DEVELOPMENT OF *LUFFA CYLINDRICA* NONWOVEN STRUCTURE AND ASSESSMENT OF ITS SUITABILITY AS A PACKAGING AND SHOPPING BAG MATERIAL

BY

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A Thesis Submitted To the School of Engineering, Department of Manufacturing, Industrial and Textile Engineering in Partial Fulfilment of the Requirements for the Degree of Master of Science in Textile Engineering

Moi University

2020

DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

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DEDICATION

I dedicate this thesis to **Mr. Wetaka William** my Grandfather.

ABSTRACT

Plastic packaging materials have been in existence since their invention by a Swedish engineer in the 1960s. Because polythene shopping bags can take up to 1000 years to degrade, they result in substantial and continuous deterioration of the environment. Some East African countries have initiated and some implemented the ban of polythene bags. It was upon this background that renewable and biodegradable luffa cylindrica nonwoven alternative was developed to help feel part of this gap. The objectives of the study were therefore, to extract *luffa cylindrica* fibres and to characterise its mechanical properties; and to produce a nonwoven structure from *luffa cylindrica* fibres and characterise their mechanical properties. The methodology entailed. The characterisation of *Luffa cylindrica* fibres in terms of fibre diameter, linear density, moisture regain, lignin content, hemicellulose content, cellulose content and effect of water retting, gauge length and concentration of sodium hydroxide on breaking load, elongation (ISO 5079:1995), tenacity and linear density(ISO 1973:1995). A dry laid adhesively bonded nonwoven structure was then produced from *luffa cylindrica* fibres and assessed for mass per unit area (ISO 9073-1:1989), thickness (ISO 9073-2:1995), tensile strength and elongation (ISO 9073-3:1989), tearing strength (ISO 9073-4:1997), and bursting strength (ISO 13938-2:1999). Full factorial experimental design was used to study *luffa cylindrica* fibres properties. Data analysis was conducted using Minitab-17 and Microsoft Excel 2010 software. The *luffa cylindrica* fibres had a moisture regain of 10.81%, lignin content of 12.03%, cellulose content of 65.69%, hemicellulose content of 19%, linear density range of (470-572) dTex, and fibre diameter of (0.0018-0.0041) mm. The determined breaking load of the fibre was (417.04-1444.19) cN after water retting and (298.05-997.81) cN after various caustic treatments. The fibre elongation was (4.0-24.0) % after water retting and (4.3-14.5) % after various caustic treatments. Tenacity of *luffa cylindrica* fibres was (6.0-25.25) cN/Tex after water retting and (5.9-20.22) cN/Tex after various caustic treatments. The nonwoven structure had mass per unit area (645-3386) g/m^2, thickness (1.48-1.80) mm, tensile strength of (1.4-110.2) N, elongation of (2.8-13.8) %, tearing strength of (2,292.5-47,952.0) mN, and bursting strength of (79.4-338.2) kilopascals. The nonwoven structure properties satisfied the requirements for bursting strength and tearing strength specified by Kenya Bureau of Standards (KEBS) for shopping bags. The study thus provides a possibility of using luffa *cylindrica* nonwoven structure as a potential substitute for polythene packaging and shopping bags on the Kenyan market.

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ACKNOWLEDGEMENTS

I am greatly thankful to:

METEGA for the study scholarship and **RUFORUM** for the research assistance.

Prof. D. Madara my main supervisor for her ceaseless guidance and encouragement during the course of this study.

Dr. D. Njuguna for always showing the right course of action whenever I was caught between the hard place and a rock.

Prof. S. Namango and **Prof. Tuigong** for their guidance and expertise they offered while I was still very naïve.

Prof. J. Igadwa for his parental guidance and humility which enabled my stay at Moi University worthwhile.

Mr. J. Khafafa the lab technician for his ceaseless availability, friendliness and dependability whenever he was needed. He is good person. God bless him in his ways.

Ms. A. Cherus for the warm welcome and great custodianship during the course of study at Moi University.

The staff members of Rivatex East Africa Limited for their hospitality and willingness to help whenever I needed any information relevant for my study.

CHAPTER ONE

INTRODUCTION

1.0 Introduction

This first chapter of the thesis contains the rationale for this study. It discusses the origin of the project ideas and the reasons as to why this study is relevant to both the society and the body of knowledge. It includes; background, statement of the problem, justification, aim, objectives and scope of the study.

1.1 Background of the Study

The global consumption of plastic bags stands at five hundred billion to one trillion bags per year which translates to approximately two million bags per minute (Keiren, 2015)**;** (Larsen and Venkova, 2014,)**.** These plastic bags range from the large trash bags, thick shopping bags and the thin grocery bags used in everyday life. Some of these plastic bags end up in landfills while most of it is transported by the streams and rivers to oceans. It is estimated that every square mile of the ocean contains 46,000 pieces of plastic bags, endangering more than 267 different aquatic species (www.reuseit.com, 2015)**.** The most affected of the species are the leather back tortoises which mistake the plastic bags for jelly fish, and fish when it gets trapped inside the plastic bags. Since the half-life of these plastic bags is over 500 years, it is possible that the same bag can find its way into several thousand aquatic animals before exiting the ecosystem.

In East Africa, the ban of plastic bags less than 100 microns thick was first announced by Rwanda in 2005 and eventually enforced in 2008 (McLellan, 2014). The same year (2005), Zanzibar banned the importation and distribution of polythene bags but enforced in 2006 (news.bbc.co.uk, 2008). In 2006, Tanzania announced a nationwide ban of plastic bags and enforced in 2013 after the East African Community Polythene Materials Control Bill, 2011 (allafrica.com, 2015). In Kenya, the ban on plastic bags was meant to take effect on the midnight of the 14th of June, 2007 as stated by the then finance minister of Kenya, in a bid to encourage industrial players to come up with innovative ways of developing shopping bags which are environmentally friendly. However, supermarkets and shops in Kenya still distribute up to 11 million plastic bags a year (www.southerninnovator.org, 2015). Uganda announced the ban on plastic bags in 2009 and was to enforce on 15th of April, 2015; however, this was called off after consultations with the Uganda Manufacturer's Association (UMA) because it could affect more than 14 companies (www.wbs.ug, 2015). The main reasons for the failure to enforce the ban on polythene bags in Kenya can be attributed to lack of proper research as regards the consumer's point of view after the retailers threatened to pass on extra costs of using alternatives of plastic bags to consumers in 2008. The absence of innovative alternatives and biodegradable bags which can serve the same purpose with minimal negative impact to the environment has also fuelled the delayed enforcement of the ban.

Therefore the need for research in the area of potential environmentally friendly materials for packaging bags suitable for the Kenyan shopping market is inevitable. Several fibres have the potential of producing such materials. In this study the focus was on *luffa cylindrica* fibres and environmentally friendly bonding agents.

Luffa (*luffa cylindrica*) gourd which comes from the Arabic word luff is sometimes called "dishcloth gourds" or "vegetable sponges." Luffa gourd is grown primarily for its fibrous tissue skeleton, commonly used as a bath or sauna sponge. The young fruits of less than 7 inches long are often cooked and eaten as squash or substituted for cucumber in salads (www.extension.umn.edu, 2016)**.**The oil extracted from luffa seeds has medicinal applications in products ranging from treatment of skin diseases to anti-tumour and skin cancer (www.essence-of-mineral-makeup.com, 2016)**;** (V.Sutharshana, 2013,)**.** In Uganda, 98% of the luffa in trade is used as bathing sponge and only 2% is used as a salad (Akankwasah Barirega and Patrick Van Damme, 24 November 2014,)**.** In composition, luffa fibres contain 60% cellulose, 30% hemicellulose and 10% lignin (V.Sutharshana, 2013,). The exploitation of this plant as textile raw material is very limited and yet it has great potential of producing enormous amount of fibre suitable for nonwoven applications. This study is aimed at filling this gap by ascertaining the possibility of including luffa gourd as a potential source of textile fibres through the project activities that are further discussed in the proceeding sections of this thesis.

