figure 4-33 Fiber fineness results of combined treatment

Summary of banana fibre chemical treatments

Sodium hydroxide (NaOH), sodium sulphide, bleaching agent (H_2O_2), acetic acid, glycerine, silicone softener and turkey red treatments were carried out and analysed on banana fibres diameter.

Figure 4-34 displays that enzyme and chemicals treated banana fibre's single fibre diameter results. Figure 4-35 shows an image of permanganate treated fibre. Combined enzyme and chemical treatment, scouring and bleaching produce the finest fibres. Banana fibres become softer and finest. To achieve the required fineness, it is necessary to treat with enzyme and chemical combined treatment. In this treatment, fibre diameter is reduced from 140µm to 48.86 µm.

This study indicates that there was continuous reduction in diameter of fibre when the concentration was increased. Figure 4-37 shows an image of enzyme treated fibre and figure 4- 38 shows caustic soda treated fibres. Figure 4-40 shows an image of the fibres treated by combination of enzyme and chemical.

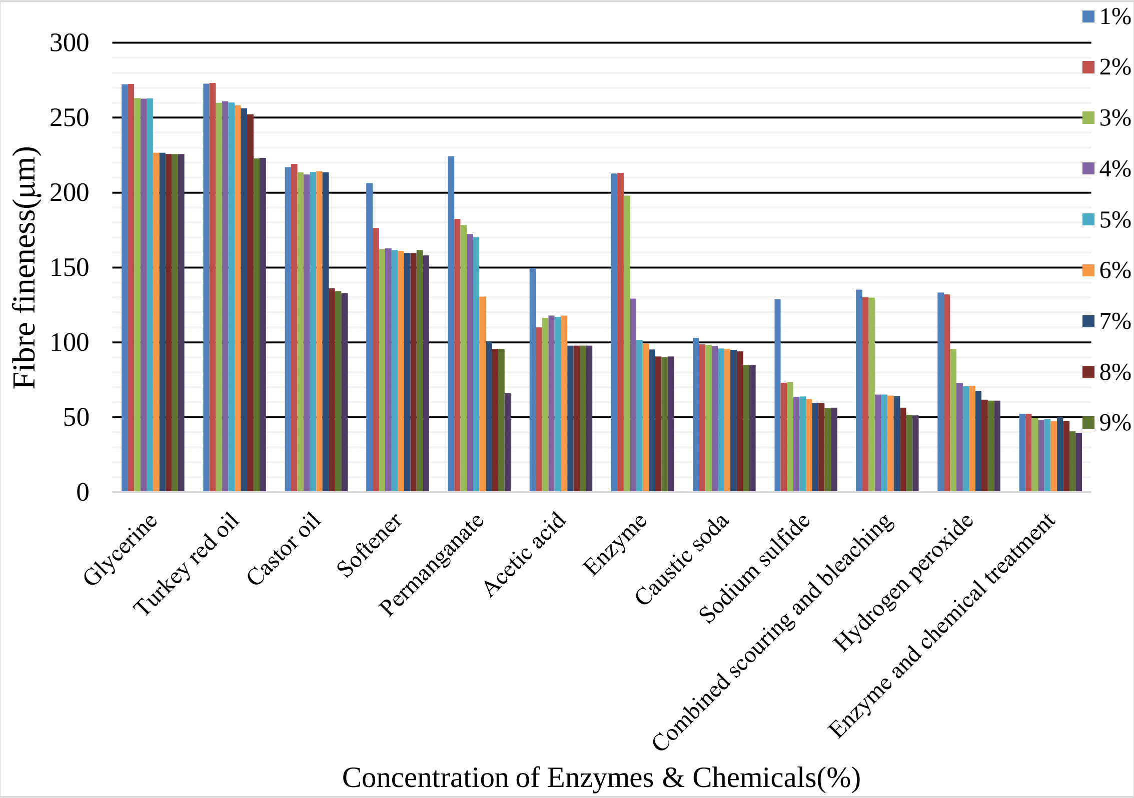


Figure 4-34 Summary of chemical and enzyme treated fibre fineness results

Figure 4-35 Permanganate treated banana fibres

Figure 4-36 Softener treated banana fibres

Figure 4-37 Enzyme treated banana fibres

Figure 4-38 Caustic soda treated banana fibres

Figure 4-39 Sodium sulphide treated banana fibres

Figure 4-40 Combined enzyme and chemical treated banana fibres

4.2.5 Single fibre strength

a) Mechanically extracted banana fibre

Figure 4-41 shown that, Atamuru, Puwalu, Ambun fibres have high strength compared to other varieties. The minimum single fibre strength was obtained from Anamalu and Seeni varieties.

The order of the tensile strength differences was found as Rath kehel < Anamalu < Alu kehel < Ambul < Seeni < Suwandel < Puwalu < Kolikuttu< Atamuru < Ambun. The different banana cultivars vary in properties,the variation being of the order of 31% (from maximum to minimum) in terms of strength. The tensile strength of these cultivars varies from 1.84 N to 2.67 N.

However, a handcraft and textile fibres must possess certain strength to use. The higher tensile strength of Ambun fibre was 2.675 N. Ambun fibres could be used in composite materials, handicrafts, and spinning purposes due to its higher tensile strength properties (Paramasivam *et al.*, 2020).

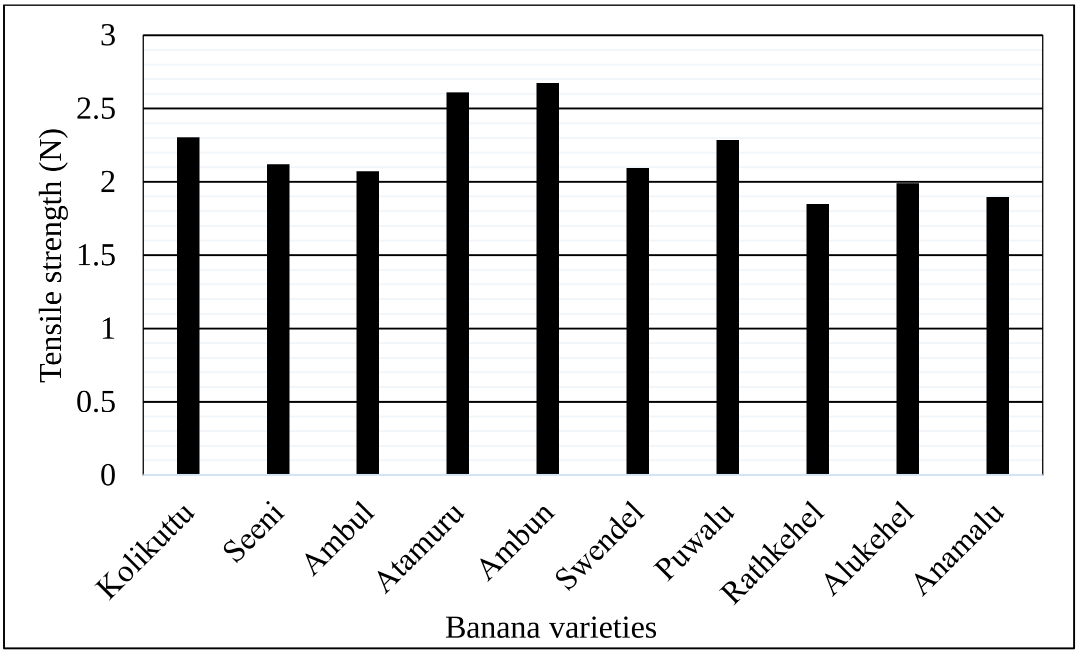


Figure 4-41 Tensile strength of banana cultivars

Table 4-22 Standard deviation and coefficient of variance of banana fibre single fibre strength from five selected varieties

Tensile strength (N) of banana fibre	Kolikuttu	Seeni	Ambul	Atamuru	Ambun	Suwandel	Poowalu	Rath kehel	Alu kehel	Anamalu
Standard Deviation	0.29	0.743	3.933	0.284	0.003	2.825	1.029	1.146	3.789	1.056
Coefficient of variation(CV)	2.3025	2.117	2.07	2.61	2.675	2.095	2.287	1.847	1.9875	1.895

Table 4-22 shows that standard deviation and coefficient of variance of five selected varieties of banana fibre single fibre strength. Figure 4-41 shows that the highest amount of the single fibre strength is achieved by Atamuru, puwalu and ambun fibres.

Single fibre strength of Ambun is lower than Atamuru and fibre diameter is smaller than other varieties. According to the results, ambun fibre is more suitable for extracting very fine fibre. Ten type of mechanically extracted banana varieties extension properties are tested. Those quantitative fibre analysis results are following in Figure 4-42.

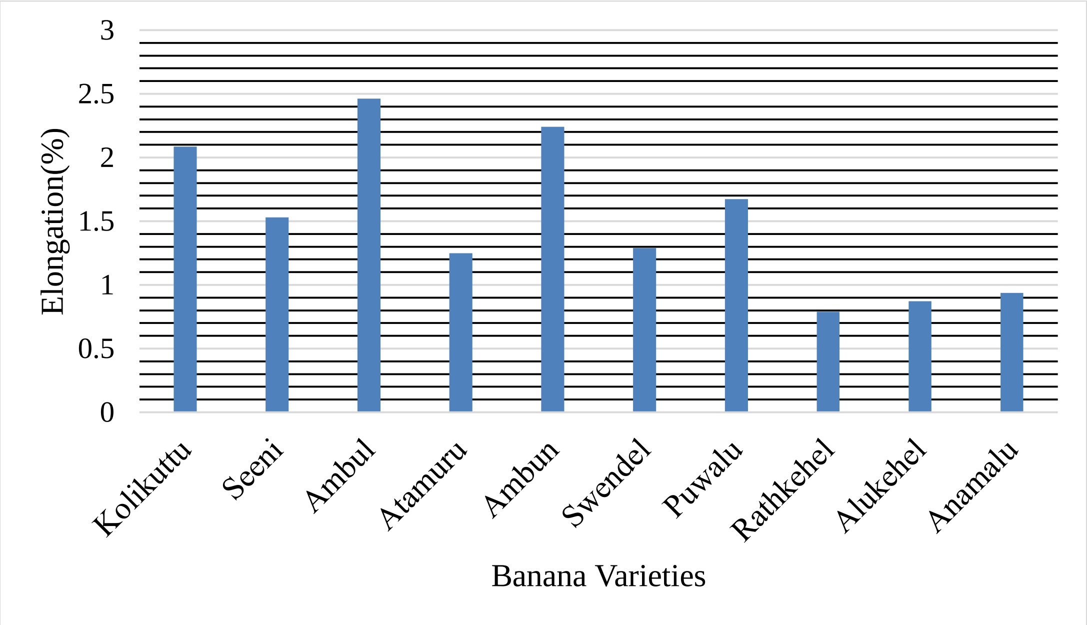


Figure 4-42 Elongation (%) of top ten banana fibres

Table 4-23 Standard deviation and coefficient of variation of top ten varieties extension properties

Elongation (%) of banana fibres	Kolikuttu	Seeni	Ambul	Atamuru	Ambun	Suwandel	Poowalu	Rath kehel	Alu kehel	Anamalu
Standard Deviation	0.61	0.32	0.39	0.17	0.46	0.45	0.51	0.14	0.26	0.26
Coefficient of variation	0.41	0.26	0.19	0.15	0.30	0.82	0.37	0.25	0.46	0.39

The result showed that the of Ambun fibre average extension percentage were lower than the other varieties. Atamuru fibre and Kolikuttu extension percentage shows higher than the other varieties. Table 4-23 and Figure 4-42 display the elongation results of banana cultivars. Elongation at break is the ratio between the starting fibre length and the length of the fibre after it is pulled with a tensile load. The order of the elongation differences was found as Rath kehel < Alu kehel < Anamalu < Atamuru < Suwandel < Seeni < puwalu < Kolikuttu < Ambun < Ambul. The elongation of fibres varies from 2.46% to 0.78%.

b) Biologically and chemically extracted banana fibre

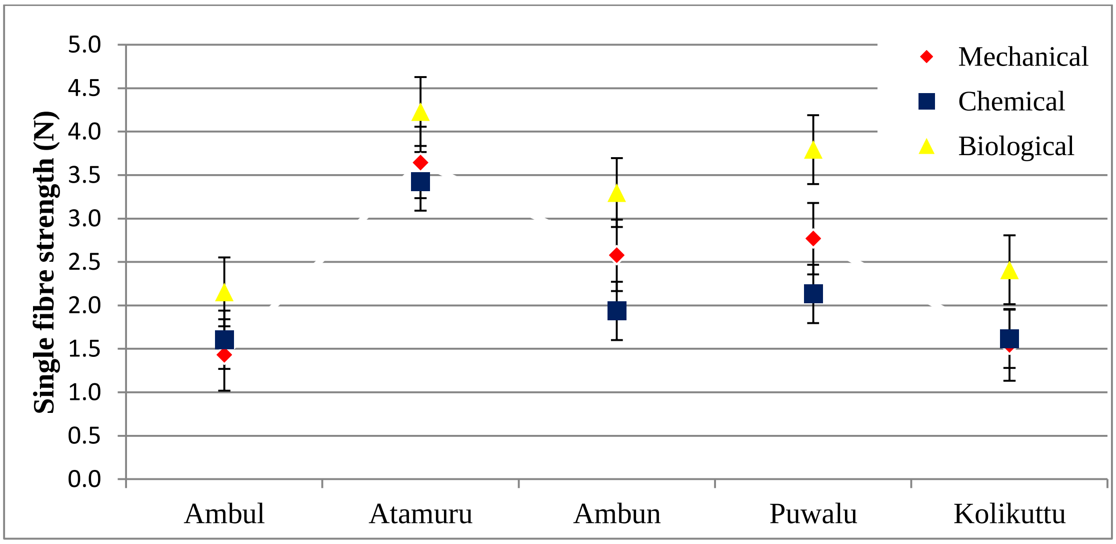


Figure 4-43 Single fibre strength of biologically and chemically extracted banana fibres

Biologically extracted Ambul fibre has a 50% higher fibre strength compared to mechanically extracted fibre strength value.

Chemically extracted Ambul fibre has a 16% lower fibre strength compared to mechanically extracted fibre strength.

Biologically extracted Atamuru fibre has a 16.1% higher fibre strength compared to mechanically extracted fibre strength.

Chemically extracted Atamuru fibre has a 5% lower fibre strength compared to mechanically extracted fibre strength.

Biologically extracted ambun fibre has increases the strength from 2.577N to 3.295N which is about 60.8% strength improvement compared to mechanically extracted fibre strength value.

Chemically extracted ambun fibre reduces the strength from 2.577N to 1.936N compared to mechanically extracted fibre strength. However, fibre strength decreases with increase of chemical concentration. Biologically and chemically extracted fibres rendered the fibres very weak and stick together.

c) Biologically treated banana fibres

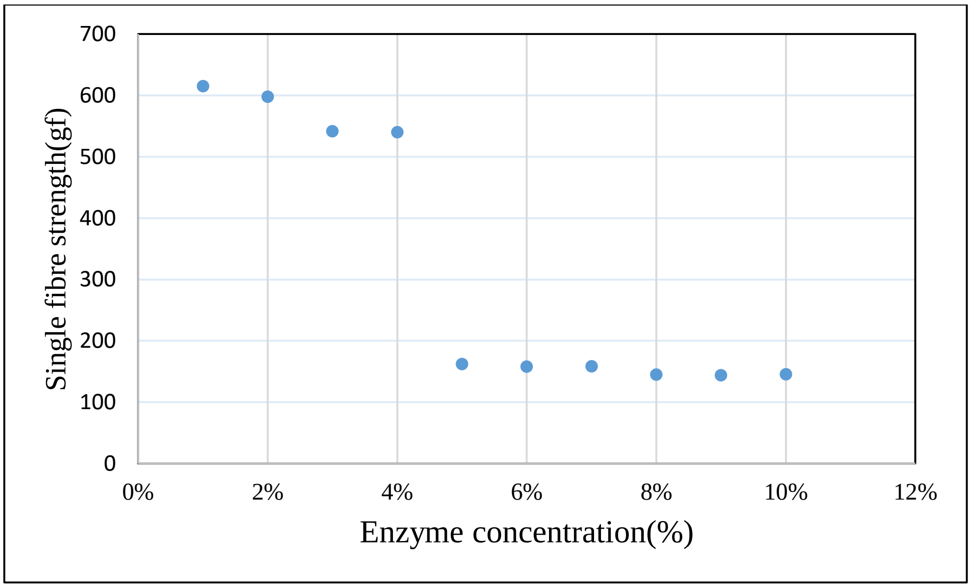


Figure 4-44 Effect of enzyme concentration on banana fibre single fibre strength

Pectinase enzyme treatment reduced single fibre strength from 615.09 gf to 145.71gf which is about 76.3% reduction compared to mechanical extraction (Figure 4-44). Biologically treated fibre single fibre strength is comparatively higher than chemical treated fibre and higher than mechanically extracted fibre strength.

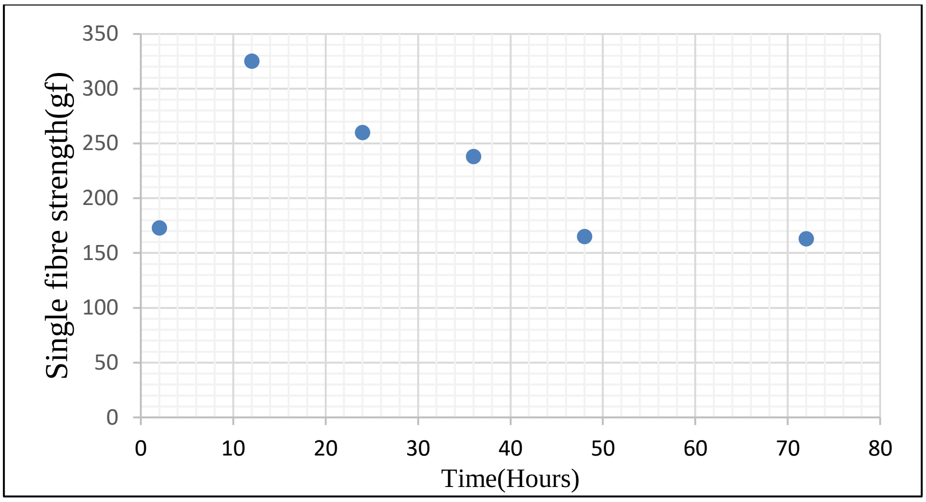


Figure 4-45 Single fibre strength of Enzyme treated fibre collected from different time intervals

This enzyme treatment reduced the strength by 6 %. The reduction in strength after enzyme treatment may be due to loss of non – cellulosic material. Higher strength value was obtained after 12 hours and minimum strength vale was obtained after 72 hours.

d) Chemical treated banana fibres

Figure 4-46 shows 5% caustic soda treatment reduced single fibre strength from 262.8 gf to 56.04 gf which is about 78.6% reduction compared to mechanical extraction. Caustic soda treated fibre single fibre strength is comparatively lower then mechanically extracted fibre strength.

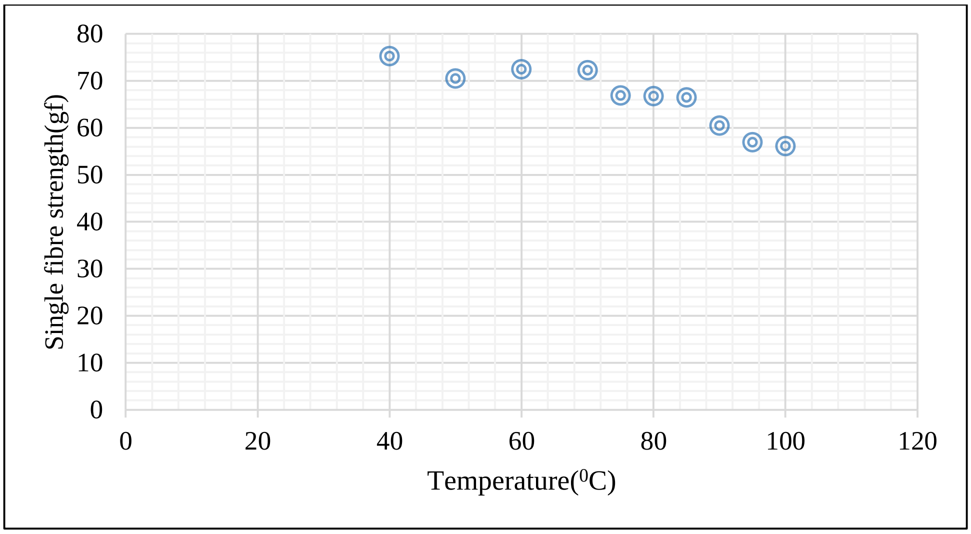


Figure 4-46 Effect of 5% caustic soda concentration on banana fibre single fibre strength

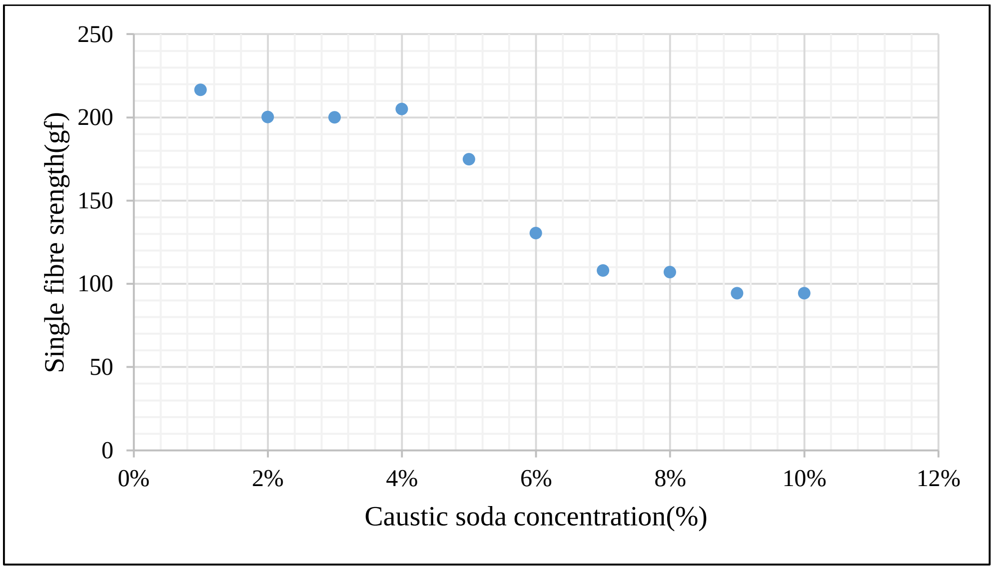


Figure 4-47 Effect of caustic soda concentration on banana fibre single fibre strength (95^{0}c)

Figure 4-47 shows caustic soda (95^{0}c) treated fibre presented 64.13% decrease in fibre strength.

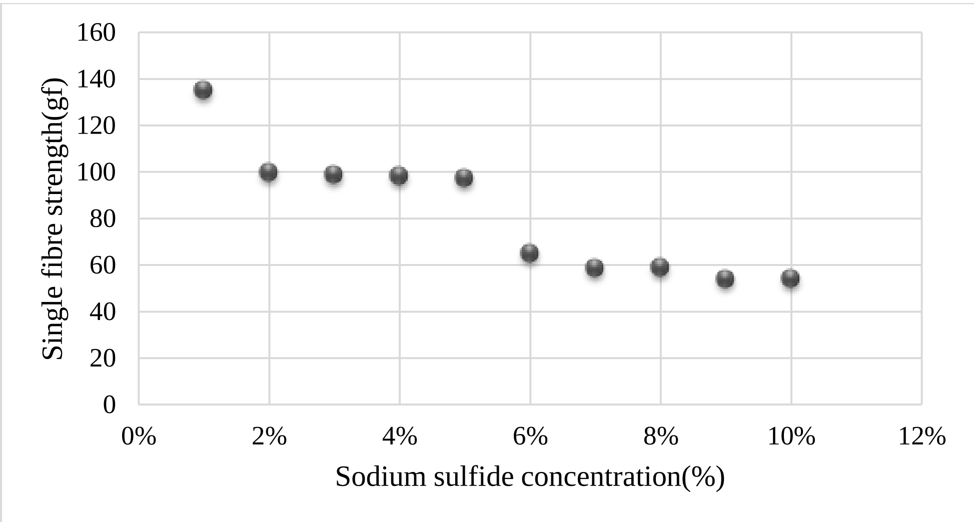


Figure 4-48 Effect of sodium sulphide concentration on banana fibre single fibre strength

Figure 4-48 shows that combined scouring and bleaching treatment reduced single fibre strength from 262.8 gf to 54.77gf which is about 79.5% reduction compared to mechanical extraction. Combined scouring and bleaching treated fibre single fibre strength is comparatively lower than biological treated fibre and mechanically extracted fibres (untreated fibres)

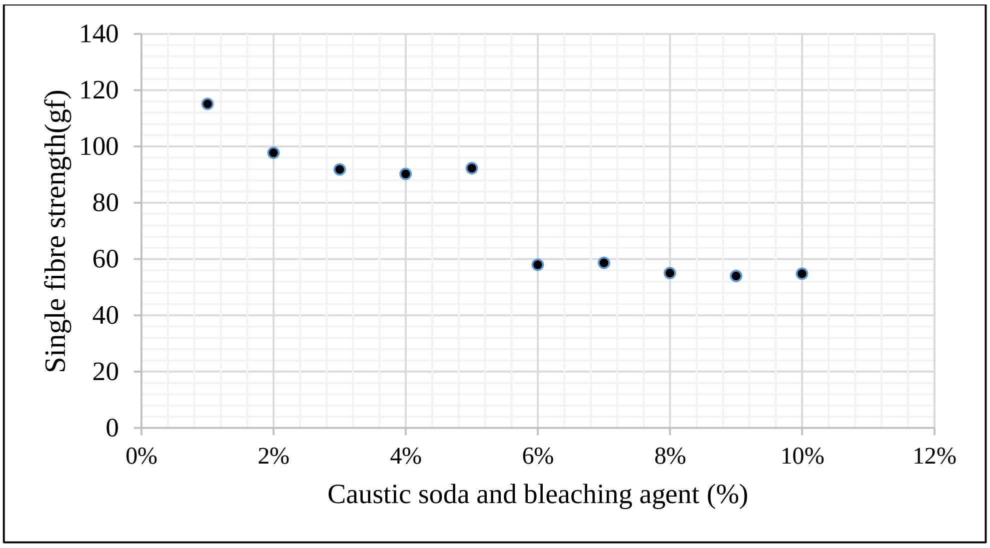


Figure 4-49 Effect of combined scouring & bleaching concentration on banana fibre Single fibre strength

e) Enzyme and chemical treated banana fibres

Enzyme and chemically treated fibre results are shown in the table 4.9 enzyme and chemical combined treatment has improve the strength from 2.577gf to 2.931 compared to mechanically extracted untreated fibres strength.

Table 4-24 illustrate that the enzyme treated fibre has a highest fibre strength in all treatments. Chemically extracted fibre has lowest strength compared to biologically treated fibres. Strength of fibres is a property, which affect a large number of characteristics of products made out of banana fibres.

Table 4-24 Fibre strength of enzyme and chemical treated fibres

Enzyme and chemically treated fibre	**Single fibre strength(N)**
Average	2.931
Minimum	2.732
Standard deviation	0.059
Coefficient of variance	2.012

4.2.6 Fibre linear density (tex) of banana fibre

Figure 4- 50 show the fibre linear density results of banana cultivars. Fibre linear density of Ambun and Ambul is about 25 tex and higher linear density was achieved by rathkehel, Alukehel and Anamalu fibres. However, the linear density of fibres varies from 25 tex to 36.2 tex.

The fibres extracted from rathkehel, Alukehel and Anamalu fibres were comparatively coarse in nature. The different banana cultivars vary in properties,the variation being of the order of 44% in terms of fibre liner density.

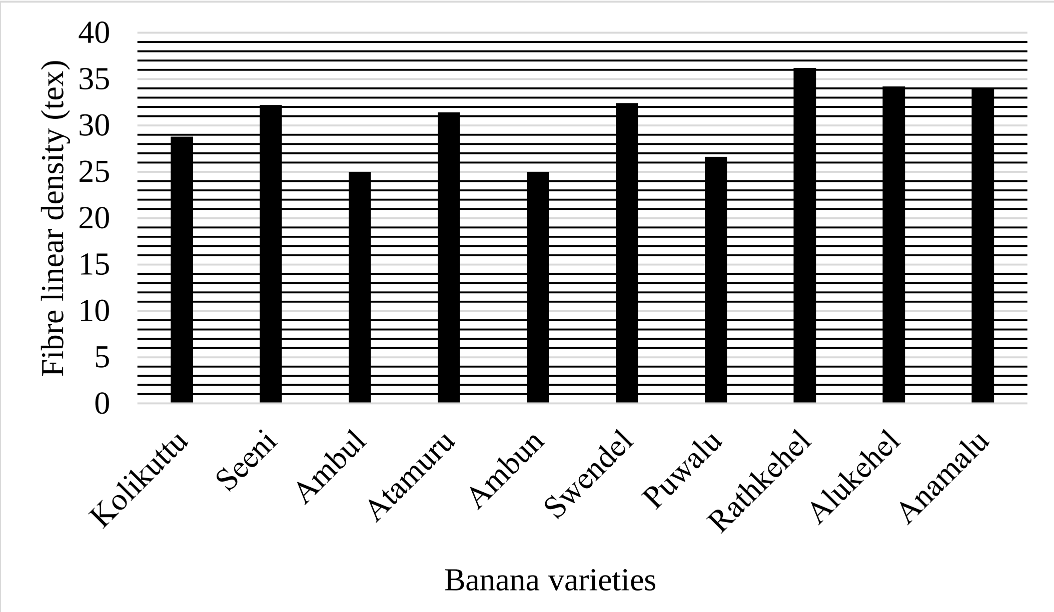


Figure 4-50 Fibre linear density (tex) of banana fibres

Table 4-25 Variance of fibre linear density of banana fibres

Fibre linear density (tex) of banana fibre	Kolikuttu	Seeni	Ambul	Atamuru	Ambun	Suwandel	Poowalu	Rath kehel	Alu kehel	Anamalu
Variance	3.49	2.16	1.87	1.34	1.87	2.30	1.81	1.30	0.83	2.73
Standard Deviation	0.14	0.07	0.09	0.04	0.09	0.08	0.08	0.03	0.03	0.09

Table 4-26 shows fibre linear density of Ambun banana fibres. The results were observed that the number of pseudostem layers varies within the same variety of banana varieties.

Table 4-26 Ambun fibre linear density of Mechanical extraction

Test Method	**1st Layer**	**2nd Layer**	**3rd Layer**	**4th Layer**
Fibre linear density - Tex	30	**25**	**25**	27

It was observed that the second and third layers of Ambun banana fibres are finer than first and fourth layer. The result showed that the average fineness of second layer is around 25 Tex. The test result showed the middle layers (second and third) to be the finest. Outer layer of banana fibres results in the production of coarser fibres which would be not suitable for textile industries.

Table 4-27 Linear density results of extracted fibres

Test Method	Mechanical extraction	Biological extraction	Chemical extraction
Fibre linear density- tex	25	23	27

Table 4-27 shows that biological extraction reduces fibre linear density from 25 tex to 23 tex compared to mechanical extraction. The chemical extraction shows higher fibre linear density than the other extractions, even though biological extraction gave moderate improvement in fibre fineness.

Table 4-28 Linear density of treated banana fibres

Test Method	Biological treatment	Chemical treatment	Enzyme and chemical treatment
Fibre linear density- tex	16	18	5.6

Table 4-28 shows that biological extraction has reduces fibre linear density from 25 tex to 16 tex compared to mechanical extraction. The enzyme and chemical treated fibres have reduced fibre linear density from 25 tex to 5.6 tex compared to mechanical extraction. It was proven that the mechanically extracted banana fibre linear density (21tex) was better than the linear density of enzyme and chemical treated fibre (5.6 tex).

4.2.7 Water absorbency of banana fibres

The water absorbency properties of natural fibres contribute to the efficient preparatory processes, dyeing, and finishing processes. The hydrophobic or hydrophilic nature of textile fibres depends mainly on the chemical groups present in it (Tang *et al.*, 2014). Water absorbency can influence the physical and mechanical properties of the textile fibre and it's influences the shrinkage, speed of drying and comfort of the wearer (Sabir, 2018).

Therefore, it is necessary to analyze the water absorbency properties of the banana fibres. If the drop is absorbed in less than three seconds, the material is concluded as suitable for dyeing and other chemical processes. In order to use textile material for printing, the time of absorption of a drop water must be less than one second

a) Mechanically extracted ambun banana fibre

Table 4-29 Absorbency test results of mechanically extracted banana fibres

Test	**Time taken to absorb (sec.)**
Test 1	Above 2
Test 2	1
Test 3	1
Test 4	Above 2
Test 5	Above 2
Average	2

b) Biologically and chemically extracted ambun banana fibre

Table 4-30 Absorbency test results of extracted banana fibres

Test	Biologically extracted fibres: Time taken to absorb (sec.)	Chemically extracted fibres: Time taken to absorb (sec.)
Test 1	2	1
Test 2	1	1
Test 3	1	1
Test 4	1	1
Test 5	1	1
Average	1	1

c) Biologically and chemically treated banana fibres

Table 4-31 Absorbency test results of treated banana fibres

Test	Biologically treated fibre: Time taken to absorb (sec.)	Chemically treated fibre: Time taken to absorb (sec.)
Test 1	Below 1	Below 1
Test 2	1	Below 1
Test 3	Below 1	Below 1
Test 4	Below 1	Below 1
Test 5	Below 1	Below 1
Average	Below 1	Below 1

According to the tables 4-29 to 4-31, the water absorbency test results of treated and untreated samples revealed that the chemically treated banana fibres have required dye absorbency property in order to carryout colouration and finishing processes. However, the enzyme and chemical combined treatment has improved hydrophilic behaviour. If the moisture content value of a material is excellent, the garment made from the material will provide superior comfort qualities to the wearer.

4.2.8 Moisture regain

Moisture regain of a material is mass of water in a material express as a percentage of the total weight of the material defined as moisture regain. The following figure 4-51 show moisture regain of banana fibre varieties. Moisture regain of banana fibre makes significant changes in the physical properties of fibre.

High moisture regains increases flexibility, toughness, elongation and tensile strength. Low moisture increases the brittleness of fibre and results in fibre breakages (Vardhini & Murugan, 2016). Higher moisture regain was obtained from Puwalu banana fibre (11.1%).

Lower moisture regain was obtained from Ambun, Atamuru, Ambul, Seeni and Kolikuttu cultivars (9.7%). The different banana cultivars vary in properties,the variation being of the order of 13% in terms of moisture regain.

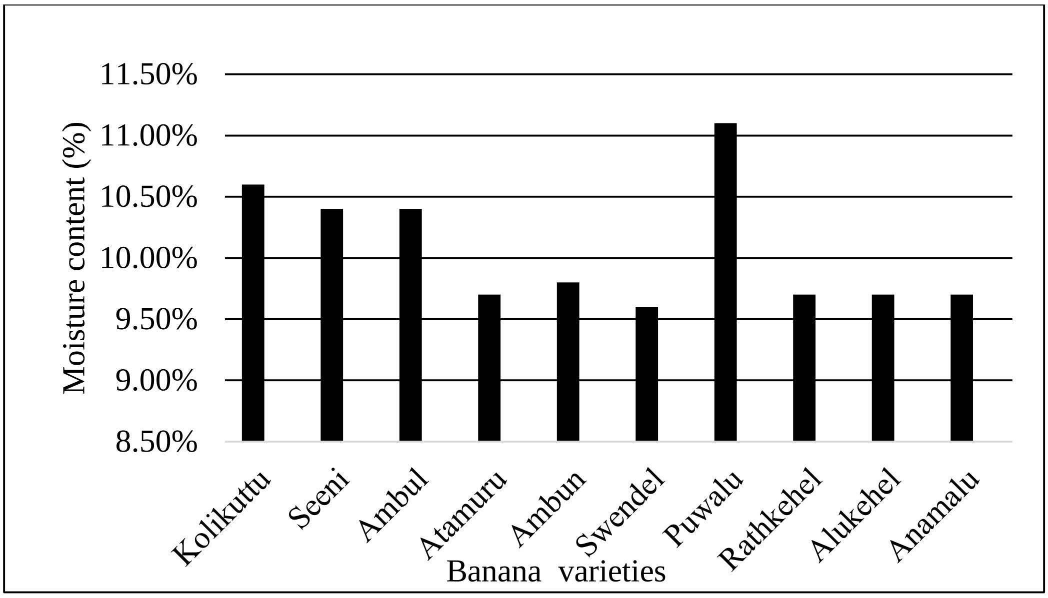


Figure 4-51Moisture content(%) of banana fibre(Ten banana cultivars)

The following table show moisture regain of ambun (AAA) banana stem layer wise fibre (table 4-32).

Table 4-32 Moisture regain test results of mechanically extracted fibres

	Pesudostem layer			
	Banana first layer	**Banana second layer**	**Banana third layer**	**Banana fourth layer**
Moisture regain (Mean)	8.90%	9.90%	9.70%	10.10%
Standard deviation	1.561	1.485	1.517	1.561
Coefficient of variance	0.175	0.15	0.156	0.154

Table 4-21 Moisture regain test results of treated fibre

	Biologically treated banana fibre	**Chemically treated banana fibre**	**Enzyme and chemically treated banana fibre**
Moisture regain (Mean)	9.6%	9.90%	11.098%
Standard deviation	1.693	0.284	1.324
Coefficient of variance	0.176	0.028	0.119

The fourth layer of moisture regains test results were similar to Amuthu *et al*., 2020 research results. Moisture regain of banana fibre makes significant changes in the physical properties of fibre. High moisture regains increases flexibility, toughness, elongation and tensile strength. Low moisture increases the brittleness of fibre and results in fibre breakages.

Combined enzyme and chemically treated fibre moisture regain were tested and found that the test results are superior to cotton fibres. The moisture regains of enzyme and chemical treated fibres improved from 8.90% to 11.098 %.

4.2.9 FTIR results of mechanically extracted and treated banana fibres

FT-IR analysis of banana fibres was done to study the components of banana and it Spectrum depicts O – H stretch, free hydroxyl, O- H stretch, H- bond, - CH_2, - CH_2, - C≡ C – and C- H alkenes compound gatherings that are available in the untreated banana fibre. Some researcher reached similar peaks with different varieties of banana pseudo-stem fibre (Amutha *et al*., 2020) and (Milani *et al*., 2016). FTIR spectra of mechanically extracted banana fibres are shown in the Figure 4-52 to 4-53. FTIR spectra of untreated four layers of banana fibres are shown in the Figure 4-44.

The absorption band at 3500 to 3600cm $^{-1}$ region exposed the presence of a strong hydrogen bonded hydroxyl stretching peak which is due to the presence of cellulose.

The absorption bond around 1400cm $^{-1}$ revealed the frequency of bending vibration of CH – bonds. The sharp peak at 1737cm $^{-1}$ absorption bend revealed C=O group.

The absorption band at 1440 to 1400cm $^{-1}$ region exposed the presence of an O-H bend. 770 to 735cm $^{-1}$ absorption bond represents C-H bend (meta) (Pereira *et al*., 2014). FTIR examination confirms the presence of cellulose group in the extract.

Earlier researches findings and the present investigation revealed that the mechanically extracted banana fibre consists of cellulose, hemicellulose, lignin as their main components.

Pectin was found to be high in all fibres of FTIR spectrum, which is the absorption band at 1650 cm^{-1} to 1750cm^{-1} region (Orona *et al.* 2010). The FTIR spectrum band around 1430 cm^{-1} to 1290 cm^{-1} region corresponds to the frequency of bending vibrations of C-H in – plane bend absorption. Band around 1690 cm^{-1} to 1630 cm^{-1} region corresponds to the frequency of bending vibrations of C=C (stretch – isolated) and 1640 cm^{-1} to 1610cm^{-1} region corresponds to the C=C stretch (conjugate) absorption. The peak near 3640.2cm^{-1} is called OH stretch absorption.

Banana fibre FTIR spectrum peak near 1732.58 cm^{-1} to 1740 cm^{-1} and 1240 cm^{-1} to 1322.21 cm^{-1} region revealed the presence of hemicellulose and lignin components (Joshi *et al*., 2018).These absorption bands are non – cellulosic components and due to the presence of these chemical components, banana fibres cell wall turn into rigidity (Wang *et al*., 2003). The Spectrum depicts O – H stretch C=C stretching and ArC=O stretching in 1636 cm^{-1} bend absorption (Pereira *et al*., 2014). This peak is responsible for the lignin component.