1.2 Statement of the Problem

The use of synthetic bags for shopping has raised a lot of environmental concerns over the years. Some East African countries like Rwanda, Tanzania, Kenya and Uganda have banned these bags in a bid to control the environmental devastation which has been experienced with the usage of synthetic bags. Because it’s much cheaper to manufacture than to recycle (Robin Konie, 2015)**,** synthetic bags have managed to reach even the most remote areas in East Africa.

The environmental devastations caused by synthetic bags are both direct and indirect when considered in terms of outcome effects. Among the direct effects, synthetic bags lead to floods especially in urban locations and towns when they block the drainage channels; in a bid to destroy these synthetic bags, most people opt for burning. When burnt, polythene bags emit dioxin toxic fumes which pollute the air and present a danger of damage to human lungs when inhaled (Graham, 2012; Harkin, 2016). Indirectly, the storage of hot food in plastic bags (a common practice among urban dwellers) can result in the chemicals such as Bisphenol-A and dioxins to leach into the food and hence be ingested. When ingested over time, dioxins get fixed to human fats resulting in the potential to cause; tissue changes which may precede cancer in breast and prostate cells (UWERA, 2016), hormonal imbalance in the adolescents which may result in early puberty (eHow-UK, 2016). In addition to the aforementioned, plastic bags usage can increase the risk of heart disease, aggravate respiratory ailments such as asthma and emphysema, rashes, nausea, or headaches, damages in the nervous system, kidney or liver, and last but not least, changes in the reproductive and development system (WECF, 2012).

There is therefore a need to come up with an environmentally friendly nonwoven structure alternative which is cheap in terms of both production and purchase costs, durable in terms of reuse, and reliable in terms of strength and availability. With due consideration to the sustainability and ecofriendliness of biodegradable materials, it will be possible for *luffa cylindrica* nonwoven materials to slowly but surely contribute to the replacement of the synthetic materials.

1.3 Justification of the Study

The packaging in most urban supermarkets in Kenya is made of synthetic non-biodegradable material which is not environment friendly. It is thus necessary to develop an environmentally friendly nonwoven material which can cater for this vast market segment with consideration to sustainable environmental management.

Luffa cylindrica locally known as *muratina* is mainly used in Kenya as a bathing sponge, for cleaning utensils, and the immature gourds are used as vegetables. Preliminary observation showed that the fibre has very light weight and considerable wet and dry strength which enables its reusability as bathing sponge. In addition to its technical significance in the nonwoven fabric, luffa farmers will be able to generate more income from the sale of their products to the nonwoven manufacturers. Also, due to the simplicity of producing the nonwoven structure from this material, farmers involved in producing luffa can be encouraged to take up commercial initiatives of producing and supplying the nonwoven structures to the already available market demand in both Kenya and the East African region as a whole.

1.4 Aim of the project

The aim of the project was to develop an environmentally friendly *luffa cylindrica* nonwoven structure which can serve as an alternative to the plastic non-biodegradable packaging and shopping bag materials on the Kenyan market. The project used *Luffa cylindrica* fibres adhesively bonded using resins to produce a nonwoven structure which was assessed for its suitability as packaging material on Kenyan market.

1.5 Objectives of the Project

In order to achieve the above stated aim of the study, the project was scaled into two specific and realistic objectives. These are the objectives that helped to keep the project focused and controllable to achieve successful outcomes.

1. To extract *luffa cylindrica* fibres and characterise their mechanical properties.
2. To produce nonwoven structures from *luffa cylindrica* fibres and characterise their physical and mechanical properties.

1.6 Scope of the Project

This project report was therefore limited to obtaining *luffa cylindrica* fibres for the purpose of obtaining an environmentally friendly adhesively bonded nonwoven material as alternative material for the plastic packaging bags.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter of the thesis discusses the works of other researchers which were used for deeper understanding of the problem under study. Methods of extracting vegetative fibres and the characteristics of *luffa cylindrica* fibres, methods and the processes involved in the production of nonwoven structures, and testing methods of the produced nonwoven structure.

2.1 Global Concern on the Issue of Plastic Packaging and Shopping Bags

A plastic shopping bag is a polymer carry bag provided or utilised at the retail point of sale for carrying and transporting retail goods and which is only intended for one way use (PRO Europe, 2010). This includes all single use plastic retail bags, but excludes produce bags used in-store, dry cleaning bags, garbage bags and other primary product packaging. Plastic bags can be either non-degradable or degradable. Non-degradable Plastic bags are made from polyethylene derived from non-renewable natural gas and petroleum. Since it is more expensive to recycle than to produce(Blumenfeld, 2015), these Plastic bags often end in landfills where they take 300 to 1000 years to photo-degrade into toxic micro particles which leach into the soil and water streams(Jacobsen, 2015). Degradable plastics are often grouped into: biodegradable, photo/oxo degradable and compostable plastics. Biodegradable polymers are capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds or biomass by the actions of microorganisms(Greene, 2006)**.**The oxodegradable plastic bags are not biodegradable but are designed to break down into small pieces after exposure to oxygen. The problem with these plastics is that the smaller pieces may lead to environmental problems if they are consumed by animals or if the small pieces are scattered over the ground (Greene, 2015). Compostable plastics are materials that undergo degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and that leave no visible distinguishable or toxic residue (The California Integrated Waste Management Board, 2007).

Development of environmentally friendly shopping bags for the Kenyan market partly helps in fulfilling the Sustainable Development Goals (SDGs) 11, and 15(Osborn, 2015;ICSU, 2015). For SDG 11, Target 11.6, the biodegradable bags can make Kenya's cities more conducive for settlement through preventing waste build-up and the regular floods caused by plastic bags which clog the drainage channels. About SDG 14, Target 14.2, the biodegradable bags prevent the accumulation of plastics in the oceans; consequently, marine and coastal ecosystems become less tampered with and hence environmentally sustainable. Since more than half of the world's population now lives in cities with a projected share that will rise to 70 per cent in 2050,(Loewe & Rippin, 2015) the perception of city dwellers in Kenya is very crucial for effective management of the problem of plastic bags. This is because failure to integrate economic, social and environmental policies and objectives can result in a country's growth weakening progress on poverty reduction, increasing discrimination and consequently damaging the environment (IRF2015, 2013). Studies considering Consumers' perceptions and usage of shopping bags in connection with respective government's policies and implementation show that the involvement of the public's point of view avails a more positive likelihood of success as opposed to a blanket ban on plastic shopping bags (Muthu, 2012; Gupta, 2011).

2.2 Methods for Extraction of vegetative fibres and characteristics of *luffa cylindrica* fibres

2.2.1 Methods for Extraction of vegetative fibres

The extraction of plant fibres with extra vegetable composition often starts with decortication followed by retting. Mechanical decortication involves subjecting the plant part containing the fibres to a succession of blows to expose the fibres and soften the vegetable mass. Retting which is sometimes referred to as degumming is a process by which the fibres in the ribbons are separated from the woody component and from the extraneous green matter by the removal of pectins and other gummy substances (Rubina Daud, 1999,). Hänninen (2011), states that tensile strength of fibres extracted from fresh stems is lower than that of fibres extracted from retted stems (Tuomas Hänninen, 2011,).Retting can be achieved by: microbial treatment, (Jiajia Fu, 2011,)**;** (RK Dhanalaxmi and Jyoti V Vastrad, June 2013,) dew retting, (Nicolas Martina, 2013,) water retting, (A.G.L.A.S. Kumara, 2011,) pectinase enzyme (Jing Zhang, 2006,) and by applying chemicals (Ebisike K., Studies on The Extraction of Naturally-Occurring Banana Fibers,, 2013,). For the purpose of this study, water retting, enzymatic retting, chemical retting and mechanical retting techniques were reviewed.