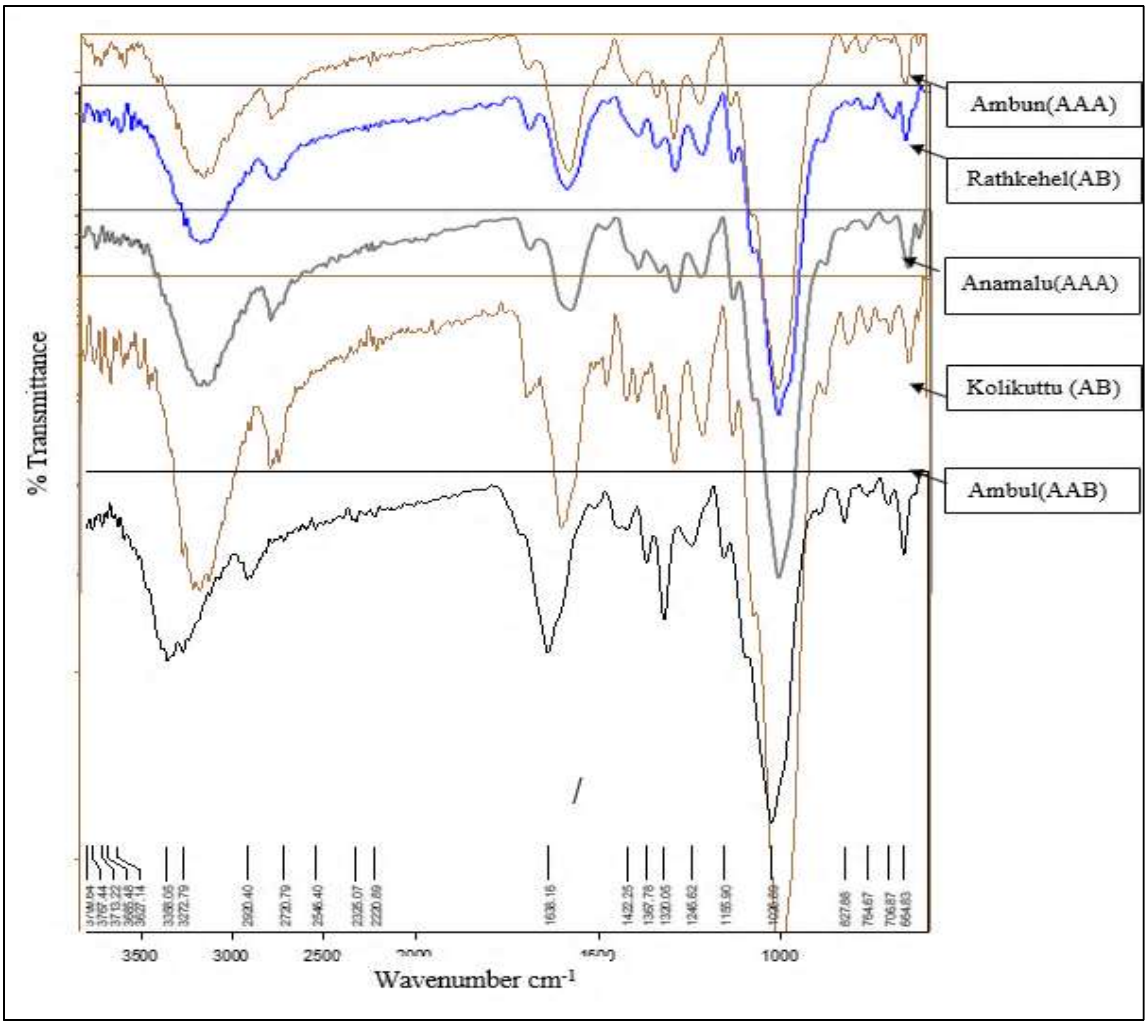


Figure 4-52 FTIR analysis of banana fibres

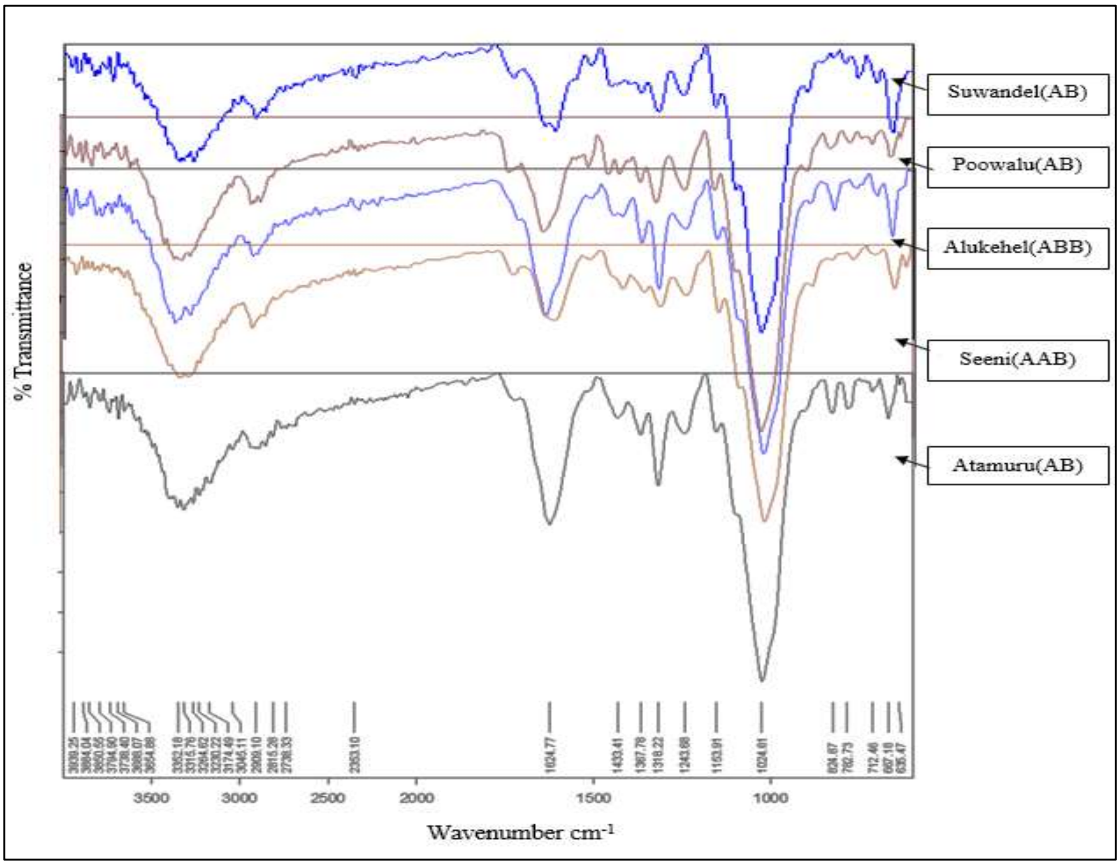


Figure 4-53 FTIR analysis of mechanically extracted banana cultivars

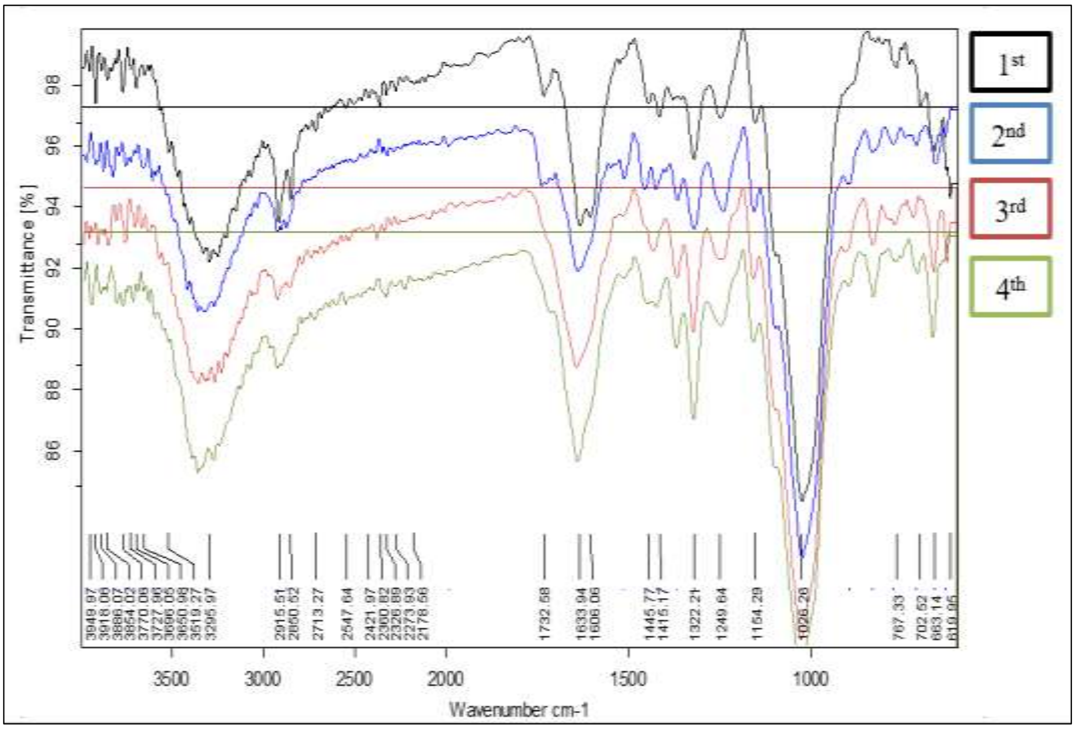


Figure 4-54 FTIR analysis of layer wise fibre of Ambun cultivar

About 25 absorption peaks were recorded in both raw banana fibres and treated banana fibres. The absorption band at 700 to 610cm $^{-1}$ region exposed the presence of –C (triple bond) C-H:C-H bend and H-C=O:C-H stretch aldehydes.

Biological treatment and chemical treated fibres the peak at 1600cm^{-1} is found to have disappeared which indicates the degradation of some lignin components. Enzyme and chemical combined treated fibres (Figure 4-59) peak at 1600cm^{-1} and 1636cm^{-1} is found to have disappeared which was indicates the less lignin components.

The absorption bands between 1730-1740 cm^{-1} and 1200-1300 cm^{-1} are particularly responsible for the hemicelluloses and lignin components. These characteristic absorption peaks are completely absent in the enzyme and chemical combined treated fibre FTIR spectrum (Joshi *et al*., 2018).

The band intensity becomes weak in the range of 1605-1637 cm^{-1} in enzyme treated fibre and insignificant in combined treatment of enzyme and chemical treated fibre (Fan *et al*, 2012). The FTIR results show that the removal performance of the lignin component is satisfying after the enzyme and chemical combined treatments of banana fibres.

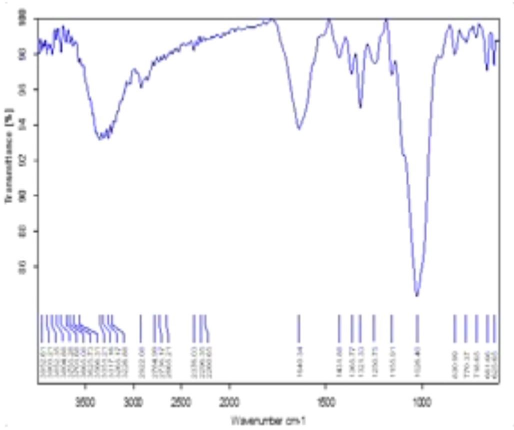


Figure 4-55 FTIR spectroscopy graph of raw banana fibre

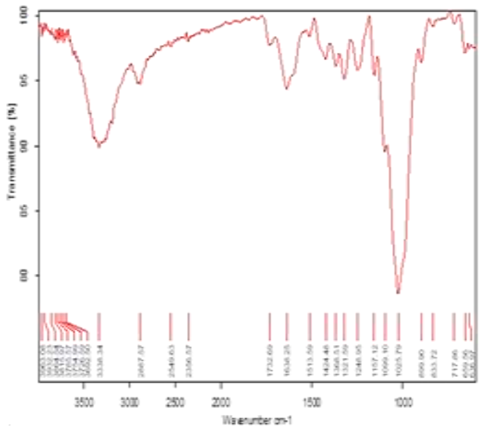


Figure 4-56 FTIR spectroscopy graph of enzyme treated banana fibre

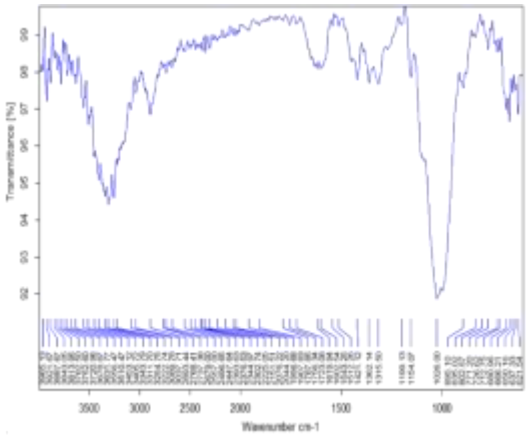


Figure 4-57 FTIR spectroscopy graph of alkali treated banana fibre

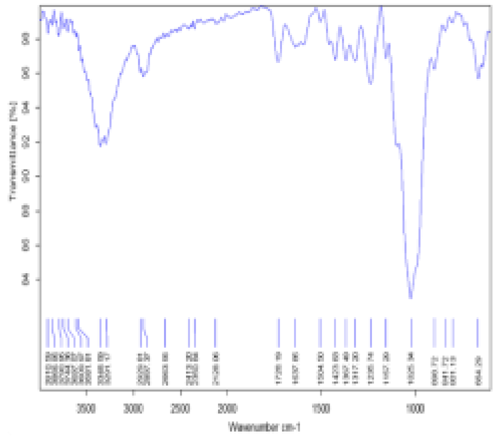


Figure 4-58 FTIR spectroscopy graph of hydrogen peroxide treated banana fibre

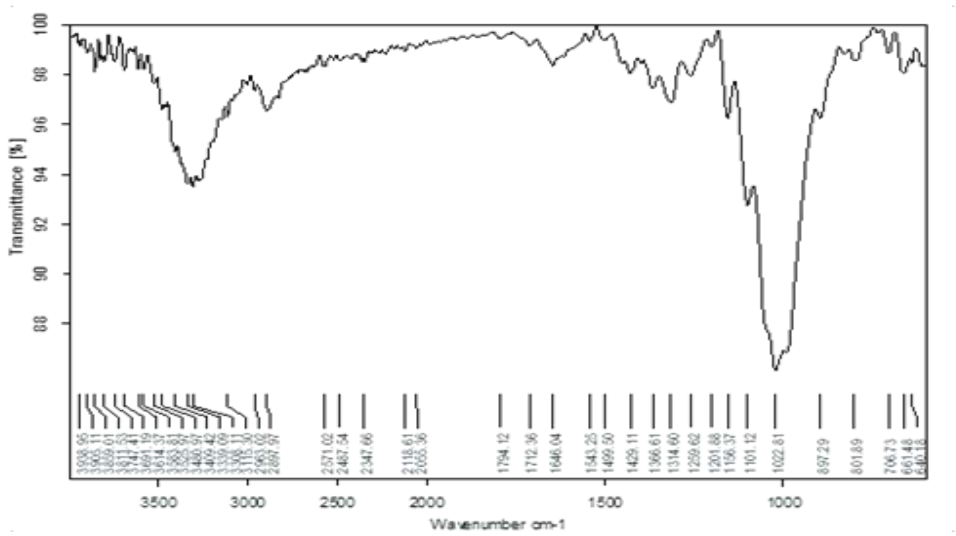


Figure 4-59 FTIR spectroscopy graph of enzyme and chemical combined treatment banana fibre

However, the enzyme treatment cannot remove lignin and hemicelluloses completely (Figure 4-59). Combined treatment breaks down phenolic compounds or molecules with chromophore groups present in lignin. Lignin was oxidized and converted soluble in the solution through the 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined experiments (Sheng *et al*., 2014).

4.2.10 Chemical analysis of banana fibres

Table 4-33 Results of chemical analysis of banana fibre

Fibre	Reagent	Soluble or Insoluble
Banana fibre	90% Formic acid, or 20% HCl,	Insoluble
	5% NaOH, boil or 5% Sodium hypochlorite, 20^0C	Insoluble
	60% H_2SO_4	Partially soluble
	70% H_2SO_4	soluble
	Dimethyl formamide,50^0 – 60^0C	Insoluble
	m-Cresol, boil	Insoluble

Chemical resistance behaviour of banana fibre is similar to other cellulosic fibres; it is confirmed that 70% H_2SO_4 soluble. Banana fibres were partially soluble in the 60% of H_2SO_4. Strong acid destroys banana fibres (Figure 4-60).

Figure 4-60 Acid (H_2SO_4) treated banana fibre

Properties of alkali treated fibre

The diameter of the fibre has been decreased by using high concentration caustic soda (NaOH). High concentration of caustic soda treatments also resulted in fibre damages (figure 4-61). Caustic treatment also resulted in length shrinkage.

Figure 4-61 Alkali treated banana fibre

Properties of bleached fibre

Hydrogen peroxide (H_2O_2) of 4% to 5 % bleaching treatment has improved the fibre fineness. Hydrogen peroxide (H_2O_2) of 4% to 5 % concentration resulted reduction of the tensile strength by 30 to 40%. Bleached fibres have more brightness and uniform in appearance (Figure 4-62).

Figure 4-62 Bleached banana fibre

4.2.11 X-ray diffraction testing method

X-ray diffraction method is used to study the structure of banana fibre. The properties of textile fibres are influenced to great extent by the polymer system of individual fibres. The mechanical properties of banana fibres depend on to what polymer molecules of fibres are arranged to build crystalline and amorphous regions in the structures.

a) Mechanically extracted ambun banana fibre

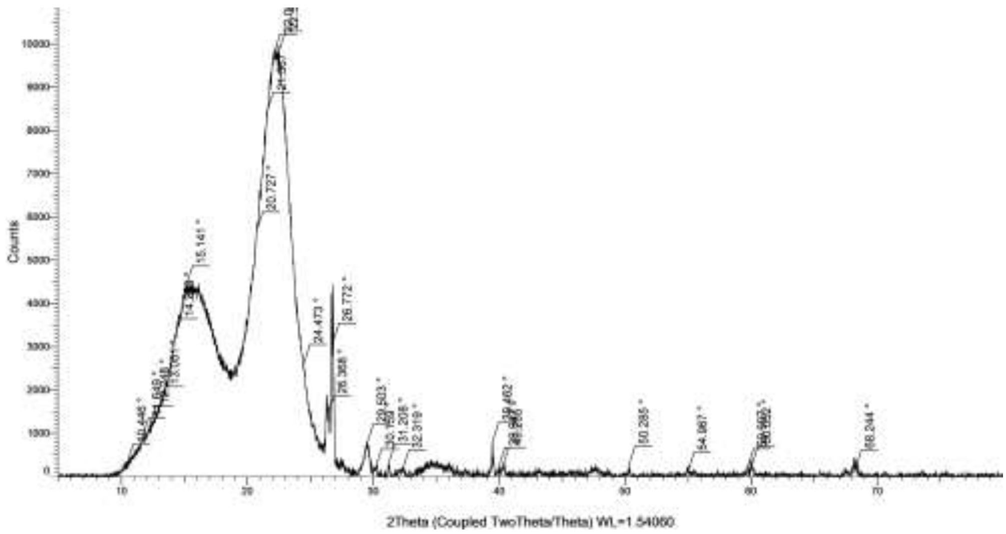


Figure 4-63 X-ray diffraction graph of mechanically extracted banana fibre

Figure 4 -63 shows that X-ray diffraction graph of mechanically extracted banana fibre. X- ray studies indicate that mechanically extracted fibres have a high degree of crystallinity with a spiral angle of about 22^0. In the crystalline region, the molecules are packed more tightly.

b) Biologically and chemically extracted ambun banana fibre

X- ray studies indicate that pectinase enzyme treated fibres have a high degree of crystallinity with a spiral angle of about 21^0 and same crystallite as mechanically extracted fibres.

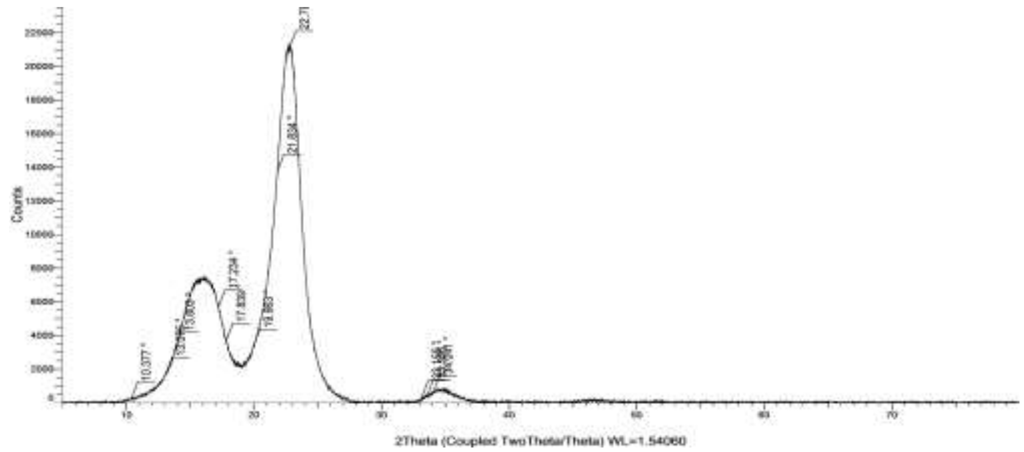


Figure 4-64 X-ray diffraction graph of enzyme treated banana fibre

Enzyme treated fibre X-ray (figure 4-64) indicate that fibres have greater amorphous regions than mechanically extracted fibres.

c) Enzyme and chemical treated banana fibres

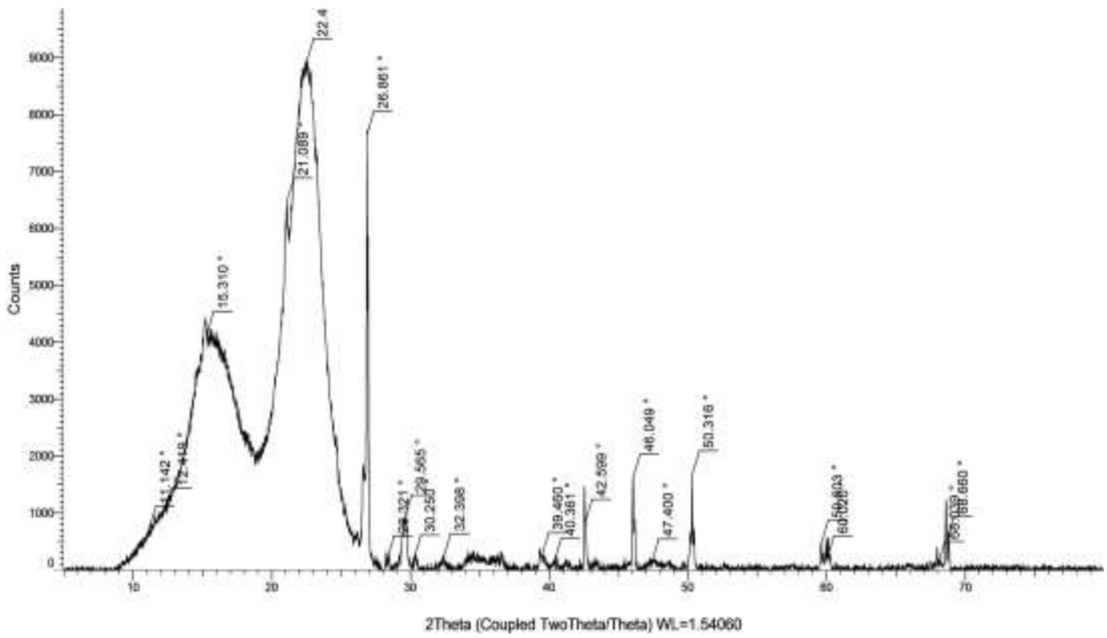


Figure 4-65 X-ray diffraction graph of enzyme and chemical treated banana fibre

Enzyme and chemical treated fibres showed (figure 4-65) greater amorphous regions than other treated and mechanically extracted fibres. Figure 4- 65 illustrates that there is a decrease in crystalline regions in the treated fibre samples. This result justifies the dye absorption power of the enzyme and chemically treated fibres.

4.2.12 Colour of mechanically extracted and treated banana fibre

The grading quality of the banana fibres depend on the cultivation of plant in different countries and different varieties in use. Colour is a key attribute in grading fibres. Fibres were observed with spectrophotometer. The focus of this test is to compare the colour of different varieties of banana fibres

Colour is an important property of textile fibres. The colour of mechanically extracted fibre affects the colour of the fibre textiles products.

Table 4-34 Colour value of top ten banana varieties

	Banana fibre variety	**L***	**a***	**b***	**C***	**h**
01	Ambun (AAA)	78.45	0.11	3.02	3.02	87.83
02	Embul (AAB)	79.12	-0.21	1.99	2.00	95.99
03	Kolikuttu (AAB)	76.12	-0.21	1.99	2.00	67.99
04	Poowalu(AB)	78.49	0.19	3.23	3.24	86.71
05	Seeni(AAB)	76.12	-0.21	1.99	2.00	67.99
06	Anamalu (AAA)	78.16	-0.19	2.88	2.89	93.75
07	Rath kehel(AB)	78.16	-0.19	2.88	2.89	93.75
08	Atamuru(ABB)	76.97	1.51	0.18	1.52	6.76
09	Suwandel(AB)	78.47	0.17	3.14	3.15	86.96
10	Alu kehel(ABB)	78.47	0.17	3,14	3.15	86.96

Table 4-34 shown that the increase in L value and visual observation of the Ambun and Kolikuttu fibres indicate that the fibres have become brighter in comparison to other varieties. The decrease in L value of the other fibre indicates that the fibres have become darker in comparison to Ambun and Kolikuttu fibres which is evident of the visual observation also. Table 4-34 give an overview of lustre property of banana fibre. Ambun and Kolikuttu fibres are more lustrous fibres among other cultivars. The colour of banana fibre varies according to the variety, from off-white natural colour to cream and have little lustre effect.

Colour properties of the banana fibre were influenced by various treatment methods. The focus of this test is to compare the colour of different treatment process for banana fibres and evaluate the suitability of the banana fibre treatment methods for dyeing process.

Table 4-35 Colorimetric coordinates of extracted and treated banana fibres

Samples	**Identification**	**L***	**a***	**b***	**C***	**h***
Mechanically extracted banana fibre	A	67	5.47	21.22	21.92	75.54
5% pectinase enzyme treated banana fibres	B	64.80	3.56	14.61	15.04	76.30
5% NaOH and wetting agent treated banana fibres	C	69.55	3.42	19.30	16.60	79.96
8% H_2O_2, 2% Na_2SiO_3 and 4% NaOH treated banana fibres	D	82.85	-0.65	6.21	6.25	95.98
5% enzyme and 8% H_2O_2, 2% Na_2SiO_3, 4% NaOH treated banana fibres	E	81.32	-0.97	8.66	8.71	96.41

The table 4-35 compares how different treatments would affect the colour properties of fibres. The largest change in colour difference was observed in combined treatment of enzyme and bleaching agent (H_2O_2) treated banana fibre samples. Results established a strong relationship of the CIE L* from the spectrophotometer.

In table 4-35, the increase in L value and visual observation (table 4-35) of the H_2O_2 treated fibre indicates that the fibres have become brighter in comparison to mechanically extracted fibres.

The decrease in L value of the enzyme treated fibre indicates that the fibres have become darker in comparison to mechanically extracted fibres. L value of mechanically extracted fibres indicates that it's became darker in comparison to treated fibres. The H_2O_2 treated banana fibres were redder as the values of 'a' is negative and the redness has also increased. The decrease in the 'b' value shows that the fibre is in the yellower and the yellowness has increased.

Table 4-36 shows that mechanically extracted and treated banana fibres samples images. Table 4-36 reveals that there is a notable change in colour due to the different treatments achieved higher ΔE values. Treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH combined experiments shows higher ΔE values then the other treated fibres.

The orders of hue difference (ΔH) of banana fibres samples were found as D>E>C>B>A. The orders of value difference (ΔL) of the banana fibres were found as D>E> C>B >A. Lightness was decreased due to the treatment of the bleaching agent.

Table 4-36 Pictures of extracted and treated banana fibre samples

<table>
<tr><td>Mechanically extracted banana fibre</td><td>5% pectinase enzyme treated banana fibres</td><td>5% NaOH treated banana fibres</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>8% H_2O_2, 2% Na_2SiO_3 and 4% NaOH treated banana fibres</td><td colspan="2">Enzyme and8% H_2O_2, 2% Na_2SiO_3, 4% NaOH treated banana fibres</td></tr>
<tr><td></td><td colspan="2"></td></tr>
</table>

Table 4-37 Total colour difference due to different treatments

Samples	ΔL*	Δa*	Δb*	ΔC*	ΔH*	ΔE*
5% pectinase enzyme treated fibres (A)	-2.20	-1.91	-6.61	-6.88	0.24	7.23
5% NaOH and wetting agent treated fibres(B)	-2.20	-1.91	-6.61	-6.88	0.24	7.23
8% H_2O_2, 2% Na_2SiO_3 and 4% NaOH treated fibres(C)	15.84	-6.12	-15.02	-15.68	4.15	22.67
Enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH combined treated banana fibre (D)	14.32	-6.44	-12.57	-13.20	5.01	20.11

The table 4-37 shows that there is significant change in colour due to the different treatments achieved higher ΔE values. Treatment of 8% H_2O_2, 2% Na_2SiO_3, 4% NaOH and softener experiments shows higher ΔE values then the other treatments.

Reflectance values of banana fibre samples

K/S is generally mentioned as a function of reflectance f(R). The K/S data of the dyed samples were also produced using Datacolor machine through the strength evaluation programme.

The Datacolour (600) computerized colour matching system was used to measure the reflectance values of different colour types (red, blue and yellow) of reactive dyes. Figure 4-66 shows that reflectance percentage of untreated banana fibre is below 60%.

Enzyme treated banana fibre sample (Figure 4-67) shows that hue value has changed from the untreated sample and 550 to 620nm wavelength have the same reflectance value.

Bleached banana fibre (Figure 4-68 and 4-70) shows the value has significantly increased in comparison to the untreated (Mechanically extracted fibre) fibre sample. Figure 4-60 shows the enzyme and chemically treated banana fibre has a maximum reflectance of above 60%.

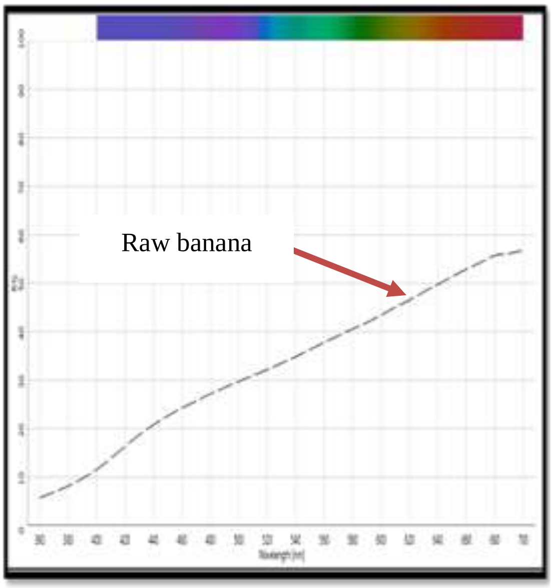


Figure 4-66 Reflectance values of mechanically extracted (raw) banana fibre

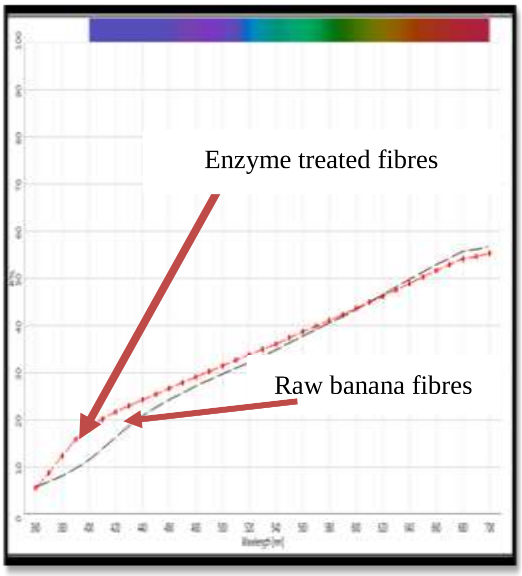


Figure 4-67 Reflectance values of enzyme treated banana fibre

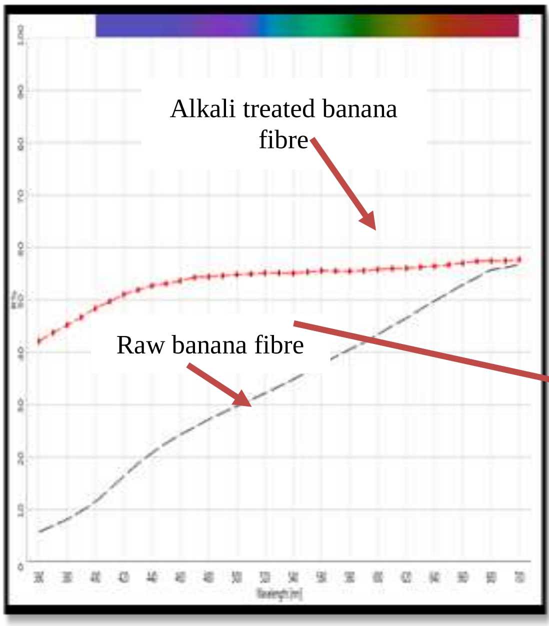


Figure 4-68 Reflectance values of alkali treated banana fibre

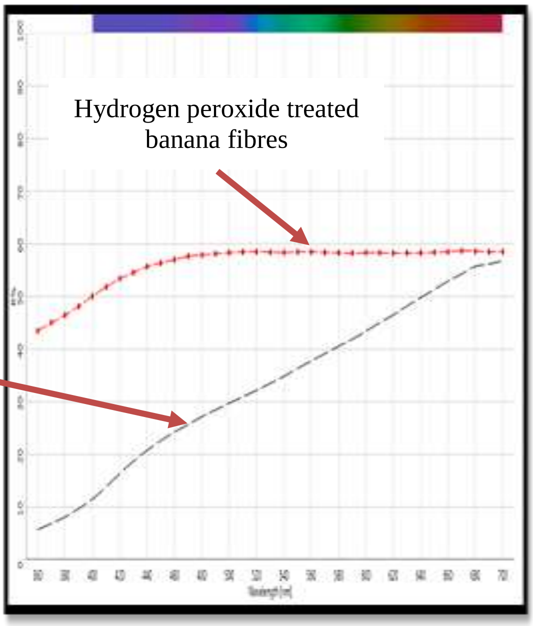


Figure 4-69 Reflectance values of hydrogen peroxide treated banana fibre

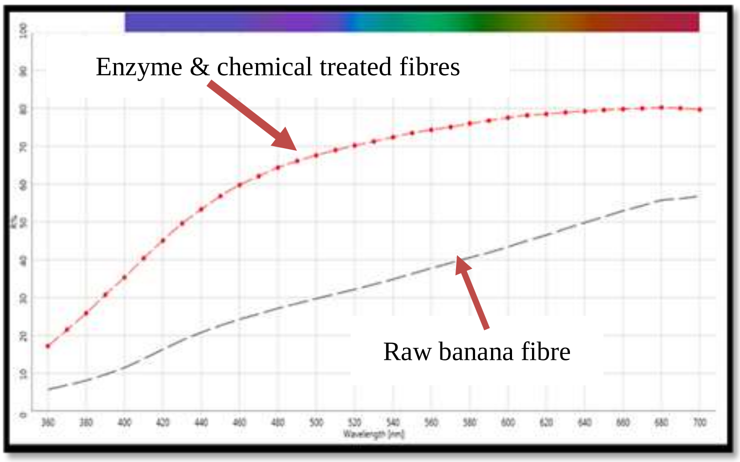


Figure 4-70 Reflectance values of enzyme and chemical combined treatment banana fibre

The results established that the colour of treated and mechanically extracted banana fibre result has a significant change in colours, which is evidence of higher ΔE values.

The increasing L value of the treated fibre indicates that the fibres have become brighter which is evident of the visual observation. The main problem to be encountered during dyeing process of banana fibre is the removal of lignin and other cementing materials which interfere with the absorption property. White colour of enzyme and chemical combined treated banana fibres reduces the chemical consumption of bleaching agents in the whitening of banana textile materials.

4.2.13 Burning test of banana fibre

Table 4-38 Burning test results of banana fibres

Fibre	Before touching fibre	In Flame	After leaving Flame	Odour	Ash
Banana fibre	Burns just as flame touches fibre	Burns	Supports combustion, burns rapidly	Burning paper	Very little, soft and grey colour

Banana fibre burning test results are similar to any other cellulose fibre behaviour. Table 4-38 determined there were no notable differences in the burning behaviour of banana varieties. This table 4-38 helps to identify their burning characteristics and smell smoke, ash, etc. Banana fibres were burned quickly with yellow to orange colour flame and continue to glow. It was smells like burning paper and the ash is grey and soft.

It was not leave any melted bead. All of the five varieties burning behaviours are similar to cotton fibre.

4.2.14 Banana fibre quality and grading

According to the above test results, mechanically extracted (Ten varieties) banana fibres were graded. For the banana fibre grading process some of the factors are consider. Those are colour, length, fineness of fibre, lustre, strength and cleanness (contamination of impurities). A strong fibre with good length, even colour and high lustre fibres were considered as good quality fibres. Golden yellow and dark in colour are two colour group which were present in banana fibres. Grades were determined from strength, colour and diameter range of banana fibre. Finally, this grading system indicates fineness, contamination of impurities, colour and strength of the fibres.

The colour of banana fibre varies according to the variety, from off-white natural colour to cream and have little lustre effect. Long lustrous fibres will usually produce lustrous yarn. Banana fibres were graded according to strength, fineness or diameter and colour properties. Based on the laboratory tests some of the textile properties of banana fibres were tested and identified as notable characteristics of specific banana fibre. To provide the sustainable handcraft and textile raw material supply, banana natural fibres grading method has been successfully identified (Table 4-39).

In this study, ten (10) varieties of banana fibres were investigated, and the results show Ambun fibre is very soft and fine, golden yellow in colour. All ten selected varieties of mechanically extracted fibres show coarser fibre in nature comparing with other natural fibres such as cotton. Lengthy fibres can be obtained from banana pesudostem. According to the results, there are no significant difference shown in their microscopic appearance, chemical solubility and burning behaviour for the selected banana fibre varieties but there were differences observed in colour, strength and diameter in the test results. The colour of banana fibre varies according to the variety, from off-white natural colour to cream and have little lustre effect. Long lustrous fibres will usually produce lustrous yarn. Banana fibres were graded according to strength, fineness or diameter and colour properties. The grading system presented in this research enhances the process of categorising the banana fibre varieties based on their qualities. The grading system also helps in the process of selecting the correct fibre to the relevant industry.

Table 4-39 Grading points for banana cultivars

Grading points	Characteristics	Type of banana variety
1 (High quality)	Golden yellow colour and lustre, Slightly soft, fine fibre. Low contamination of impurities. Diameter range:≥75 to 85μm. Tensile strength range: ≥ 2.5N	Ambun and Kolikuttu
2 (Medium quality)	Golden yellow colour and lustre, Slightly soft. Medium contamination of impurities. Diameter range:≤85 to 87 μm. Tensile strength range: ≥ 2.4N to 1N	Atamuru and Puwalu
3 (Medium quality)	Dark in colour, lustre. Medium contamination of impurities. Diameter range: ≤87 to 110 μm. Tensile strength range: ≥ 2.4N to 1N	Seeni, Suwandel and Ambul
4 (Low quality)	Dark in colour, No lustre. Medium contamination of impurities. Diameter range: ≤ 111 μm ≤ . Tensile strength range: ≤ 1N	Rath kehel, Anamalu and Alu kehel

Lustre is the characteristic surface appearance of fibre. Ambun and Kolikuttu banana fibres are golden yellow in colour and lustrous. This natural lustre enhances the value of banana fibres. The colour of Puwalu, Rathkehel and Alukehel banana off-white natural colour to cream and have little lustre effect (Table 4-39).

4.3 Summary of mechanically extracted and treated banana fibre

These extraction methods remove heavily coated, non-cellulosic gummy material from the cellulosic part of banana pseudostem fibres. There are pros and cons of each method.

Biological methods are eco-friendly and chemical methods causes environmental pollution.

Mechanical extraction method neglects to expel the gummy material from the fibre surface.

4.3.1 Analysis of layer wise Ambun banana fibre mechanical properties

Table 4.40 shows mechanical properties of Ambun banana fibres. It was observed that the fibre of second and third layers of Ambun banana are finer than fibre of first and fourth layers.

The different layers of Ambun banana fibres vary in properties, the variation being of the order of 16% in terms of linear density (from maximum to minimum), 4 % in terms of strength, 6 % in terms of fibre diameter, 19 % in terms of tenacity, 25% in terms of oil content, 11 % in terms of moisture content and 33% in terms of elongation. Second and third layer of Ambun fibres were not vary in mechanical properties. Lower diameter of Ambun fibre shown better tenacity property. Fibres with increasing diameter was improved the uniformity and fibres with less diameter became irregular in structure.