2.2.1.1 Water retting

Water retting can be defined as a wet process by which bundles of cells in the outer layers of the plant are separated from non-fibrous matter by the removal of pectins and other gummy substances (Huda A. H., 2012,). Water retting is often preferred to dew retting because it produces finer and high quality fibres (Zofija, 2013,)**;** (Dave, 2014,). The stalks containing fibres are submerged in a pool of water for a duration ranging from 5 to14 days followed by a drying of 1 to 2 weeks (Müssig, 2010). However, by using river water or water from natural sources, the duration can be reduced to 3 days due to absence of chlorine which may interfere with the microbial activity (M. Di Candilo1, 2009,). During the period of immersion in water, either aerobic or anaerobic microorganisms hydrolyze the matrix carbohydrates binding the fibres together resulting in the release of the cellulose fibres. Such microorganisms are the Bacillus species which lead from the first 10 to 40 hours of the retting process followed by spore-forming anaerobic Clostridium spp. when oxygen concentration in water tanks becomes lower, and finally Clostridia, the major group of bacteria, which possesses pectin-degrading activity responsible for water retting (Nair, 2013). It is also possible to subject the materials to double retting which implies retting the materials aearobically for some time before submerging in an anearobic tank to complete the retting process (Fuller & Norman, 1946). The water retting process is considered labour and capital intensive at commercial level especially since the water from the retting process is often required required to be assesed and treated if neccesary before discharging to the main streams (Industrial Hemp in the United States, 2016). In cases where the water is carelessly dicharged, the fungi and bacteria responsible for retting accelerates the polluting process of natural water causing high turbidity and local chemical reactions that convert sulphates into foul smelling sulphides (Girija, 2011).

2.2.1.2 Enzymatic retting

This technique was originally developed by Sharma and his colleagues in Europe and the United Kingdom in the 1980s (Akin, 2013). Enzymes such as polygalacturonase (PG), pectin lyase (PNL), xylanase, pectinase and cellulose are used to remove the gum and pectin material from the plants (Biswapriya DAS, 2011,; Kyung Hun Song and S. Kay Obendorf, 2006). The process is carried out under controlled conditions based on the type of enzyme. Compared to water retting, enzymatic retting is preferable for its high selectivity of pectin degradation (A. Thygesen, 2013,).Proper enzyme selection and treatment often results in the hydrolysis of pectins and hemicellulases without damage to the cellulose fibres through the partial degradation of the components separating the cellulosic fibre from non-fibre tissues (Evans, 2002). The process is faster (12 to 24 hours) and cleaner but often produces fibres with low strength due to defects caused by the enzymes in the fibre structure during processing (Thygesen et al, 2013). However when compared to water retting, enzymatic retting is more complicated and costly (Martina, 2013).

2.2.1.3 Chemical retting

Chemical/physical retting consist of treatments such as boiling in Sodium Hydroxide, (Ebisike K., Studies on The Extraction of Naturally-Occurring Banana Fibers,, 2013,) boiling in Sodium Hydroxide in the presence of Sodium Sulphite, boiling in Sodium Hydroxide in the presence of Sodium Bisulphite , boiling in Sodium Hydroxide in the presence of sodium chloride, EDTA and Sodium Sulphite , boiling in Sodium Hydroxide in the presence of EDTA , boiling in Sodium Hydroxide after soaking in Hydrochloric Acid and boiling in Oxalic Acid at high pH and steam explosion (J. Hurren, 2002; H. S. Shekhar, 1988). The main limitation associated with chemical retting is the unfavourable colour and high processing cost involved as compared to water retting. Chemical retting produces coarse, rough to feel and relatively stiff fibres which require additional softeners which increase the cost of the process (Ahmed & Akhter, 2001). Chemical retting is however a quicker process than the natural processes of dew, water and enzymatic retting often taking 75 minutes to 1 hour when retting Kenaf, jute and flax (Umoru, 2014). In chemical retting process, the strength of the fibres has been found to decrease to a constant minimum as the concentration of the medium increases (Peter, 2015).

2.2.1.4 Mechanical retting

In mechanical retting, the fibres are separated by hammer mill or decorticator. In this process the leaves are crushed by a rotating wheel with blunt knives to produce massive quantities of short fibre in short time (Indu &Kumar, 2016). Decorticated fibres are dried under the sun light. The main limitations are high cost of machinery and lower fibre quality. It is mainly used for extraction of Kenaf fibres. An example of such machinery is a tractor-drawn harvester-ribboner capable of harvesting green plants, removing the leaves and low fibre top portion of the plant, decorticating the bark of the plant, bundling the core removed from the bark, and tying the decorticated bundles (Webber, 2002).

2.2.2 Textile applications and characteristics of *luffa cylindrica* fibres

Natural fibers are nowadays increasingly employed for making nonwoven materials for various applications; replacing the synthetic materials due to economic and environmental considerations (Lassaad Ghali, 2014,).

Luffa cylindrica is an annual climbing vine, which produces a fruit containing a fibrous vascular system (Aluyor, 2009). When separated from the skin, flesh and seeds, the fibre network can be used as a bathroom sponge. Luffa can also be used as packing material, for making crafts, and as filters. Because luffa has a compact network of close fibres, its resilience makes it useful for many products like filters, slipper soles, baskets. Luffa is environmentally safe, biodegradable and a renewable resource (www.caes.uga.edu, 2015; www.caes.uga.edu, 2015)**.** To obtain the fibres, it is necessary to subject the gourds to a retting process to separate the fibres from the extra pectin. A comparative study on different bast fibres showed that *luffa cylindrica* has a cellulose content of 66.59%±0.61%, Bagasse has 54.87%±0.53% and Banana fibre has 50.15%±1.09%. Cellulose crystallinity degree observed in *luffa cylindrica* fibres was

50%, Bagase was 48% crystalline and banana fibres had 39% cellulose crystallinity. The lignin content was 17.44%±0.19% for Banana, 23.33% ±0.02% for Bagasse and 15.46%±0.02% for *luffa cylindrica*. Sorption properties of banana and bagasse were 8.57±0.19 and 9.21±0.01, respectively very similar to cotton fibres, whereas *luffa cylindrica* had moisture content of 4.79±0.02 (M. Sfiligoj Smole, 2013,). In another study, *luffa cylindrica* fibres from the Aegean region of Turkey had 77.4% holocellulose, 63.0% α-cellulose, 14.4% hemicellulose and a lignin content of 1.6% (Seki, 2011).Figure 1shows the structure of *luffa cylindrica* fibres.

Figure 1: Structure of *luffa cylindrica* fibres (Laidani, 2012)

Alkali treatment of cellulosic fibres results in improved fibre-matrix adhesion in composite materials due to the removal of natural and artificial impurities (Ebisike et al, 2013). A study conducted in 2005 concluded that the Treatment of *luffa cylindrica* fibres with Sodium Hydroxide for a duration ranging from 10 to 90 minutes adequately modifies the fibre's surface (Valcineide et at , 2014; Valcineide et al, 2005); however, they did not explore the additional effect of water retting on mechanical properties of the fibres. A study conducted in 2012 involved the treatment of *luffa cylindrica* fibres with 0.1 M Sodium Hydroxide for 20 minutes in order to improve fibre hydrophilicity (López–Vásquez, 2012). Surface modification of areca and hemp fibres with Sodium Hydroxide has also been found to improve absorbency and mechanical properties of the resultant products (Sampathkumar, 2012; Mehta, 2005). A similar study involving the treatment of cotton with Sodium Hydroxide concluded that treated fabrics have better interfacial bonding between the matrix and reinforcement (Achukwu, 2015). A treatment of flax fibres with 5% NaOH for one hour at room temperature resulted in improved performance of the fibres with epoxy resins (Zhu, 2015). The improvement of properties as result of Sodium Hydroxide treatment stems from the ability to form a charged intermediate species between Sodium Hydroxide and the fibre (FIBRE-O-Na^+) which allows the faster nucleophilic addition of the matrix materials as illustrated in equation 1 (Cicala, 2010).