The result showed that the average fineness of fibre of the second and third layer is around 25 Tex and the diameter value is around 80 µm. The test result showed the middle layers (second and third) to be the finest. The highest tex values were obtained for fibre of fist layer. The result showed that the average single fibre strength of the second layer is approximately 270 gf. The lowest single fibre strength values were obtained for fibre of fourth layer. The test results presented that, the average breaking tenacity of the banana fibre was 9.9 gf/tex and the average elongation at break was 1.22 %. Layer-wise analyses indicate, the linear density and diameter test results showed the middle layers of ambun pesudostem fibres to be the finest. The results showed that the average linear density of the ambun middle layer is 25 tex, the average diameter value is 80 µm and range of single fibre strength is 273~270 gf. Moisture content was varying in between 9.9% ~9.7%.

Table 4-40 Mechanical properties of Ambun banana pseudostem fibre

	Fibre Properties	**1 st layer**	**2nd layer**	**3 rd layer**	**4 th layer**
01	Fibre linear Density - Tex	30	25	25	27
	Standard Deviation	0.816	0.83	0.40	3.33
	Coefficient of variation(%)	4.08	6.43	3.14	14.48
02	Single fibre Strength - gf	264	273	270	260
	Standard Deviation	6.82	2.28	1.32	29.35
	Coefficient of variation(%)	2.43	0.85	0.55	11.37
03	Elongation	1.10%	1.20%	1.00%	1.50%
	Tenacity – gt/Tex	8.8	10.92	10.8	9.62
04	Fibre diameter	83.42	80.32	80.04	85.99
	Standard Deviation	2.40	1.49	0.96	9.31
	Coefficient of variation(%)	2.88	1.85	1.15	10.83
05	Oil Content	0.40%	0.40%	0.40%	0.30%
06	Moisture content	8.90%	9.90%	9.70%	10.10%

In this study, mechanically extracted fibre of the second and third layer were treated with enzymes and chemicals with concentrations ranging between 1 to 10%.

4.3.2 Analysis of mechanically extracted and treated banana fibres mechanical properties

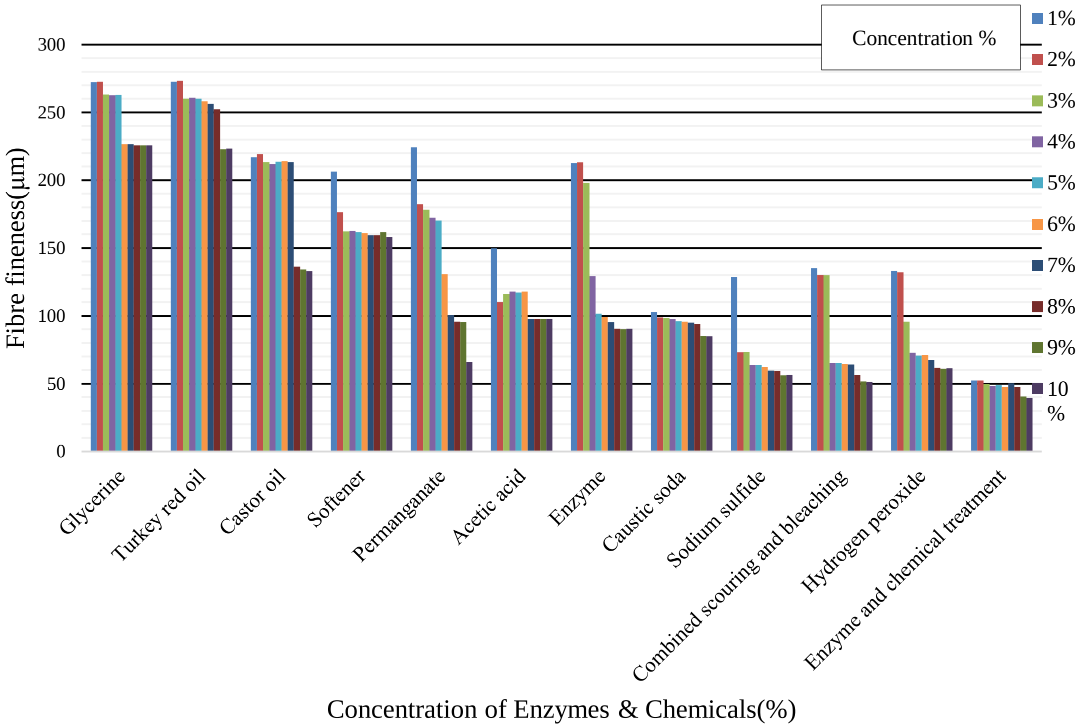


Figure 4-71 Fineness results of different treatments

Chemical treatment and enzyme and chemical combined treatment results show that fibre fineness has reduced and single fibre strength of the Ambun fibres (Figure 4-71) has increase due to the alkali treatment.

The effect of enzyme has proven to be useful for banana fibre treatment, achieving an improvement in terms of cleanliness. According to the biological treatments, the linear density, fibre diameter, as well as the single fibre strength decreases. The enzymes were hydrolyzed pectic substances and this enzyme treatment removed pectin components and incresed proportion of cellulose contents. From the biological and chemical treatment result, it was observed that the fibre fineness was influences the diameter and linear density properties.

The fibre diameter has reduced after biological and chemical treatments (Figure 4-71). Biologically treated banana fibres show higher strength value than the other treated banana fibres

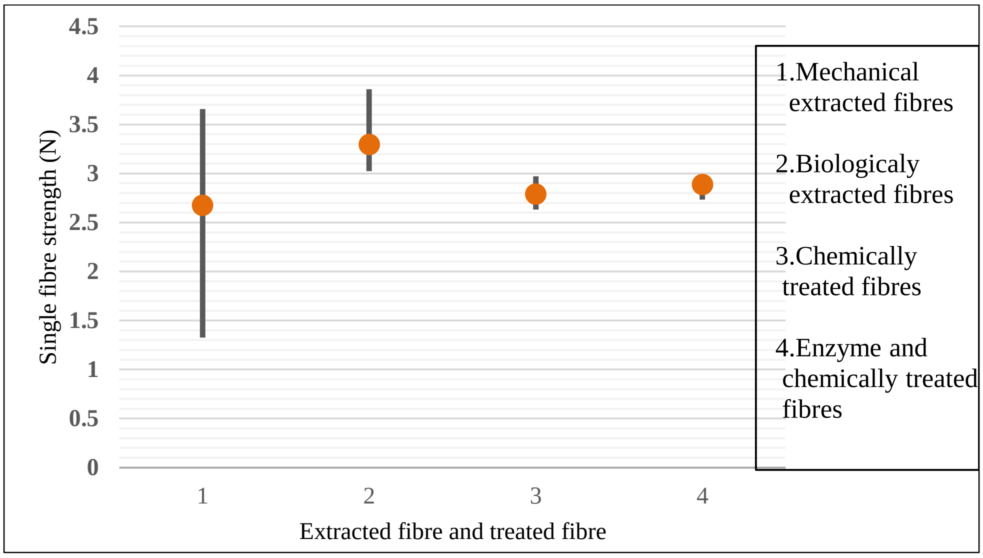


Figure 4-72 Single fibre strength of Ambun fibre

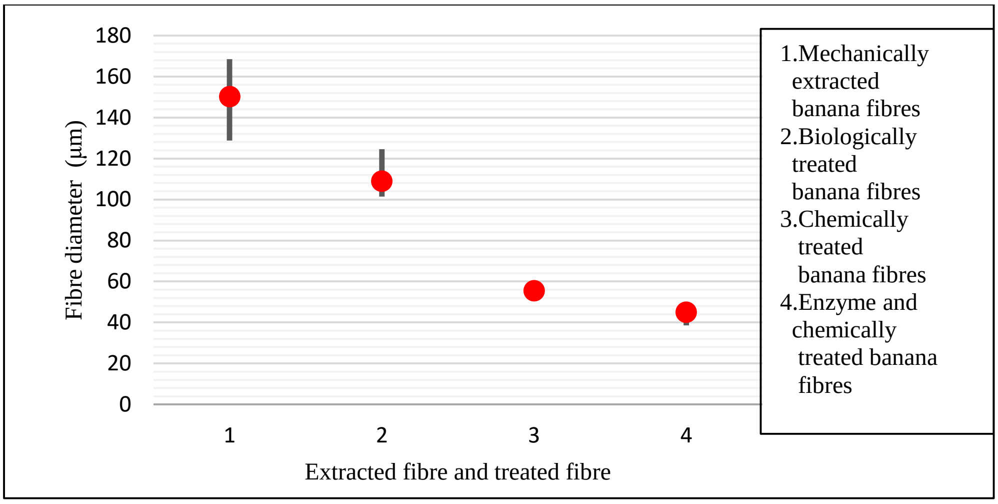


Figure 4-73 Diameter of Ambun fibre

Figure 4-73 shows that enzyme and chemical combined treated fibre diameter (µm) is the lower than other treatments.

Table 4-41 Mechanical properties of mechanically extracted and treated fibres

Properties	Mechanical Extraction	Biological treatment	Chemical treatment	Enzyme and Chemical treatments
Fibre diameter (µm)	168.4	101.45	60.5	48.8
Fibre linear density- tex	25	21	18	4
Single fibre strength - N	2.670	3.298	2.973	2.931
Tenacity- gf/tex	10.89	16.01	25.23	53.37
Moisture content (%)	9.90	9.60	9.60	11.10

Enzyme treatment reduces the diameter from 168.4 to 101.45 µm and which is about 39.75 % diameter reduction. The linear density of banana fibre has also reduced from 25 tex to 21 tex as shown in table 4- 41. Enzyme treatment shows higher strength values (19%) than the other treatments and mechanically extracted fibres. Chemical treatment reduces the diameter from 168.4 to 60.5µm which is about 64 % diameter reduction. The linear density of banana fibre is also reduced from 25 tex to 18 tex as shown in Table 4-41. Chemical treatment resulted 10% increase in fibre strength compared to mechanical extracted untreated fibres.

Enzyme and chemical combined treatment have reduced the diameter from 168.4µm to 48.86 µm and which is about 70.9% diameter reduction. Treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined experiments shows (Table 4-41) 4 tex linear density, diameter of 48.8 µm and strength value is 2.931gf.

Out of all treatments, the treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined treatment improved the fibre diameter (48.8 µm), strength value is 2.931gf and fibre linear density (4 tex) compared to mechanically extracted fibre.

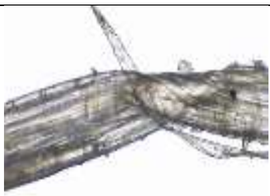
It was proven that the banana fibre fineness was better than the fineness of silk fibre (58.8 µm) and jute fibre (59.39 µm) at this instance, which is suitable for blending with cotton for short staple yarn spinning. Moisture content were tested and found that the test results are superior to cotton fibres.

4.4 A comparison between the mechanical and chemical properties of banana fibre with other bast fibres

This research was focused on the most important bast fibres of plants including hemp (Cannabis sativa), flax (Linum usitatissimum L.), jute (Corchorus olitorius), and ramie (Boehmeria nivea) (Sadrmanesh & Chen, 2018).

Table 4-42 shows structural features of bast fibres with treated banana fibres.

Table 4-42 Microscopic view of bast fibres

Fibre type	20X	10X	4X
Banana fibre			
Treated banana fibre			
Jute fibre			
Flax fibre			
Hemp fibre			

The structure of bast fibres is very similar to many fibres (Table 4-42). Longitudinal images of banana, flax, hemp fibre samples show little difference between the fibres and shown irregularly spaced cross markings, some markings appear singularly, and others are in multiples.

Table 4-43 shows a comprehensive evaluation of bast fibres with treated banana fibres. Fibre extracted from banana pseudo-stem and conversion of this fibre into textile materials is of recent origin (Bai & Yu, 2011). But they are slightly stiff and feel the worst softness. Treated banana fibres have achieved more fine and hydrophilic.

Table 4-43 shows that treated banana fibre is a fine fibre compared to sisal and jute fibres. The length of textile fibre can be infinitely long. However, it should not be shorter than 6 –12 mm (¼–½ inch) because it may not hold together for spinning (Fatma, 2019). Therefore, treated banana fibre has better spinning properties because of its longer single fibre and spun in yarn at the unique performances of its style, which results in better yarn quality (Bai & Yu, 2011).

The order of the diameter differences was found as raw banana fibre> jute> treated banana fibre> ramie> hemp> flax. Treated banana fibres are finer and smoother surfaces than compare to sisal (50-200µm) and coir (100-450µm) vegetable fibres (Amutha *et al*., 2020).

Mechanically extracted banana fibres have a larger diameter and coarser than treated fibres and jute, hemp, and flax. Therefore, mechanically extracted fibres are not suitable for making a finer yarn. Tenacity is one of the fundamental properties of spin ability. Higher tenacity of fibre obtained in treated banana fibres. It has a higher yarn tenacity.

The stiffness of natural fibre decreased with increased moisture content. It may occur covalent bonds in the hemicellulose macromolecular structure are replaced with hydrogen bonds. It resulted in a more flexible and more comfortable fabric (Sadrmanesh & Chen, 2018). The order of the moisture content differences was found as jute> treated banana fibres> flax> raw banana fibre> hemp> ramie. It concludes treated banana fibres and jute fibres are more flexible.

The comparison between the bast fibres with banana fibre presented in this research enhances categorizing the bast fibre varieties based on their qualities. The research also helps in selecting the correct bast fibre for the relevant industry such as geo-textiles, fashion textiles, functional textile, interior textile, non-woven fabrics, fibreboard materials, insulation materials, reinforcement, filler, light-weight concrete, bricks and composites.

Table 4-43 Comparison between jute,hemp,ramie, flax and banana fibres

	Properties	**Treated banana fibres**	**Jute fibre**	**Flax fibre**	**Hemp fibre**	**Ramie**
1	Fineness (µm)	48.8	59.39	17–20	15–30	40-60
2	Fibre linear density- Tex	5.6 - 4	4.066	0.34-0.47	2.554	1.90 – 4.4
3	Elongation (%)	1.5	1.5 – 1.8	2.7-3.2	1.6	2.5
4	Tenacity-cN/tex	52.31	4.4	6.5	12	18
5	Moisture regain	11.1	12	9.24-10.50	9	6.81-9.80
6	Water absorbency	High	High	Low	Low	Low
7	Strong acid	Destroy	Destroy	Destroy	Destroy	Destroy
8	Strong alkalis	Do not injure	Do not injure	Do not injure	Do not injure	Do not injure

Table 4.43 shows banana fibres have a lower strength. Comparing with other common bast fibres, very longer fibres can be obtained from pesudostem fibres. Banana fibres have the property of good water absorbency and high moisture regain properties. Mechanically extracted untreated banana fibres are hydrophobic in nature (High water absorbency).

Table 4-44 shows colorimetric coordinates of bast fibres. The increase in L* value of treated banana fibres and hemp fibres shows fibre becomes brighter (Table 4-44). Surplus of all bast fibres are greener (a*) and yellower (b*) side except raw banana fibre.

Table 4-44 Colorimetric coordinates of extracted, treated banana fibres and other bast fibres

Fibre type	**L***	**a***	**b***	**C***	**h***
Treated banana fibre	81.32	-0.97	8.66	8.71	96.41
Raw banana fibre	78.45	0.11	3.02	3.02	87.83
Jute fibre	79.69	-0.65	1.98	2.09	108.22
Flax fibre	77.52	-0.36	2.14	2.17	99.62
Hemp fibre	80.46	-0.31	0.39	0.50	128.11

Table 4-45 shows total colour differences between the bast fibres. Table 4-45 expressed as ΔE* > 1, the colour differences are noticeable to the human eye. Mechanically extracted banana fibre ΔE value is 7.23 while comparing to all bast fibres, significant colour differences can observe in mechanically extracted banana fibres.

Table 4-45 Total colour difference of treated banana fibres with other bast fibres

Samples	**ΔL***	**Δa***	**Δb***	**ΔC***	**ΔH***	**ΔE***
Jute	1.20	-0.75	-1.24	-1.14	0.89	1.88
Hemp	0.75	-0.50	-2.94	-2.76	1.14	3.08
Flax	-1.15	-0.44	-1.09	-1.07	0.50	1.64
Mechanically extracted banana fibres	-2.20	-1.91	-6.61	-6.88	0.24	7.23

4.5 Dyeing properties

The focal problem to be faced during the dyeing process of banana fibre is the removal of lignin, pentosane and other cementing materials which interfere with the absorption property and thus lead to poor scouring, bleaching and dyeing properties of the fibre. The raw banana fibres were darker in colour. Higher colour deterioration is more challenging for dyeing and finishing process. Hence, it is necessary to have an idea about the colour of mechanically extracted fibres and fibres treated under different conditions.

These treated fibres were very suitable for dyeing process. Scoured and bleached banana fibres were applied with reactive class of dye and it was found that the dye absorption properties and the wash fastness properties satisfied the quality level (5 is excellent) required for textile fibre.

Generally, reactive dyes are produced due to covalent bond between cellulose fibre and the hydroxyl groups of a fibre. Therefore, reactive dyes give better wash and light fastness properties (Chinta & Vijaykumar, 2013). Reactive class of dyes was used to dye banana fibres because of their superior performances for dying cellulosic goods (John Shore,1995). Banana fibre (15g) and cotton fibre (15g) (on the basis of oven-dry fibre samples) were dyed with three standard colours (Red, blue and yellow) each with four concentrations (0.25%, 1%, 4% and 6%).

Table 4-28 shows that reactive blue dyed of banana fibre samples were darker, less saturated and more yellow than the blue reactive dyed of cotton samples (Table 4-46).

Table 4-46 Colorimetric coordinates of banana fibres

Samples	**Concentration (%)**	**L***	**a***	**b***	**C***	**h***
Red dyed banana fibres	0.25	76.03	3.83	1.61	4.15	22.74
	1.00	75.04	3.71	1.39	3.96	20.54
	4.00	75.16	3.48	1.31	3.72	20.57
	6.00	74.4	3.44	0.84	3.55	13.73
Yellow dyed banana fibres	0.25	79.11	-1.91	6.15	6.11	106.80
	1.00	79.09	-1.83	6.47	6.72	105.80
	4.00	78.54	-1.61	5.88	6.10	105.33
	6.00	79.40	-2.03	7.03	7.32	106.09
Blue dyed banana fibres	0.25	76.84	-4.45	-1.74	4.78	201.38
	1.00	75.42	-3.84	-2.60	4.64	214.04
	4.00	75.80	-4.27	-2.48	4.94	210.11
	6.00	74.98	-3.42	-2.27	4.10	213.54

Table 4-47 Colorimetric coordinates of cotton fibre samples

Samples	**Concentration (%)**	**L***	**a***	**b***	**C***	**h***
Red dyed cotton fibres	0.25	75.95	4.69	1.32	4.87	15.68
	1.00	75.36	4.14	1.34	4.35	17.89
	4.00	74.85	4.11	1.13	4.27	15.41
	6.00	74.83	4.36	0.99	4.47	12.79
Yellow dyed cotton fibres	0.25	80.34	-3.15	12.15	12.55	104.51
	1.00	80.20	-2.07	6.40	6.73	107.90
	4.00	80.57	-2.02	5.62	5.97	109.77
	6.00	79.84	-2.16	6.33	6.69	108.87
Blue dyed cotton fibres	0.25	78.09	-4.31	-4.34	6.12	225.20
	1.00	76.74	-3.90	-4.05	5.63	226.10
	4.00	76.77	-4.14	-3.88	5.67	223.13
	6.00	76.36	-4.32	-4.72	6.40	227.51

Reactive red (1%, 4% and 6%) dyed of banana fibre samples were darker, less saturated and dye bath of 0.25% concentration samples were lighter, less saturated and darker shade of yellow than the cotton red reactive dyed samples. 0.25% and 1 % concentration of yellow dyed banana fibre samples were darker, less saturated and more yellow, 4 % and 6 % concentration of yellow dyed samples were darker, more saturated and more yellow than the yellow reactive dyed cotton samples.

Dyed banana fibre- Red colour (4%)	Dyed banana fibre-Blue colour (4%)	Dyed banana fibre- Yellow colour (4%)

Figure 4-74 Dyed banana fibre samples

Figure 4-74 shows that dyed banana fibre with three standard colours (Red, blue and yellow) each with 4% concentrations of reactive red, reactive blue and reactive yellow dye types. The table 4-48 presents that there is significant change in colours due to the different colours of dyed fibres achieved higher ΔE values.

Blue and red dyed of banana fibres shows higher ΔE values than the other dyed samples. With an increase in the concentration of the dye bath, ΔE values narrowed down for a yellow dye. With an increase in the concentration of the dye bath, ΔE values rise for a red dye.