$\text{FIBER-OH} + \text{NaOH} \rightarrow \text{FIBER-O-Na}^+ + H_2O$ Equation 1*(Cicala, 2010).*

Besides surface modification, caustic treatment can result in the modification of the fibre internal structure of cellulosic fibres causing the fibres to have more voids and rough surface and hence reduced tensile properties (Mwaikambo, 2009). Ultrasonic and microwave surface modification techniques have also been studied on *luffa cylindrica* fibres (Şahinbaşkan, 2015; Merdan, 2012). Sanna et al (2015) established that the surface modification of foam formed cellulose fibres with plasma resulted in a positive adhesion effect at 8kW (Sanna et al, 2015). However no study explored the combined effect of water retting and Sodium Hydroxide treatment on the mechanical properties of *luffa cylindrica* fibres.

Gauge length is defined as the length in millimetres of the specimen under specified pretension, measured between two clamping points of the jaws of the holding clamps in their starting position at the beginning of the test (Indian Standard, 2000). Gauge length has been observed to affect the results of mechanical properties of textile fibres and the resulting structures in which they are employed. A study by Pardini et al (2002) stated that the tensile strength of carbon and glass fibres decreased at higher gauge length testing due to increase in flaw population (Pardini, 2002). Cui & Thibodeaux (2010) studied the effect of gauge length on strength of cotton fibres and obtained higher values at gauge length 3.2mm than at 13mm for the same test equipment and environment (Cui & Thibodeaux, 2010). Study on sisal revealed that strain-to-failure decreased from approximately 5.2–2.6% when the gage length was increased from 10 to 40mm while the tensile strength was independent of the gauge length (Silva, 2008). Fidelis et al (2013) study on jute fibres shows that the tensile strength is not influenced by gage length, but Strain-to-failure results were higher for the 20 mm gauge length and did not show significant variation for the lengths of 30mm and higher (Fidelis, 2013). Similar studies on Vietnamese coir, bamboo and Bangladesh jute fibres revealed that tensile strength and strain to failure decreases with an increase in the gauge length of the single fibres (Biswas, 2011). The decrease in tensile properties with increasing gauge length is because most natural fibres have voids or flaws which cause weak links. High length segment subjected to stress increases the probability of such defects consequently resulting in decreased strength at higher gauge length (Müssig, 2010; Jinchun, 2013). Bharani &Gowda (2012) observed that the increase in gauge length from 150 mm to 500 mm resulted in a continual decrease in yarn tenacity and breaking extension (Bharani & Gowda, 2012). Ghosh et al (1994) revealed that tensile properties of polypropylene nonwoven structure improved at higher gauge lengthof the polypropylene fibres (Gosh, 1994). This study intends to further explore the combined effect of water retting and varying concentrations of Sodium Hydroxide at different gauge length on the mechanical properties of the *luffa cylindrica* fibre.

Luffa cylindrica has found application as a carrier used for immobilization of microbial cells during the production of polymethyl galacturonase enzyme (Angelova, 1998) and fructose enzyme (Mahmoud, 2011). The seeds from the plant provide a good source of seed oils (Adewuyi, 2013) which can be used to produce soap for textile applications (Gafar, 2012). The fibres have also been applied as biofilm for supporting domestic sewage filters (Vianna, 2012). The filter potential of the luffa gourds in water quality analysis has also been investigated (Adie, 2013). *Luffa cylindrica* gourds have been studied to be good absorbents for phenol (Amin, 2013), methylene blue dye (López–Vásquez, 2012), cationic dyes (Boudechiche, 2016), Brilliant Green dye (Esan, 2014), divalent metals (Oboh, 2011) and toxic metals like cadmium (Lindino et al, 2014) from textile effluent.

Researchers have studied the use of *luffa cylindrica* fibres in composites as a matrix material with polyester resin (Valcineide, 2014), resorcinol formaldehyde (Parida, 2013), recycled low density polyethylene (rLDPE) (Paschal, 2015), and epoxy (Acharya, 2015) and a comparative study of the composites from the different resins has also been investigated (Contreras-Andrade, 2014). *Luffa cylindrica* fibres have also been studied for application as reinforcement in polymer concrete (Martínez-Barrera, 2014). Besides the use as a matrix, cellulose from *luffa cylindrica* fibres has found application as a binder in Acetaminophentablets (Macuja, 2015). The use of *luffa cylindrica* as a filler material has also been found to improve sound absorption properties of soft foam at frequency ranges of 540Hz to 6300Hz (Ekici, 2012). However, there is no study that has been conducted as regards the use of *luffa cylindrica* fibres in nonwovens suitable for packaging materials.

2.3 Production of Nonwoven Structures

From ISO 9092, nonwoven is defined as "a manufactured sheet, web or batt of directionally or randomly oriented fibers, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments or felted by wet-milling, whether or not additionally needled."

Nonwoven fabrics are the oldest technique of fabric production discovered around 3500-3000 BC as a felt of animal hair (Reeta Ghosh, 2014,). They essentially consist of fibres laid together by different bonding processes instead of weaving, knitting or crocheting. The processes are characterised by producing a fibre batt, bonding the batts to form a nonwoven web, and finishing the nonwoven (Dr. Kim Anderson, 2016); Singh , 2014). The desired properties and applicability of nonwovens is mainly influenced by choice of the fibres for developing the nonwoven, technological process of web production, methods of web bonding and finishing imparted to the developed nonwoven (Polona Dobnik Dubrovski, July / September 2005,; thenonwovensinstitute, 2016).

2.3.1 Batt formation methods

All nonwoven fabrics are based on a fibrous web which is arranged to form a batt (IIT Delhi, 2016). Batt characteristics depend on the web geometry, which includes the predominant fibre direction, whether oriented or random, fibre shape (straight, hooked or curled), the extent of inter-fibre engagement or entanglement, crimp, contact angle, fibre diameter, fibre length, web weight, and chemical interaction between the fibres and bonding agent employed (Winchester, 1970; Sayeb, 2013). There is a number of batt formation methods used in nonwoven technology today. Among these include; dry laying, wet laying, spun bonding and melt blown batt formation technologies.

a. Dry laid web formation

The most common form of dry laid web formation is carding, but heavier weight webs containing waste fibres are also commonly formed into webs using Garnett machines (Mr. S. Sakthivel, 2012,). Besides carding, aerodynamic processes which can carry and disperse the fibres through an air flow known as arilaying, and direct bonding of the fibres in staple form to produce compact structures with uniform aerial mass are also called drylaid webs (Tanchis, 2008). In a carded web the fibres are aligned more or less parallel to each other and to the direction in which the card produces the web. Such web is stronger when pulled lengthwise than crosswise because there is more friction between the fibres in lengthwise direction (Sakthivel S., 2014,).Dry laid webs can be longitudinal laid, cross-laid or random-laid. Sawhney et al (2012) concluded that random air-laid webs, when compared to the carded webs, consistently have a significantly higher tensile strength in the machine direction, with minimal difference in the cross direction (Sawhney, 2012).

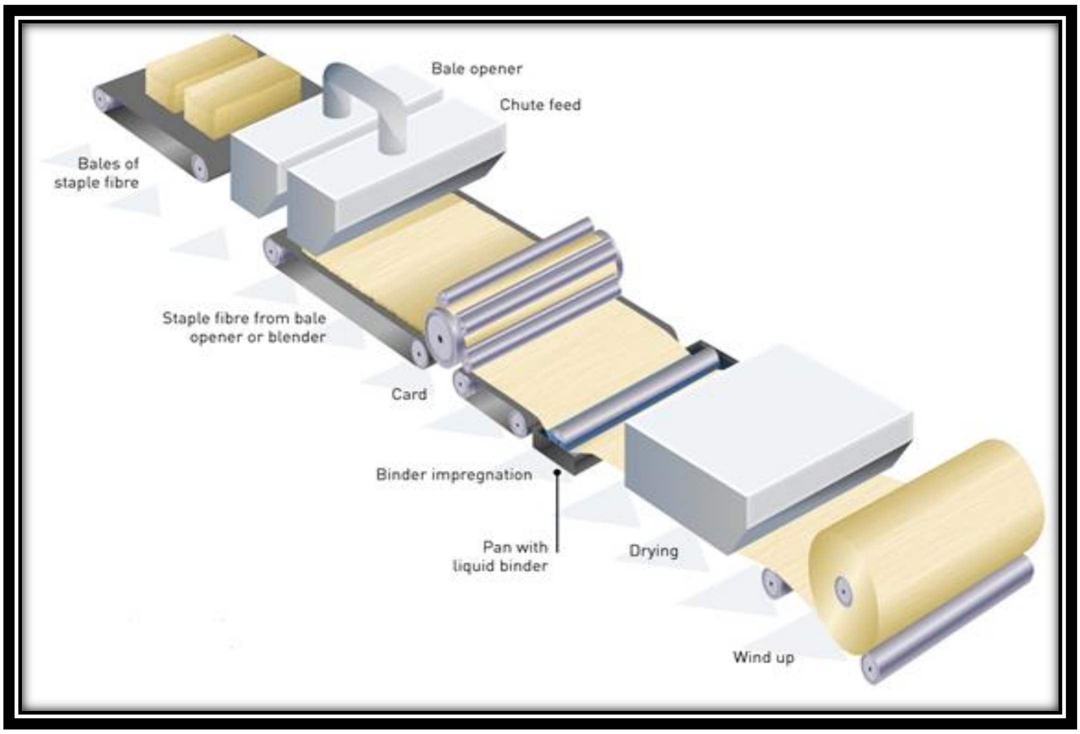


Figure 2: The drylaid process of nonwoven production (edana, 2016)

b. Wet laid web formation

Figure 3 shows the Wet-laid process of nonwoven web formation which has its origins in the papermaking process (Dahiya, 2004). Wet-laid nonwoven preparation method is simple and flexible in choosing raw materials and excellent uniformity provided the fibre has ability to disperse in wet-lay aqueous medium which can be water or a mixture of water and ethanol (Yin-Kui, 2013; Doh, 2013). There are three characteristic stages in the manufacture of nonwoven bonded fabrics by the wet-laid method: Swelling and dispersion of the fiber in water; transport of the suspension on a continuous travelling screen; Continuous web formation on the screen as a result of filtration; Drying and bonding of the web (Chengyan Zhu, 2013).Due to tangling issues in the water tank, fibres processed using the wet-lay system are required to be 6mm or less but some commercial products from the wet-lay process have been found with fibres of 35 – 50 mm in length (Hutten, 2007).

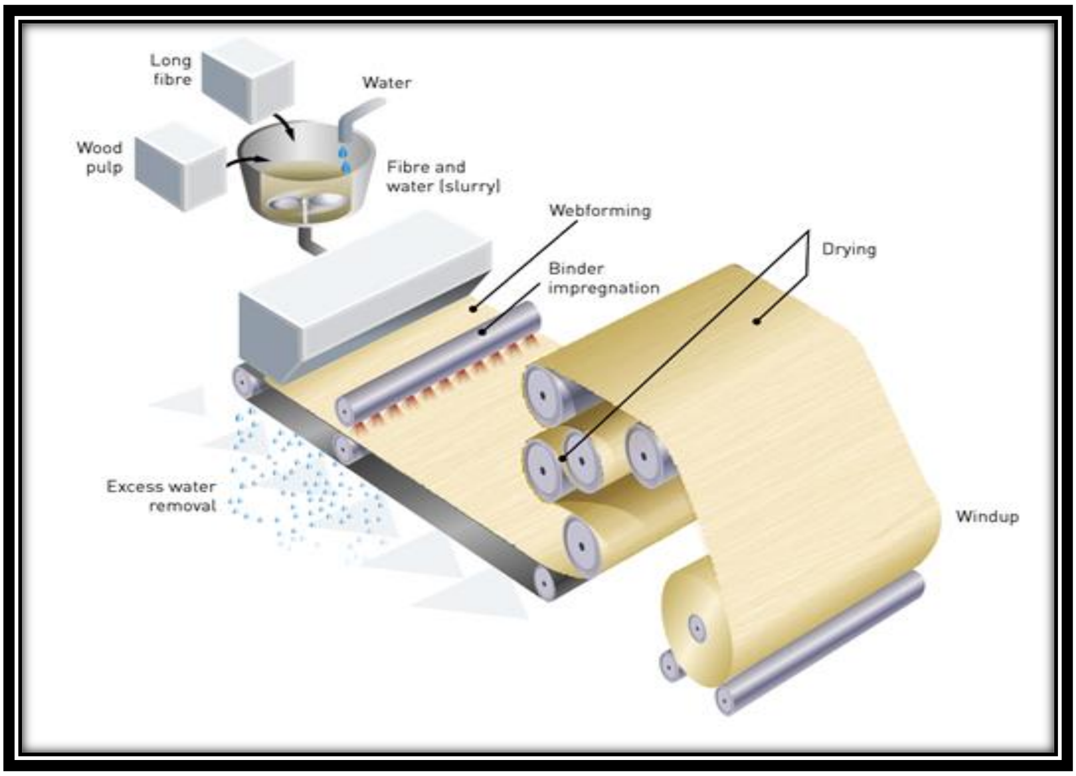


Figure 3: The wetlaid process of nonwoven production (edana, 2016)

c. Melt blown web

Figure 4 shows the Melt-blowing process of nonwoven web formation which involves a polymer being melted and extruded through a capillary or die consisting up to 40 holes per linear inch while heated air is blown through an air nozzle. The aerodynamic drag of the air jets on the polymer provides the attenuation force that draws the polymer streams into fine diameter fibres as they fall from the die (Lewandowski, 2007; Biovation LLC, 2016). The resultant web is collected into rolls and subsequently converted to finished products. These products are characterised by their unique micro structure, low porosity, absorbency, light weight and high surface area, making microfiber melt blown nonwovens materials of the future (Duran, 2012).

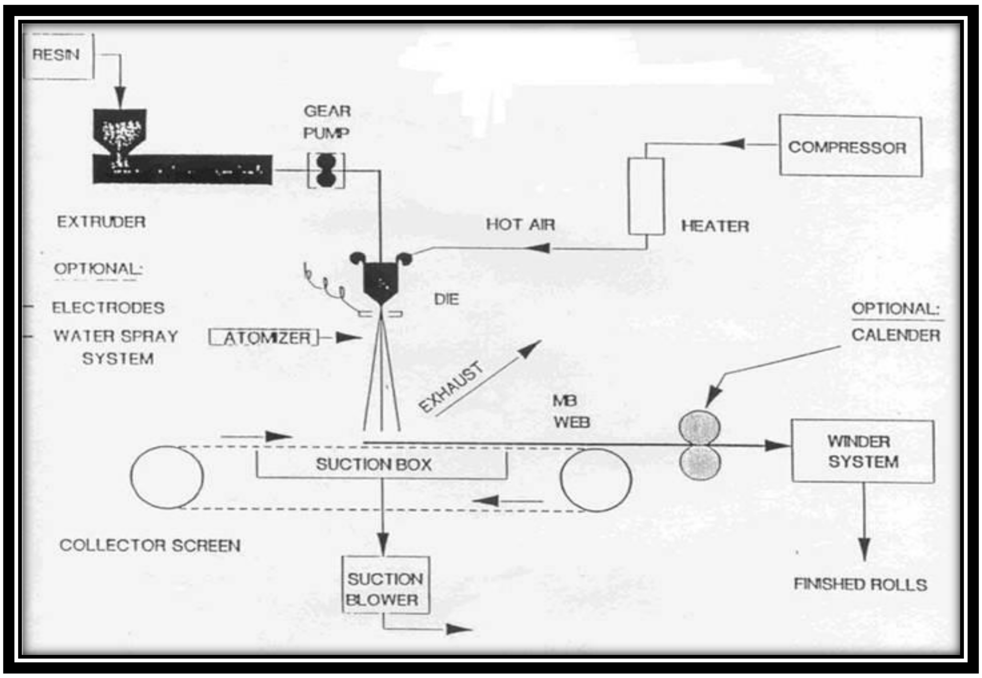


Figure 4: The melt blown process of nonwoven production(Dahiya, 2004)