*Table 4-48 CIE L*a*b* colour difference delta E values for banana fibres and cotton fibres*

Colours	Concentration (%)	ΔE Values
Dyed banana fibre-Red colours	0.25	0.91
	1	0.54
	4	0.72
	6	1.02
Dyed banana fibre-Blue colours	0.25	2.89
	1	1.97
	4	1.71
	6	2.95
Dyed banana fibre-Yellow colours	0.25	1.18
	1	1.13
	4	0.08
	6	0.84

Delta E value and reflectance values of the dyed samples were measured by using Data colour (600) spectrophotometer. The red shade of dyed (with increase in the concentration) samples were no any significant differences reported according to the ΔE values.

The blue shade of dyed samples shows much more significant differences. ΔE values narrowed down for yellow shades an increase in the concentration.

Banana fibres of blue and red dyed samples were performed visually darker shades when contrasted with the shades obtained on cotton fibres. The Blue colours dyed samples have crossed the "Just Noticeable Difference" value 2.95. Therefore, the above-mentioned concentration of blue colour dyed banana fibre deterioration is visible to human eye.

The reflectance curves of dyed banana fibre and cotton fibre samples were plotted Figure 4-75 to 4-86. According to the figure, the red colour line represents reflectance curves of cotton dyed samples and the black colour line represents reflectance curves of dyed banana fibre samples.

The reflectance curves of dyed banana fibre and cotton fibre samples were plotted Figure 4-75 to 4-86. Figures showed the banana fibres of the blue colour dyed reflectance curve lower than blue-dyed cotton fibre.

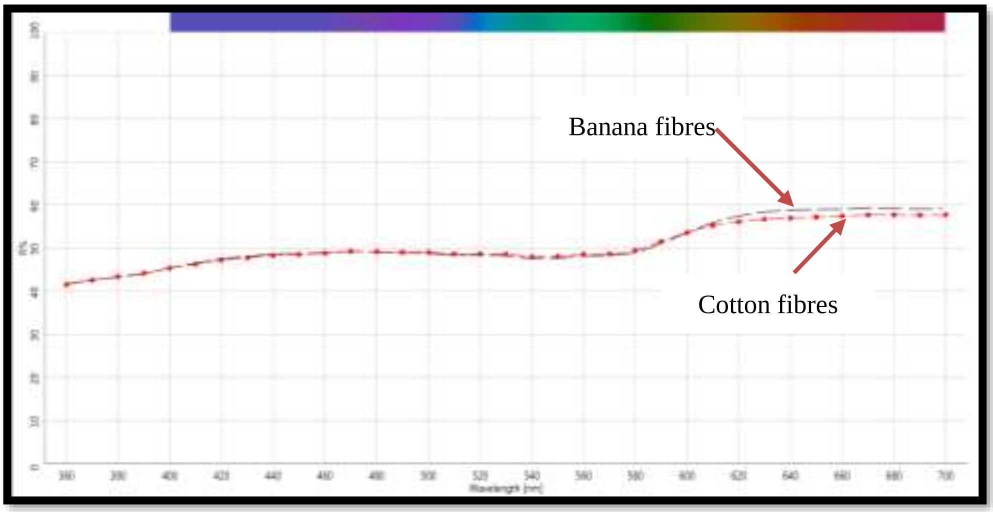


Figure 4-75 Reflectance values of dyed banana fibre (0.025 % red)

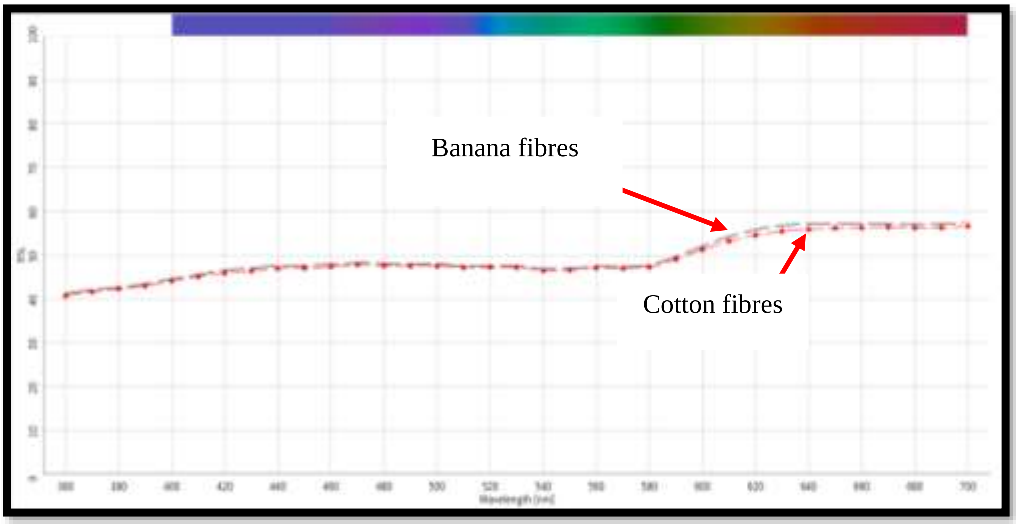


Figure 4-76 Reflectance values of dyed banana fibre (1% red)

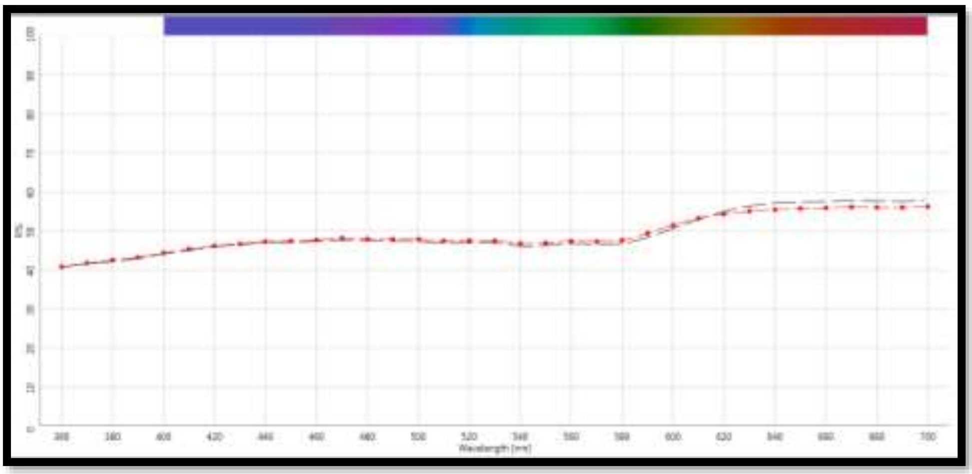


Figure 4-77 Reflectance values of dyed banana fibre (4% red)

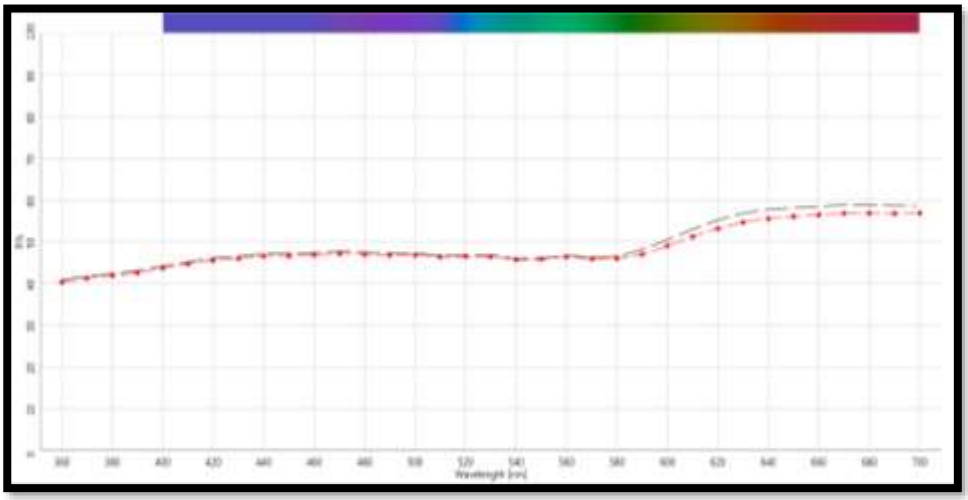


Figure 4-78 Reflectance values of dyed banana fibre (6 % red)

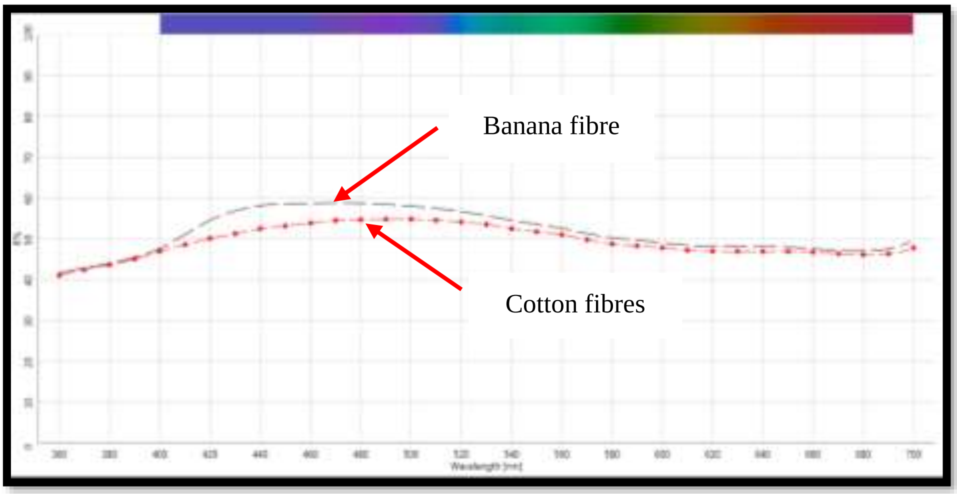


Figure 4-79 Reflectance values of dyed banana fibre (0.025% blue)

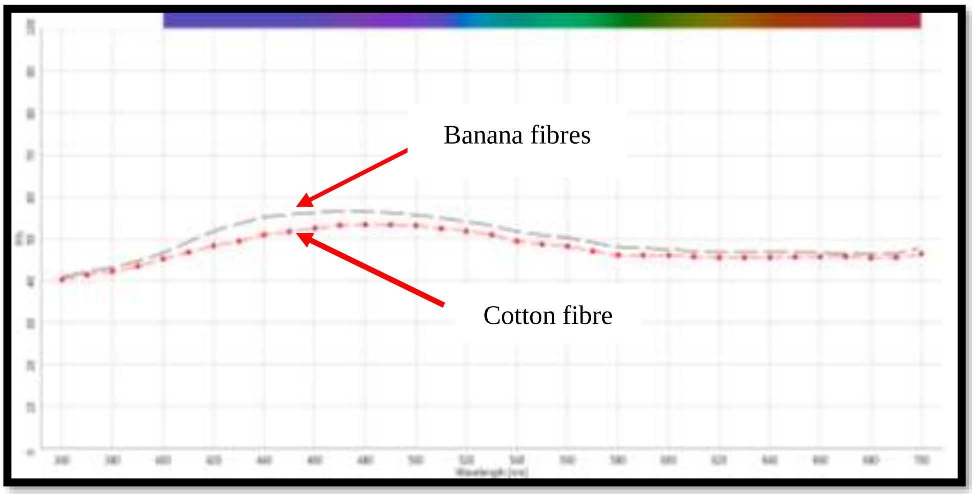


Figure 4-80 Reflectance values of dyed banana fibre (1 % blue)

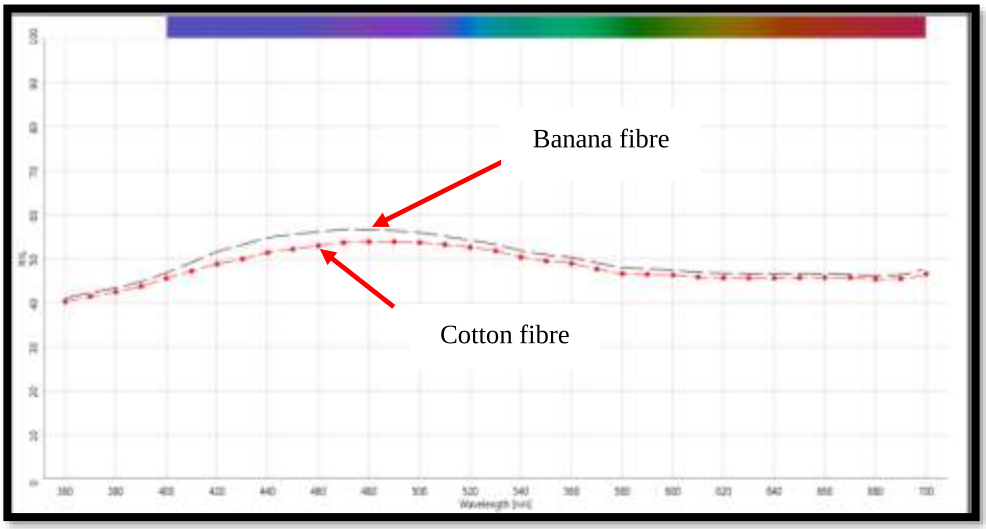


Figure 4-81 Reflectance values of dyed banana fibre (4 % blue)

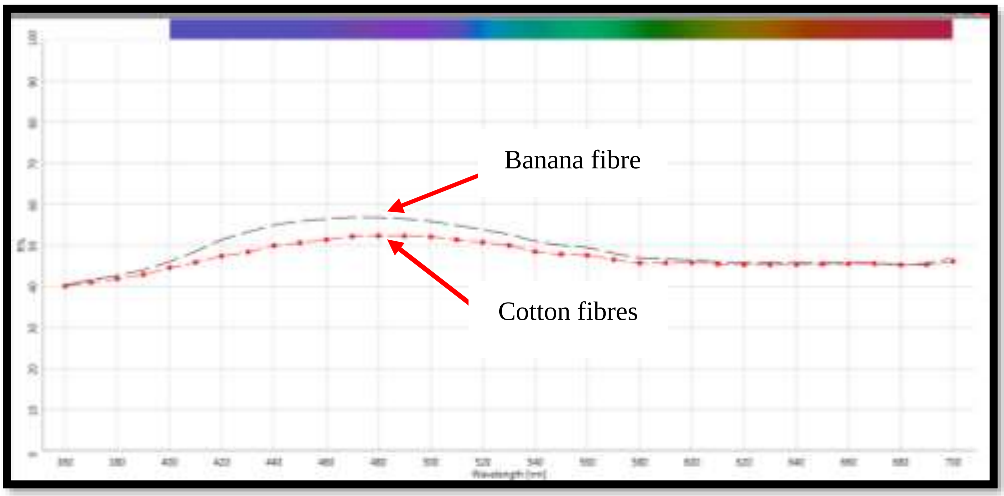


Figure 4-82 Reflectance values of dyed banana fibre (6 % blue)

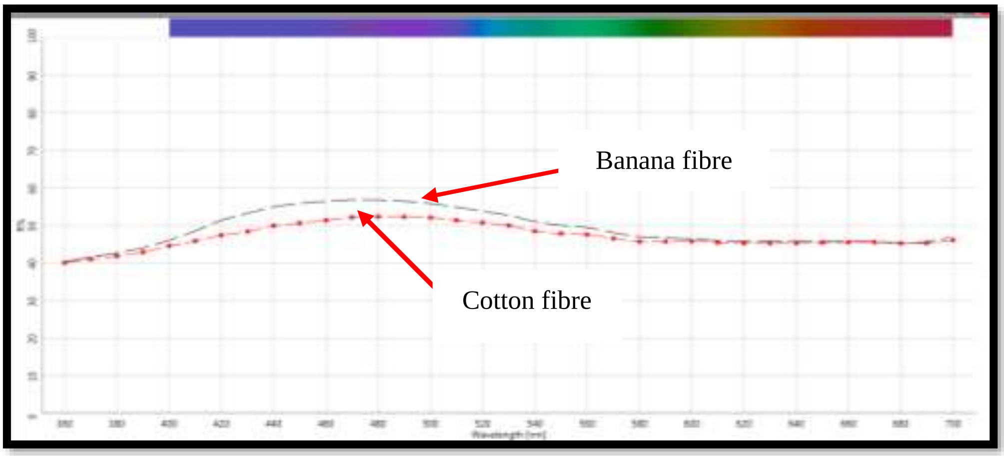


Figure 4-83 Reflectance values of dyed banana fibre (0.025 % yellow)

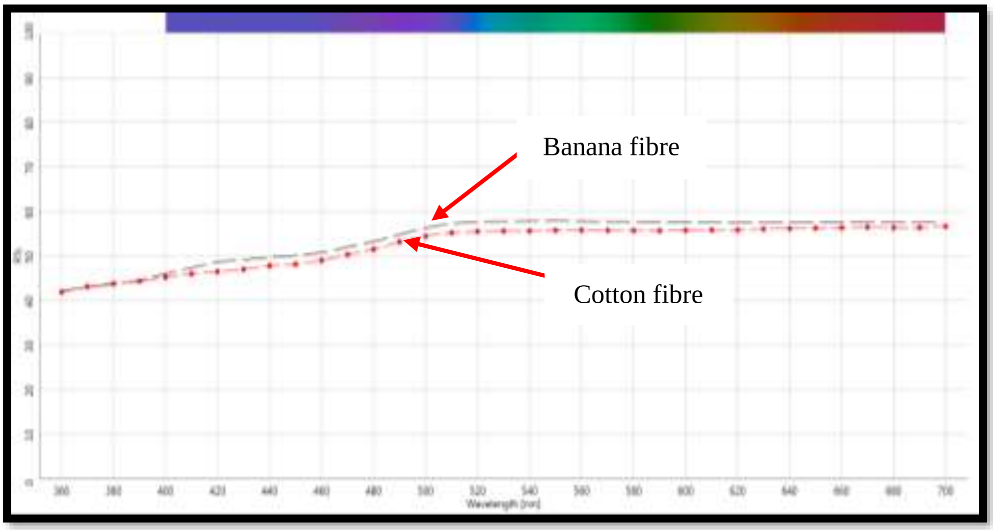


Figure 4-84 Reflectance values of dyed banana fibre (1 % yellow)

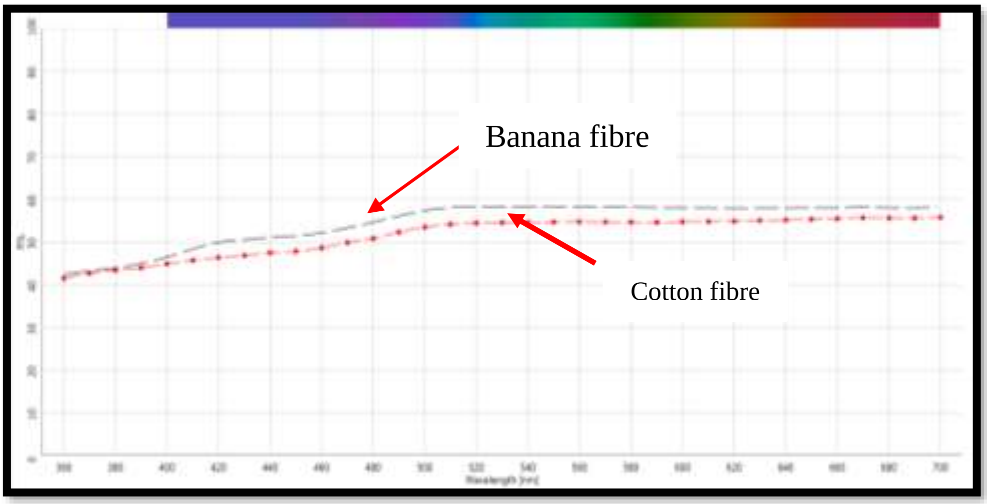


Figure 4-85 Reflectance values of dyed banana fibre (4 % yellow)

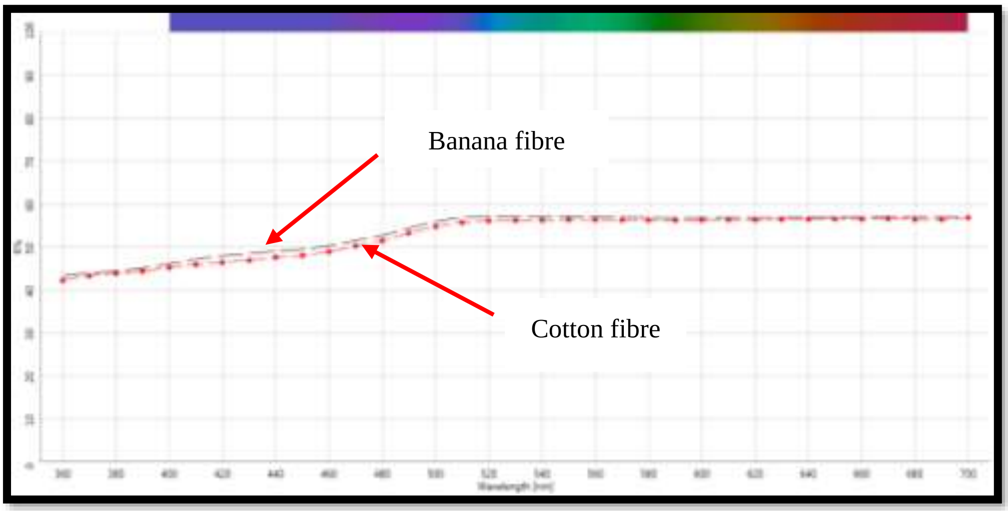


Figure 4-86 Reflectance values of dyed banana fibre (6 % yellow)

This reflectance curve results confirming the higher dye absorption tendency of dyed banana fibre than the cotton dyed fibre. This could be due to the high moisture absorbency of banana fibre. Reflectance values of all blue dyed and yellow dyed banana fibres were found higher than blue and yellow dyed cotton fibre samples.