d. Spun laid web

Figure 5 shows the Spun bond technology of nonwoven web formation which involves depositing extruded spun filaments of around 15–35 micrometer diameter onto a collecting belt in a uniform random manner followed by bonding the fibres (Dahiya, 2004; IIT DELHI, 2016). Bonding can be achieved using needle punching, hydroentanglement, chemical bonding as well as thermobonding depending on the required characterisitcs in the end product (Lim, 2010). For example in case of filters, needle punched strcutures showed better filtration efficieny as compared to thermobonded spun-laid nonwoven strucutres due to better pore size in the former (Das, 2009).

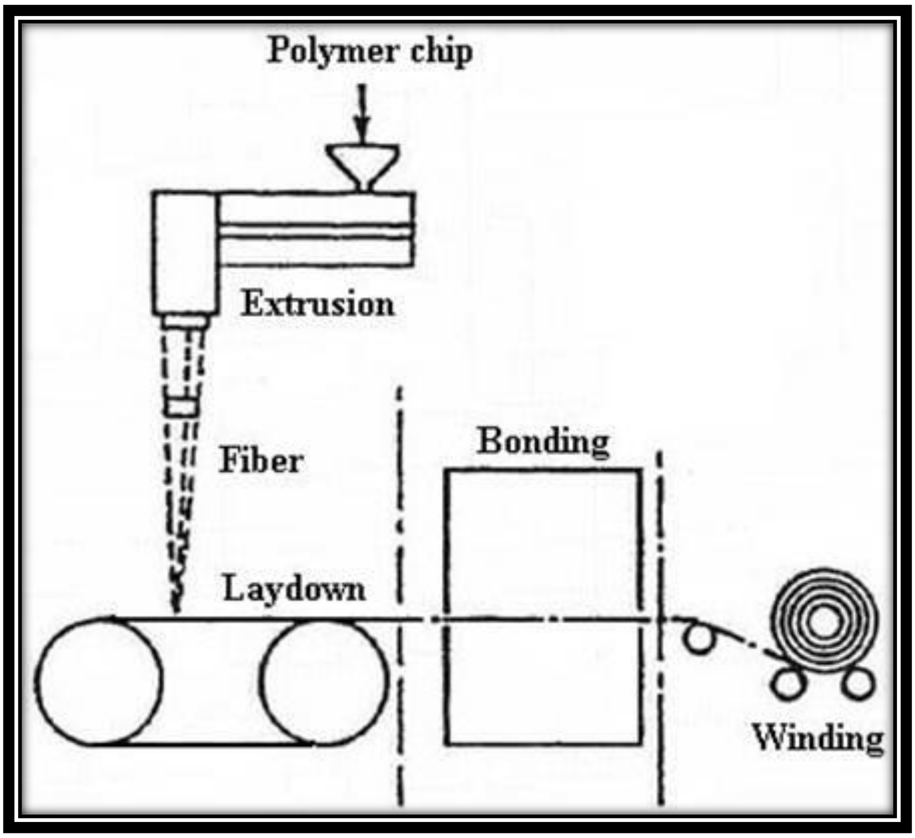


Figure 5: The spun laid process of nonwoven production(Dahiya, 2004)

2.3.2 Web bonding methods

A study conducted in 1995 shows that the tensile properties of nonwoven fabrics are governed by the bonding properties of the constituent fibres and not the fibre strength (Erik, 1995,). A bonding agent works as glue, as it binds the fibre laid web firmly together to make bonded nonwoven fabric (Reeta Ghosh, 2014,). There are several methods of web bonding but the choice often depends on the characteristics and required fabric quality in the end products.

2.3.2.1 Resin bonding.

Resin can be applied to nonwoven fabrics with the help of spray, impregnation and foam techniques. In the spray technique, the top of the batt is sprayed with resin, dried in the oven and then flipped so that the other side can be sprayed with resin, oven dried and cured before cooling, slitting and winding into rolls. The application of resin to batts using foam techniques avails a cleaner and most economical use of resin especially on materials exceeding 100 GSM. Resin can be added to the batt using a size press, as a liquid or foam, or spraying, or by rotary screen printing. The properties of webs bonded in this way depend on the base web structure and properties, the characteristics of the resin polymer - relative stiffness or softness, relative strength and resilience, the relative proportions of the bonding agent and substrate web after drying and crosslinking, and the method of addition (Atul, 2004)**.**The resin helps to bind the fibres in the nonwoven structure by means of adhesive forces. There are a number of theories that explain the phenomenon involved during adhesion.

Adhesion theories in the bonding of cellulose fibres include: mechanical interlocking, adsorption or wetting theory, chemisorption theory, electrostatic theory, diffusion theory, and the theory of weak boundary layers (Douglas, 2008; Beardmore, 2011). The mechanical interlock theory: This theory bases its argument on the porosity and surface roughness of the material as a result of crevices, cracks and pores (Packham, 2016). The adhesive penetrates these features and hardens such that it keys into the surfaces and forms a strong surface bond. For fibrous materials such as paper, cloth, leather, or wood, the theory provides an explanation which is demonstrably satisfactory up to micron level (Allen, 1993). However, this theory does not explain the adhesion phenomenon between smooth and resin compatible materials. It mainly considers the topography of the material and adhesive filling power (AdhesiveandGlue.com, 2016).

The adsorption theory: This theory is based on the assumption that the adhesive "wets" the surface of the adherent surface resulting in molecular contact between adhesive and material provided the respective surfaces are not separated by more than a distance of five angstroms (Petrie, 2008). Examples supporting this theory include epoxy resins which wet steel and result in a good bond - these resins do not wet PE or PTFE and result in a poor bond.(May, 1987). According to this theory, in the event of intimate contact between the adhesive and the adherent, the adhesive strength arises as a result of secondary intermolecular forces at the interface. These may include Van der Waals forces (dipole-dipole, dipole-induced dipole interactions and hydrogen bonds) (Butt, 2007-2008).

The chemisorption theory: This is a variation on the adsorption theory in that stronger chemical bonds (ionic, covalent metallic) form across the joint interface due to proper wetting of the substrate (May, 1987). Introduction of molecular bonding between the adhesive and the adherent results in improved adhesive bond strength especially when compatible agents between the adhesive and substrate are employed as additives. Such additives can be reactions at the substrate surfaces, using proper surface treatments, or by using additional coupling agents (AdhesiveandGlue.com, 2016).

The electrostatic theory: this theory was introduced by Derjaguin from the Soviet Union in the 1940s. It states that a free charge is formed when a material is condensed causing an electrochemical potential difference across the interface between two materials in contact. In the case of adhesive and substrate, free electronic or ionic charge carriers tend to move across the contact interface resulting in the formation of an electric double layer and corresponding coulomb attraction forces between the components in contact (Lucas, 2011; Gierenz, 2008).

The diffusion theory: this theory is attributed to the work of Voyutski and co-workers. It assumes that polymer molecule diffuse beyond the substrate interface to form mechanical locks to the surface of the substrate. However, this theory has limitations of unpredictability and the fact that it only considers the diffusion of adhesive to interface hence not suitable for explaining the adhesion to some impenetrable metal oxides (Oliver, 2013).

The weak boundary layer theory: This theory assumes that clean surfaces can give strong bonds to adhesives but the presence of surface impurities like rust, oils and greases results in formation of a weak cohesive layer. However, some acrylic structures have the ability to dissolve oils and greases (Adams, 2005).

a. Use of starch as bonding agents for cellulosic fibres

Figure 6 shows the chemical structure of starch, cellulose; 1-butyl-3-methylimidazolium chloride (BMIM-) and 1-alkyl-3- methylimidazolium (AMIM-) ionic liquid salts.

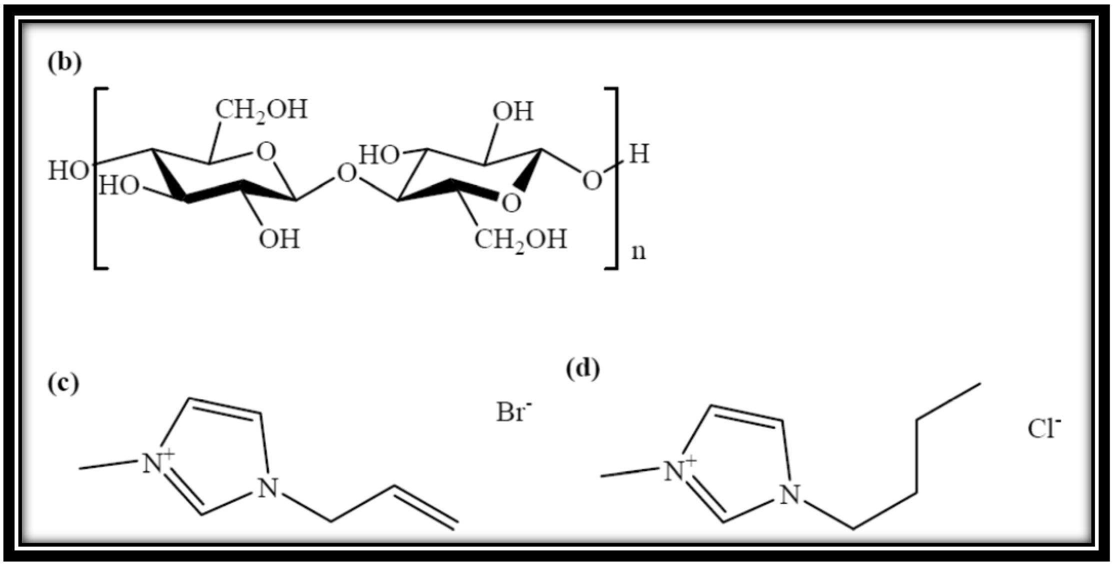


Figure 6: Chemical structures of (b) cellulose biopolymers as well as (c) AmimBr and (d) BmimCl ionic liquids.

Starch is a polysaccharide found in plants such as maize (corn), potato, cassava, wheat, and rice, represents a typical model with a naturally complex structure involving strong intermolecular hydrogen bonding (Zhanga, 2016). The physicochemical and functional properties of starch vary according to the amylose/amylo-pectin ratio and hence according to the plant source (Sylvia, 2015). A major source of starch is corn but it can also be extracted from potato, wheat and rice (Karmakar, 2014). The polymer is crystalline due to the presence of the amylo-pectin component (NGCC, 2016).Being hydrophilic in nature; the physical properties of starch based materials are dependent on air relative humidity (RH) during processing and storage (Rossana, 2010). There is therefore a tendency to modify the physical and chemical properties of the native starch in order to achieve desired end results (Abbas, 2010). Examples of these modifications include the treatment with emulsifiers to influence thermal stability and solubility (Qingyu, 2015), acetylation to improve solubility and swelling power (Ayucitra, 2012) as well as hydrophobicity and hydrophilicity (Rahim, 2015), a combination of acetylation and oxidation to produce a gel with more hardness than native starch (Khan, 2014; Nur & Purwiyatno, 2010), microwave treatment to improve pasting temperature enthalpy change of gelatinization (Stevenson, 2005), and cross-linking with ginger and garlic to decrease moisture, water and oil absorption (Sudhakara, 2014).In another study, addition of 30 pph citric acid as a cross-linking agent resulted in reduced moisture content and diffusion coefficient of the starch up to higher relative humidity values than starch films containing glycerol as plasticizer (Menzel, 2014). As the major component in most vegetable plant fibres, it is possible to dissolve and process starch with ionic liquids to give materials with tunable properties (Mehmet, 2014). As a result of the potential for modification of starch which leads to improved interactions between starch and other polymers, the use of starches in packaging materials has increased (Clerici, 2012).In this study, maize starch modified with ionic liquid and distilled water as plasticizers was used to bond *luffa cylindrica* fibres to produce a nonwoven structure. More emphasis was put on the effect of maize starch dissolved in ionic liquid on the mechanical properties of *luffa cylindrica* nonwoven structure. Figure 7 shows some of the possible modification that can be made to starch using ionic liquid.

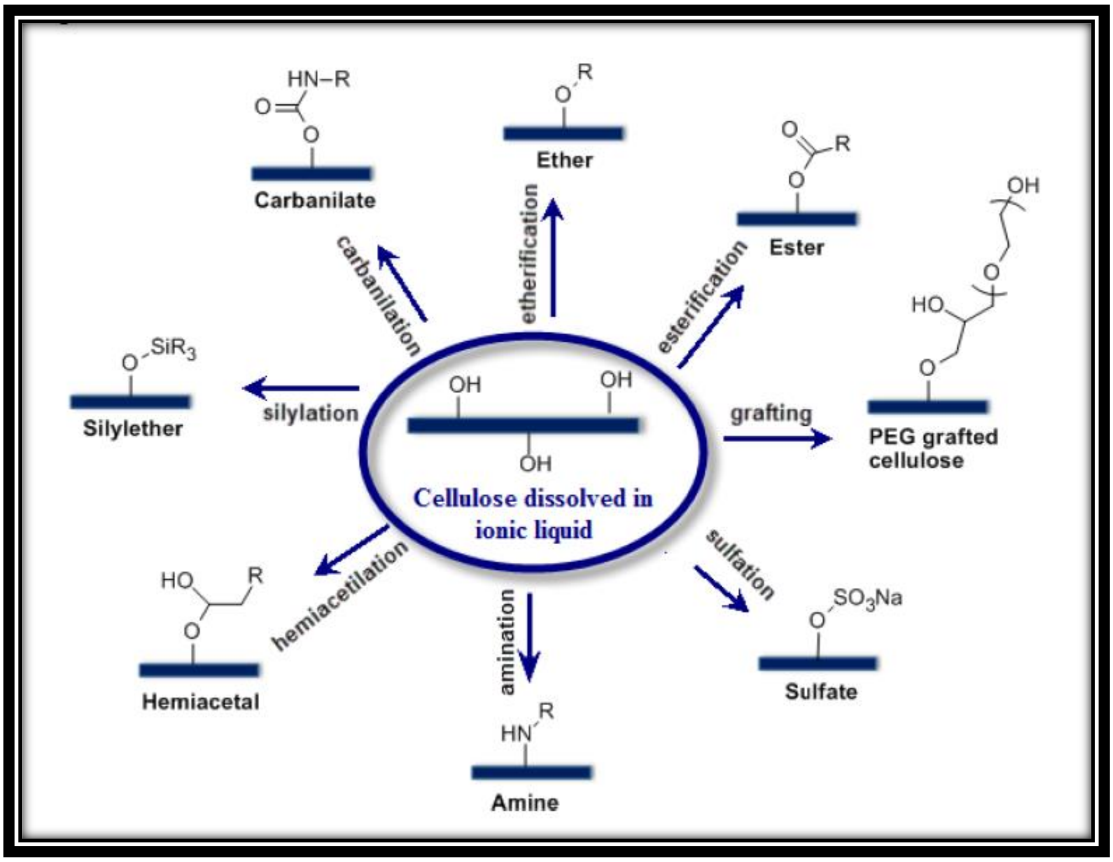


Figure 7: Possible chemical modifications that can be conducted to cellulose dissolved in ionic liquids.