Reflectance values of red dyed banana fibres were found similar to red dyed cotton fibre. This reflectance values conforms the higher dye absorption tendency of dyed banana fibre than the cotton dyed fibre. This could be due to the high moisture absorbency of banana fibre.

4.6 Fastness of washing properties of dyed banana fibres

Fastness of washing properties of dyed banana fibre samples were analysed and reported. Table 4-49 presents that, the washing fastness properties of dyed banana fibres. The fastness of washing rating also varied with type of colour and dye concentration. Dyed banana fibres revealed 4 (good) rating than cotton, nylon 6.6 and polyester type of fibres. Yellow dyed banana fibre showed 4-5 (very good) improvement results in fastness of washing. Fastness of Washing test results showed acceptable results, that there was a good fixation of the dye in the banana fibre.Consequently, it was determined that the banana fibre is easily dyed with reactive dyes. Generally, change in colour and staining on other material values 4 or above is satisfactory for the general usage. The banana dyed samples ratings were obtained for the degree of colour change better than the degree of staining.

Table 4-49 Colourfastness to washing results for banana dyed fibres

Dyed standard colours types	**Concentration**	**Colour change**	**Diacetate**	**Cotton**	**Nylon 6.6**	**Polyester**	**Acrylic**	**Wool**
Red dyed banana fibre	0.025	4- 5	4-5	4	4	4	4-5	4-5
	1	4- 5	4-5	4	4	4	4-5	4-5
	4	4- 5	4-5	4	4	4	4-5	4-5
	6	4- 5	4-5	4	4	4	4-5	4-5

Blue dyed banana fibre	0.025	4- 5	4-5	4	4	4	4-5	4-5
	1	4- 5	4-5	4	4	4	4-5	4-5
	4	4- 5	4-5	4	4	4	4-5	4-5
	6	4- 5	4-5	4	4	4	4-5	4-5
Yellow dyed banana fibre	0.025	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	1	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	4	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	6	4-5	4-5	4-5	4-5	4-5	4-5	4-5

Washing fastness test results showed acceptable results indicating that there was a good fixation of the dye in the banana fibre. The washing fastness rating also varied with the type of colours (Michael, 2016). Washing fastness test results were revealed satisfactory and it indicated good fixation of dye into the fibres (Raza *et al*., 2017) Consequently, it was determined that the banana fibre is easily dyed with reactive dyes. Considering the colour fastness values of washing test results, dyed banana fibres have satisfactory wash fastness qualities required for textile end-uses.

4.7 Comparison between treated fibres and dyed fibres.

Figure 4 -87 and 4 -88 shows the mechanical properties of raw banana fibre, pre-treated (Enzyme and chemical) and dyed banana fibres results. Pre - treatment process resulted 77.6% increase in fibre linear density and 9.7% increase in fibre strength compared to raw banana fibre. Dyeing process resulted 35% increase in fibre linear density compared to pre- treated banana fibres.

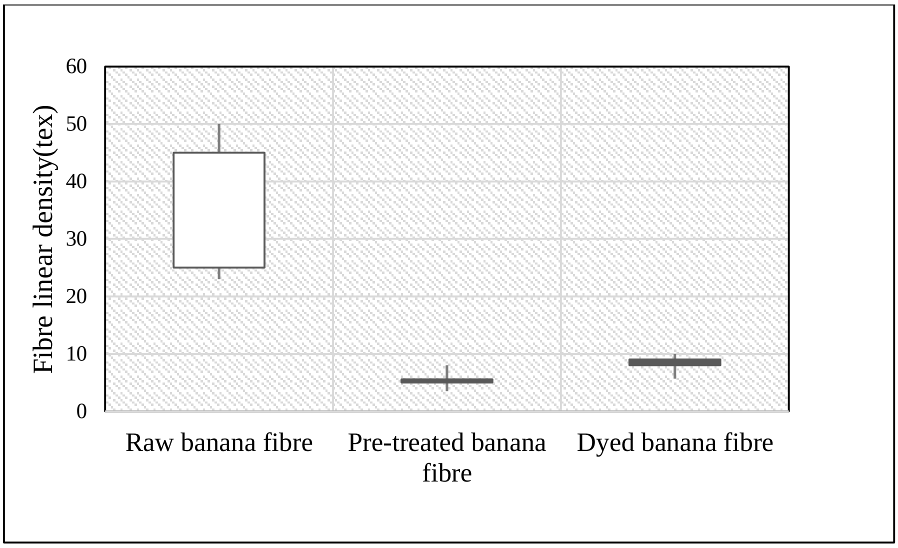


Figure 4-87 Fibre linear density results of treated and dyed fibre

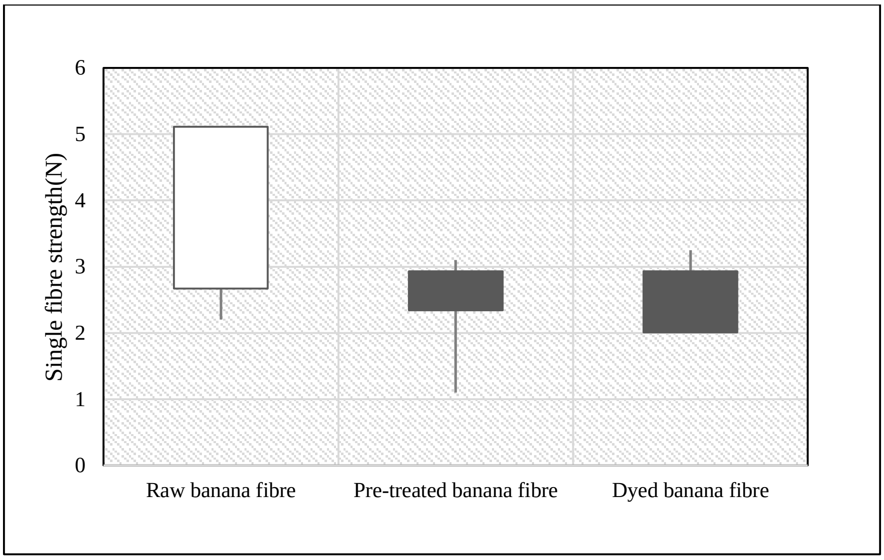


Figure 4-88 Single fibre strength of treated and dyed fibre

Figure 4 – 88 shows that pre-treatment and dyeing process reduced single fibre strength from 262.8 gf to 54.77gf which is about 79.5% reduction compared to mechanically extracted fibre. Pre-treated fibre single fibre strength is comparatively similar to dyed fibre single fibre strength. Enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined treated fibre and dyed fibre average value is 2.931 N. The results indicate that the linear density and single fibre strength of fibres is affected after the enzyme and chemical combined treatment. This treatment removes the lignin impurities and reduces the space utilized for impurities and result the reduction of diameter.

Pre-treatment breaks down phenolic compounds or molecules with chromophore groups present in lignin (Sheng *et al*., 2014). Lignin was oxidized and converted soluble in the solution through the 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined experiments. The moisture content of the raw banana fibre was very poor than the other plant fibres. Figure 4- 89 shows that pre- treated banana fibre moisture content were tested and found that the test results are superior to raw banana fibres.

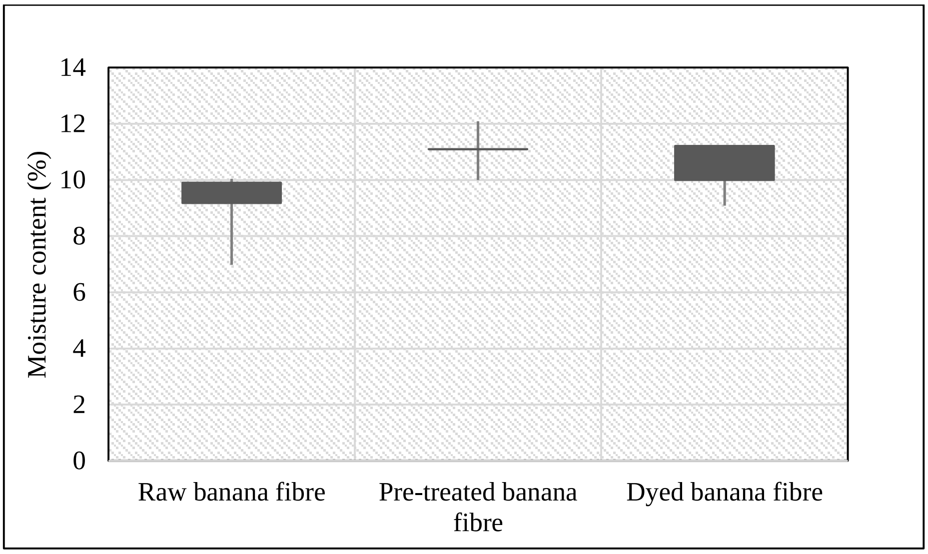


Figure 4-89 Moisture content (%) of treated and dyed fibres

As per the observation of SEM images of Figure 4-90, mechanically extracted fibres have an irregular surface and contains impurities. In addition, mechanically extracted banana fibres have a higher diameter around 140 µm compared to pre-treated and dyed banana fibres.

Figure 4-90 shows that pre- treatment reduces the diameter from 140µm to 48.86 µm which is about 71% diameter reduction compared to raw banana fibre diameter value. From the experimental results, the raw banana fibres have been improved their fineness by approximately 71%.

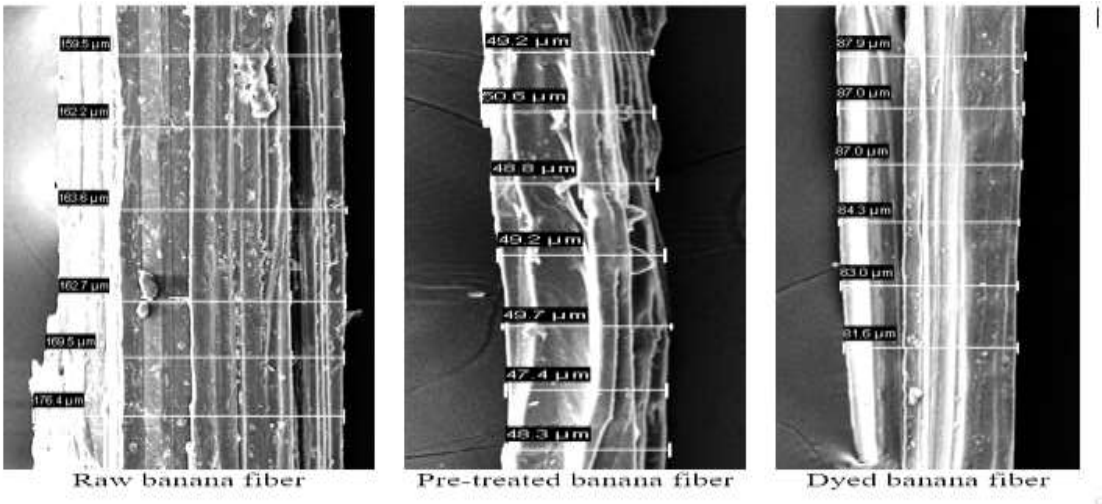
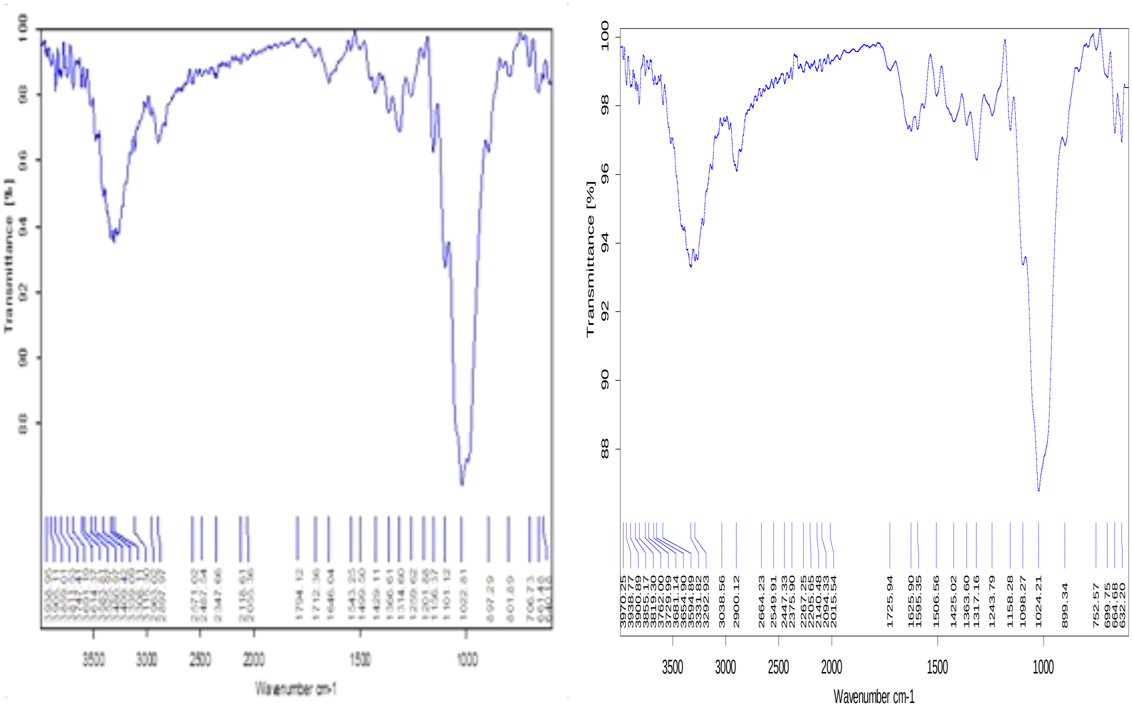


Figure 4-90 SEM images of treated and dyed fibre

Dyed fibre diameter was increased from 48.86 µm to 80.11 µm which is about 39% increase compared to pre-treated fibres.



Pre-treated banana fibre

Dyed banana fibre

Figure 4-91 FTIR spectroscopy graph of treated and dyed fibre

Figure 4-91 show that FTIR spectroscopy graph of raw banana fibre, pre-treated banana fibre and dyed banana fibre samples. About 25 absorption peaks were recorded in both raw banana fibres and treated banana fibres. The absorption band between 1730-1740 cm^{-1}, 1600cm^{-1} and 1636cm^{-1} and 1200-1300 cm^{-1} are particularly responsible for the hemicelluloses and lignin components (Joshi *et al.*, 2018). These characteristic absorption peaks are completely absent in the pre-treated fibre and dyed fibre FTIR spectrum. The FTIR results show that the removal performance of the lignin component is satisfying after the pre- treatments of banana fibres. Dyed banana fibre absorption band at 3600 cm^{-1} to 3200cm^{-1} region exposed the presence of a strong hydrogen bonded hydroxyl stretching peak which is due to the presence of strong covalent bond. In dyeing of fibres using the same recipe of primary three colours such as red, blue and yellow were applied on both cotton and banana fibre, resulting banana fibres achieved visually darker shades in blue colour when compared with the shades obtained on cotton fibres.

Therefore, a lesser amount of dye can be utilized in the dye liquor to get a specified shade on banana fibre material than cotton material. However, the brilliant colours and lustrous effects were obtained on cotton fibres than banana fibres. The readings of colour values are not same because of the variation of colour depth and variation of lustre of both fibres. In comparing the colour achieved on mechanically extracted banana fibre with the colour achieved on treated banana fibres, treated fibres give brighter shades. Therefore, treatment processes such as enzyme and combined scouring and bleaching treatments are essential to get brighter and darker shades on banana fibre with reactive dyes.

Reactive dyeing of banana fibre using exhaust method shows better colours strength and fibres become more lustre. Banana fibre reactive dyeing is darker and less saturated. The reflectance curve results establish that the dye absorption tendency of dyed banana fibre is similar to cotton dyed fibre. Dyed banana fibre washing fastness results varied with types of colours. However, the results indicate “good to excellent” washing fastness of dyed banana fibre. Therefore, the Reactive dyes on banana fibre give good colour fastness to washing property.

4.8 Chapter Summary

This chapter provides complete results and discussions from the experimental study. The overall findings of the studied testing results have presented. Results obtained from each experiment were collected and selected the best fibre extraction and treatment methods before the conclusion. Data accumulation is done by quantitative research methodology and experiments research strategies for this investigation.

Sri Lanka cultivates about 56,216 hectares under banana cultivation producing around 463 million tons of pseudostem waste per year. These waste stem can be lead effectively used for extracting about 160 billion tons of fibres. These extractable amount of fibres are a strong indication that Sri Lanka has the potential to extract banana fibres for the use of its textile industry. This chapter outlines the physical and chemical properties of ten selected banana fiber varieties in Sri Lanka. Fiber properties of the ten Sri Lankan banana varieties have not been researched and reported yet, hence this study aims to find the fiber properties such as fineness, tensile strength, chemical composition, fiber linear density, moisture content and surface structure. Mechanically extracted fibers show coarser fiber in nature. Comparing with other natural fibers such as cotton, very long fibers can be obtained from banana pesudostem. The tested banana fibers from different variety showed significant difference in physical properties. The colour of banana fiber varies according to the variety, from off-white natural colour to cream and have little lustre effect. These banana varieties of fiber diameter values vary from 78.02 µm to 214.4 µm. Fiber linear density varies from 25 tex to 36.2 tex. The tensile strength of these cultivars varies from 1.84 N to 2.67 N. The minimum diameter and fiber linear density was obtained from Ambun fiber (78.025 µm and 25 tex) and the maximum diameter and fiber linear density were recorded in Rathkehel fiber (214.4 µm and 36.2 tex).

This research investigates the factor influencing the quality of the fiber inside the banana pseudostem to determine which layers are suitable for delivering fine banana fiber. This research identifies the banana pseudostem layer-wise properties. Extracted banana fiber layer wise physical and chemical characteristics can be obtained. The characteristics of banana fiber vary with the position of the leaf sheath, method of extractions, species, and they are ecological conditions.

It is already done in India (Jayaprabha, *et al*., 2011) and Southern Highlands of Tanzania (Livifile *et al*., 2019) but not done in Sri Lanka. Jayaprabha *et al*., (2011) mentioned only for chemical composition, strength, fiber diameter and surface structure properties and Sri Lankan ecological condition also different from India and Southern Highlands of Tanzania. Livifile *et al*., (2019) reported that, peeling of these interior sheaths in full length is difficult because of their poor strength and brittle nature. Livifile *et al*., (2019) also mentioned, the banana fibers of the Southern Highlands of Tanzania revealed a slight variation in the number of pseudostem layers. The layer-wise stiffness properties show that a decrease from the outer to the inner part of the banana trunk and elongation at break increased. Inner fibers exhibit lower force at the break as compared to outer fibers. Such differences in properties were attributed to the reasons cited. This research study investigation middle layer was very strong, full length (stem height) and fine fibers than the outer layers. However, it is surprising to note that cited researcher have not taken the potentially useful step of experimenting the layer separation, FTIR analysis, linear density, moisture content and oil content properties of layer - wise banana fibers.

The linear density and diameter test results showed the middle layers of ambun and puwalu pesudostem fibres to be the finest. The results showed that the average linear density of the ambun middle layer is 25 tex, the average diameter value is 80 μm and range of single fibre strength is 273~270 gf. Moisture content was varying in between 9.9% ~9.7%. The results revealed that the average linear density of the puwalu middle layer is 29 tex, the diameter value was varying in between 98 to 100 μm and range of single fibre strength is 270~271gf. Moisture content of puwalu fiber was varying in between 10.9% ~9.9%. A high absorption band at 1736.39 cm^{-1} - 1026.36 cm^{-1} and 1606.06 cm^{-1} - 1732 cm^{-1} revealed the presence of first and fourth layer of ambun and puwalu fibers than the middle layers which is presence of lignin and hemicellulose component.

The conclusion of this research will help anybody to select suitable layer of Sri Lankan banana cultivars fibers based on physical and chemical properties.This study indicates that there was continuous reduction in linear density of enzyme treated fibres when the concentration of pectinase enzyme in the liquor were increased.

This research investigates the banana fiber extraction and treatment methods to improve fiber fineness to produce fiber suitable for textiles. Pectinase enzyme treatment of banana fibre with different concentration of testing shows that, with the increase in enzyme concentration, the fineness and strength was decreased. Enzyme treatment reduces the diameter from 168.4 to 101.45 µm and which is about 39.75 % diameter reduction. The linear density of banana fibre has also reduced from 25 tex to 21 tex. Enzyme treatment shows higher strength values (19%) than the other treatments and mechanically extracted fibres. Chauhan and Sharma (2014) reported that the minimum fineness and maximum strength (12 tex, 286 gf, and 15.6 tex, 381gf) was obtained which was treated with after 24 and 36 hours of pectinase enzyme. However, in the present research, the maximum fineness was 73.44 µm or 16 tex and the strength value is 162.3 gf which was treated with three days (72 hours) in the pectinase enzyme. Chemical treatment reduces the diameter from 168.4 µm to 60.5µm which is about 64 % diameter reduction. The linear density of banana fibre is also reduced from 25 tex to 18 tex. Chemical treatment resulted 10% increase in fibre strength compared to mechanical extracted untreated fibres. However, fibre strength decreases with increase of chemical concentration. Enzyme and chemical combined treatment have reduced the diameter from 168.4 µm to 48.86 µm and which is about 70.9% diameter reduction Treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined experiments show 5.6 tex linear density, diameter of 48.8 µm and strength value is 2.931gf.

Treatment of enzyme and 6% H_2O_2, 2% Na_2SiO_3, 3% NaOH, combined experiments shows higher ΔE values than the other treatments. The FTIR results show that the removal performance of the lignin component is satisfying after the enzyme and chemical combined treatments of banana fibres.

Dye ability of banana fibre results showed that pre-treated (Enzyme and chemical treatment) fibres become brighter (whiteness) than the mechanically extracted banana fibres. The results established that the color of pretreated and raw banana fiber results shows that there is a brighter color change, which is evidence of higher ΔE values.

The main problem to be encountered during dyeing process of banana fiber is the cementing material of lignin which interferes with the absorption property. Therefore, pretreatment process removed lignin impurities, which is proven that banana fiber dyeing behaviors are more similar to cotton dyeing.

Reactive dyeing of banana fiber using exhaust method shows better color strength and that fibers become more luster. Banana fiber reactive dyeing is darker and less saturated. The reactive dyes were achieved excellent color yields of banana fibers.

Furthermore, cotton reactive dyeing process can have successfully applied for banana fibers. Dyed banana fiber washing fastness results varied with types of colors. However, the results indicate “good to excellent”(4–5) washing fastness of dyed banana fiber.

This research will help future research scholars who are working on bast fibres to design their experiments. The outcome of this research will also help anyone to select suitable Sri Lankan banana fibres based on strength and finesse for textile materials.

5 SUMMARY, CONCLUSION, LIMITATIONS AND FUTURE STUDIES

5.1 Introduction

This chapter summarises the research conclusions, findings, implications, limitation and recommendations of the study. It is then followed by a proposed direction for future studies in this area.

5.2 Summary of the study

Plant fibres are cellulosic materials. Vast number of industrial applications are possible with the use of plant fibres, such as in the manufacturing of textiles, paper, packaging, etc. The banana plant is cultivated in mass quantities in Sri Lanka. Around 50,000 hectares of land is used for the cultivation of the banana plant. The fibre from the banana plant is an agricultural waste and due to the abundance of the plant in the island, it is recognised as a renewable resource of fibre.

The fibre material from banana plant has higher degradability in nature, hence it is environmentally friendly. The extraction of fibres from the banana pesudostem and conversion of these fibres into textile products are recent discoveries that has led to considerable interest of its usage around the world. The banana fibres can be used for the making of fine textile fibres. Even though it is vastly available and has benefits in its usage, the banana fibre is not utilized in the apparel industry in Sri Lanka due to the lack of knowledge of its applicability in the textile industry.

Therefore, the main goal of the current research was to investigate the suitability of using the banana fibre in the apparel industry in Sri Lanka. The banana stems were obtained from selected geographical areas that cultivate the banana plant in Sri Lanka. In this research, the banana fibres are separated from the discarded banana pseudostem, which is agricultural waste, by using an extraction machine. In line with the goal of the current research, different fibre extraction methods and treatments were utilized.

Apparel products are commonly made from fine fibres and microfibres. The fine fibres are the reason for the availability of softer, denser, and more comfortable apparels in the textile markets. The research discovered that extracted banana fibres are strong and coarser fibres. Furthermore, the study investigated the impact of the parameters of the treatment on the fineness of the fibre.

The results generated in this study are used to propose a suitable method to reduce the fineness to enable the use of the banana fibre as a textile material. The study successfully extracted the fibres from the waste created by the banana harvest using mechanical extraction, chemical and biological extraction or degumming methods. The biological and chemical treatments were carried out on the banana fibres that were treated with different concentrations of sodium hydroxide, sodium sulphide commercial softeners, hydrogen peroxide, wetting agent, turkey red oil and glycerine. Pectinase enzyme was also used in this study for the banana fibre extraction or degumming and treatment methods.

The study also used different instruments to conduct the experiments, namely tensile strength machine, scanning electron microscope (SEM), Spectrophotometer, X-ray diffraction and FT-IR spectrophotometer. The enzymatic extraction has proven to be useful for banana fibre treatment, since it resulted in an improvement of fineness of the fibre extracted. The results from the chemical extraction method revealed that the strength of the fibre decreased, affecting the fibre properties such as strength and fineness of the fibre. The combined treatment of biological and chemical extraction treatment on the other hand showed an improved fineness of the fibre fineness and had the least fibre linear density (5.6 tex) compared to the mechanically extracted fibres.

5.3 Conclusions

This investigation mainly studied the physical and chemical properties of extracted and treated banana fibres, the dyeability and the wash fastness properties to determine the suitability of the banana fibre as a textile raw material in the textile industry in Sri Lanka. Based on the laboratory tests carried out in this research, some of the textile properties of banana fibres were tested and identified as notable characteristics of banana fibre compared to other bast fibres.

The comparison between the bast fibres with that of the banana fibre was done to highlight that different varieties of the bast fibres were categorized based on their qualities. The data from the research also helps in selecting the correct treatment method to use with banana fibre for the use of different industries such as geo-textiles, fashion textiles, functional textile, interior textile, non-woven fabrics, fibreboard materials, insulation materials, reinforcement, filler, light-weight concrete, bricks and composites.

Identifying a suitable mechanical fibre extraction method

- Extracting fibres using the stripping method is not very suitable to extract long fibres like the banana fibre, due to the high percentage of fibre breakage.
- It was also discovered that the fibres extracted using the stripping method were not fine and it was difficult to extract large quantity of fibres.
- On the other hand, it was found that the Decortication fibre extraction method extracts 15 kg of fibres in 8 hours. This method provides fibre of superior quality in terms of length, softness, strength, and colour.
- Compared with the stripping process, the decortication fibre extraction method reduces the labour work, gives higher efficiency and increases fibre production.

Selection of banana variety

- The fibres from Embul (AAB group), Kolikuttu (AAB), and from the Cavendish subgroup Anamalu (AAA), Rath kehel (AAA) and Ambun (AAA), Atamuru, Seenikesel (ABB), Alu Kesel (ABB) and Poowalu (AB), Suwandel (AB) were investigated in the present study.
- They all showed similar properties in structure and morphology.
- The diameter of the mechanically extracted fibre through the SEM images showed it had a high variability.
- The diameter values from the ten cultivars of banana fibre vary between 78.02 μm to 214.4 μm.
- The fibre linear density varies from 25 tex to 36 tex.
- The tensile strength of these cultivars varies from 1.84 N to 2.67 N.
- The minimum diameter and fibre linear density was observed from the Ambun fibre (78.025 μm and 25 tex) and the maximum diameter and fibre linear density were recorded in the Rathkehel fibre (214.4 μm and 36.2 tex).
- Higher fibre strength was observed in the Atamuru, Puwalu and Ambun fibres.
- Higher moisture regains came from the Puwalu banana fibre (11.1%). And the lower moisture regain was observed from the Ambun, Atamuru, Ambul, Seeni and Kolikuttu cultivars (9.7%).

- The FTIR absorption bonds revealed that the cellulose and the non- cellulose components (lignin, hemicellulose and pectin) were present in these cultivars of banana fibres.
- Mechanically extracted fibres showed coarser fibre in nature.
- When compared with other natural fibres, such as cotton, it was discovered that very longer fibres can be obtained from the banana pesudostem.
- The colour of the banana fibre varies according to the variety of the cultivar, from off-white natural colour to cream and it was further observed to have little lustre in effect.
- The fibre linear density and diameter results indicated that the Ambun fibre was more suitable for extracting fine fibre in comparison to the other varieties used in this study.
- Furthermore, the linear density and diameter test results showed the middle layers of the Ambun pesudostem fibre to be the finest.
- The average linear density of the middle layer was found to be 25 tex, the average diameter value 79.8 µm and the average single fibre strength at 2.577 N. Hence, these middle layers of the Ambun fibre were used in the chemical and enzyme treatments.

Properties of biologically extracted fibre

- The biologically extracted Ambun fibre was found to have reduced its diameter from 357.9 µm to 140.23 µm, which is about a 60.8% diameter reduction compared to the diameter value of the mechanically extracted fibre.
- Biologically extracted Ambun fibre also had a reduced fibre linear density, from 25 tex to 18 tex and its strength was found to have increased from 2.577 N to 3.295 N, which is about a 60.8% improvement in its strength compared to the strength of the mechanically extracted fibres.

Properties of Chemically extracted fibre

- The chemically extracted Ambun fibres had their diameter reduced from 357.9 µm to 80.59 µm, which is about a 77.4% diameter reduction.
- Also it was revealed that the fibre strength was reduced from 2.577 N to 1.936 N, compared to the strength of the mechanically extracted fibres.

- The chemically extracted fibres had a reduced fibre linear density from 25 tex to 5.6 to 4 tex compared to those that were obtained from mechanical extraction process.

Properties of enzyme and chemical treated fibres

- The fibres treated using the Pectinase enzyme had reduced its diameter from 213.2 µm to 90.6 µm, which is about a 57.5% reduction compared to the mechanically extracted untreated fibres.
- The diameters of the biologically treated fibre had a comparatively higher value than the chemically treated fibre and its diameter was also lower than the mechanically extracted fibre (untreated fibres).
- The single fibre strength had reduced to 76.3% and the fibre linear density had reduced from 25 tex to 18 tex compared to the fibres from the mechanical extraction.
- The treatments using the commercial softeners (Silicone softener) showed an improvement in soft feel of the fibre, but the fibres subjected to the wetting agent, castor oil, turkey red oil, aloe vera gel and glycerine treatments did not demonstrate any huge distinction.
- The banana fibres were found to be resistant to alkalis when treated with a 75% concentration of H_2SO_4.
- The pectinase enzyme and the chemical combination treatment reduced the diameter of the fibre from 140 µm to 48.86 µm.
- The results from the experiment showed that the raw banana fibres had improved their diameter by approximately 71%.
- During the enzyme and chemical combined treatment, the cells are progressively divided. Therefore, the average diameter was reduced.
- Enzyme and chemical combined treatment have improved the strength from 2.577 N to 2.931 N and reduced the fibre linear density from 25 tex to 4 tex compared to the fibres obtained from the mechanical extraction method.
- The enzyme and chemical treated fibre that were analysed using the SEM images revealed that the fibrous bundles were not well separated in technical fibre and its surface was clearer.
- FT-IR analysis is attributed to the removal of some lignin from the mechanically extracted banana fibres.

- FTIR analysis of mechanically extracted fibre revealed the presence of non-cellulosic components such as lignin, hemicellulose and pectin, whereas the band is between 1738 cm^{-1} to 1600 cm^{-1}.
- The fibres treated with a combination of enzyme and chemical solution peaked at 1600 cm^{-1} and 1636 cm^{-1}, and were found to have absent in the FTIR spectrum which indicates the degradation of lignin components.
- The absorption bands between 1730-1740 cm^{-1} and 1200-1300 cm^{-1} are particularly responsible for the hemicelluloses and lignin components. These absorption peaks are absent in the enzyme and chemical combined treated fibre.
- Lignin was oxidized and converted in to a soluble in the solution through experiment that combined a 6% H_2O_2, 2% Na_2SiO_3 and 3% NaOH, solution.
- The data from the experiments conducted further revealed that the combination of enzyme and chemical treatment improved the hydrophilic behaviour of fibre.
- The results from the water absorbency test of the banana fibre revealed that the fibres have sufficient dye ability in order to carryout colouration and finishing processes satisfactorily.
- The banana fibres that were treated with enzyme and chemical process also showed that the lignin impurities were removed, which helps to prove that the dyeing behaviours of the banana fibre are more similar to that of the dyeing of the cotton fibre.

Dyeing properties of the treated banana fibres

- To understand the dyeing properties of the banana fibre, reactive class of dye was applied to the enzyme and chemical treated banana fibres.
- The exhaust method under the reactive dyeing of banana fibre shows that these fibres had better colours strength and more lustre.
- The reactive dyeing process of the banana fibre is darker and less saturated.
- The results from the reflectance curve established that the dye absorption tendency of dyed banana fibre is similar to the cotton dyed fibre.
- The results of the washing fastness of the dyed banana fibre varied with types of colours. However, the results indicate "good to excellent" washing fastness of dyed banana fibre.

The quality of the banana fibre and the grading system

- The banana fibres are graded according to its length, fineness, strength, colour and cleanliness.
- Golden yellow and dark in colour are two colour groups which were frequently present in the selected banana fibres.
- Ambun and Kolikuttu banana fibres are golden yellow in colour and lustrous.
- It is also important to note that the banana fibre is a low crimp fibre and there was no difference in crimp property amongst the banana varieties used in this study.

The treatment method that is suitable to use with banana fibres

- Out of all the treatment methods used in this study, the method with a combination of enzyme and chemical improved the fibre fineness (48.8 µm) and fibre linear density (4 tex) compared to the mechanically extracted fibre.
- Biological and chemical combined treatment were found to yield better results of fineness and strength which is suitable for yarn spinning.
- It was proven that the banana fibre fineness was better than the fineness of jute fibre, which is at 59.39 µm.
- The results revealed that the average breaking tenacity of the banana fibre was 53.37 cN/tex and tenacity of jute fibre was 4.4 cN/tex.
- Consequently, the tenacity of the banana fibre (52.31 cN/tex) is higher compared with the tenacity of the cotton fibres (25- 50 cN/tex). Banana fibres have sufficient strength to produce spun yarns with a lower twist insertion for weaving and knitting.
- Analysing the properties of the banana fibre is a prime requirement to determine the feasibility of utilizing banana fibres as textile raw material.
- Banana fibres can also be used as a non-woven textile material, which is another economic benefit of the fibre.

5.4 Implications

5.4.1 Implication of this research study

This research can be applied to look at the experiment designed, selection of fine fibre extraction methods, treatment types and the production of spinning machinery units for the manufacture of banana yarn. Furthermore, the research outcomes of this study highlights the practical implications of the banana fibres for the textile and apparel sector for countries like Sri Lanka.

5.4.2 Implication for Industry

The fashion industry has adopted the applications of banana fibres to get a competitive advantage in the market. Sustainable natural fibres are increasing in popularity and value by textile and apparel manufacturers due to recent global campaigns that focus on the environment safety when manufacturing garments. The end consumer must be engaged in order to develop and maintain an affinity for natural fibres.

The fibre industry has the potential to provide livelihood to the rural poor by generating employment. The banana fibre industry uses low cost raw materials and machinery. Industrialists can gather fibres directly from farmers or banana cultivators by providing fundamental raw materials and machinery, while training the rural populace about the manufacturing industry. According to bio-economy concept, entrepreneurs can supply fibre to make yarn for textile products. They can also help to manufacture paper, paper-based products and handicrafts.

5.4.3 Implication for Policy makers

Based on the conclusions reached by this research, the following recommendations are suggested for the textile and apparel sector in Sri Lanka. Currently, the world is focusing on minimizing the waste materials incurred through the apparel industry and to find ways to utilized the waste products.

In the textile and apparel industry, stakeholders of the synthetic textile fibres are in control of the industry due to the low-cost raw materials that they use. But it is now well documented how Synthetic fibres are non-degradable and create pollution. Even though many countries have already adopted the natural fibre for textile materials, gaining a distinctive advantage in the market.

Sri Lanka is yet to implement the use of natural fibre in the production of textile in its industry. To provide a sustainable textile raw material supply, many natural fibres have been identified and investigated to evaluate their suitability for the textile applications.

The textile industries need a sustainable material to deliver natural fibres to make yarn for textile products. In Sri Lanka, large quantities of banana plants grow in all seasons all over the country. Banana fibres are completely biodegradable and are environment friendly than synthetic fibres. Therefore, it is the view of this research that the Banana fibres from the pesudostem of the banana plant is a highly suitable export fibre source for the use in Sri Lankan textile industry.

5.5 Limitation of the study

This research used the most popular variety of banana, namely Ambul Kolikuttu, Anamalu, Rath kehel, Ambun, Atamuru, Seenikesel, Alu Kesel, Poowalu and Suwandel. For enzyme treatment only the pectinase enzyme was used.

Findings of this study was also limited by time constraint and limited to extracting textile feasible fibre. Data collection was limited to quantitative data.

5.6 Direction for future research

Banana fibres are not only integral to the textile industry but play an important role in economic development. The banana fibre decorticating machine extraction can be promoted among poor farmers and small rural entrepreneurs. Researchers have recently concentrated on developing the usage of banana fibres as a natural raw material. This has lead researchers acquire enough practical knowledge on extracting banana fibres efficiently and effectively from the pseudostem. They have found that these methods add value, decreases the cost of extraction, and motives the large-scale use of these fibres. Advanced technology needs to be developed in order to increase fibre yields from extraction processes.

Future scholars and researchers can examine the impact of better techniques on yarn spinning. Spinning trials with banana fibre combined with other natural or manmade fibres could be investigated. A research can also be carried out to find how characteristics of the banana yarn and blend fabrics differ mechanically and in terms of its comfort.

Researchers should also look in to further developing machines that can extract, treat, spinning and weave banana fibres that could help manufacture different products using the banana fabric.

A potential study can evaluate the properties of the banana fabric colour fastness and dye ability. An assessment of the cost and economic viability of the banana fabric and the improvement in fibre quality can be investigated.

A study could be carried out to investigate the percentages of major chemical constituents present in untreated and treated fibre samples. Furthermore, a study on banana yarn properties and durability analyses could be obtained and it can lead to an investigation on the enhancement of yarn hand feel, and quality of the fibre. However, to study the banana fibre and yarn quality further, an evaluation system should be standardized.

In conclusion, it is the view of this research that a future research ought to incorporate the use of the whole banana plant after organic product reaping is carried out. This would cover the use of the banana leaf, banana sap, banana fibre, and banana pulp as a raw material for the textile industry.

Publications

International Journals

S Balakrishnan, GLD Wickramasinghe, UG Samudrika Wijayapala, Investigation on improving banana fiber fineness for textile application, Textile research journal, Volume 89 Issue 21-22, November 2019

Impact factor: 1.926 : Scopus: Science citation (Expanded)

S Balakrishnan, GLD Wickramasinghe, UG Samudrika Wijayapala, Study on dyeing behavior of banana fiber with reactive dyes, Journal of Engineered Fibers and Fabrics, Volume: 14, Article first published online: October 22, 2019; Issue published: January 1, 2019.

Impact factor: 0.814 : Scopus: Science citation (Expanded)

S Balakrishnan, GLD Wickramasinghe, UG Samudrika Wijayapala, "A novel approach for banana (Musa) Pseudo-stem Fiber grading method: Extracted fibers from Sri Lankan Banana Cultivars"

Impact factor: 0.814 : Scopus: Science citation (Expanded)

S Balakrishnan, GLD Wickramasinghe, UG Samudrika Wijayapala, Physical and chemical characteristics of mechanically extracted banana (Musa) fibers from top ten Sri Lankan cultivars

Impact Factor -2.622 : Scopus: Science citation

International Conferences

S Balakrishnan, GLD Wickramasinghe, UG Samudrika Wijayapala, Influence of enzyme and chemical pretreatment processes on the colours of banana fibres, 5th International Multidisciplinary Engineering Research Conference, Date Added to IEEE Xplore: 29 August 2019.

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