Ionic liquids (ILs) are organic salts with melting point below 100 °C. They consist only of an organic cation and a smaller organic or inorganic anion. Because of unique properties, such as non-flammability, non-volatility, ionic conductivity, catalytic activity, thermal, chemical as well as electrochemical stability and recyclability ILs have attracted much interest in the last years (Zdanowicz, 2011; Daik, 2015). Deep eutectic solvents (DES) based on chorine chloride (ChCl) are good candidates for starch modification because they interact strongly with OH groups of glycosidic units, decrease chain interaction and plasticize the polymer. ChCl is nontoxic and readily available as a bulk commodity chemical (vitamin B4). Starch is soluble at 80 ^{o}C in ionic liquids such as 1-butyl-3-methylimidazolium chloride (BMIMCl) and 1-butyl-3-methylimidazolium dicyanamide (BMIMdca) in concentrations up to 10% (w/w) (Biswas, 2006).1-alkyl-3- methylimidazolium ionic liquid salts have been the most promising as regards the homogeneous chemical modification of cellulose (Liebert & Heinze, 2008). However, 1-ethyl-3-methylimidazolium acetate is the most commercially available ionic liquid due to its lower viscosity and high cellulose dissolving ability (Mehmet, 2014).

Through chemical grafting, potential replacements for petroleum-based materials can be developed with such properties as; temperature responsiveness, hydrophobicity and oleophobicity, flexibility, sorbancy, ion exchange capability and polarization (Mehmet, 2014). 1-butyl-3-methylimidazolium chloride has been used as a solvent to blend cellulose with starch. Mixtures containing different cellulose-starch ratios were prepared and films were obtained by casting the homogeneous solution in between two glass plates followed by the removal of the solvent with acetone or ethanol. Natural biopolymer wool has as well been blended with cellulose by dissolving both materials in a mutual ionic liquid solvent such as 1-butyl-3-methylimidazolium chloride. The solution containing both materials was precipitated in water giving a composite material with better thermal stability than the individual components. The mechanical strength of the composite was improved with increasing cellulose content and the elongation at break values were considerably enhanced with respect to individual components (Mehmet, 2014).

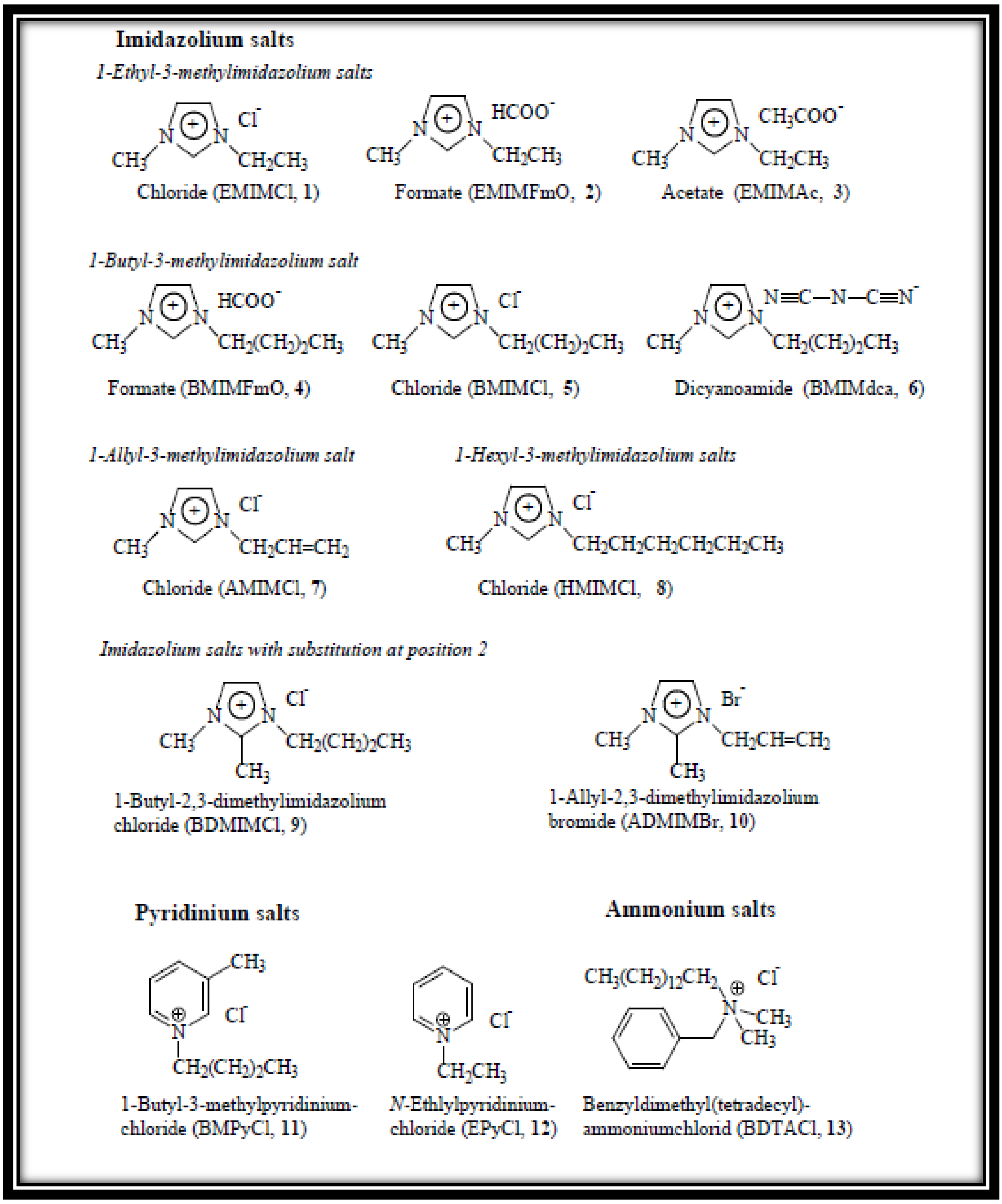


Figure 8: Ionic liquids suitable for desolution of cellulose(Mehmet, 2014)

b. Use of vinyl acetate emulsions as bonding agents for cellulosic fibres

An emulsion is a mixture of two immiscible substances. One substance (the dispersed phase) is stably dispersed in the other (the continuous phase) by a dispersed effect of the surfactant (Sumika Chemtex Company, 2016). Emulsion polymerization products like; poly(vinyl acetate) emulsion homopolymer and vinyl acetate based emulsion copolymers have a great importance in industrial aspect as well as scientific aspect because of their good durability, availability at low cost, compatibility with other materials, excellent adhesive characteristic, environmental friendliness, and ability to form continuous film upon drying of the emulsions (Berber et al , 2013; Berber, 2013).

Emulsion polymerization is a complex process in which the radical addition polymerization proceeds in a heterogeneous system. This process involves emulsification of the relatively hydrophobic monomer in water by an oil-in-water emulsifier, followed by the initiation reaction with either a water-soluble or an oil-soluble free radical initiator. At the end of the polymerization, a milky fluid called “latex”, “synthetic latex” or “polymer dispersion” is obtained (www.britannica.com, 2016). In the synthetic latexes, the most important groups are styrene/butadiene copolymers, vinyl acetate homopolymers and copolymers, and polyacrylates. Other synthetic latexes contain copolymers of ethylene, styrene, vinyl esters, vinyl chloride, vinylidene chloride, acrylonitrile, cloroprene and polyurethane (Berber, 2013).

Many applications of emulsion polymers such as paints, floor polishes, inks, varnishes, carpet backing, paper coatings, and adhesives, lead to the isolation of the polymer by the removal of water. By this way, latex is transformed into a polymer film. The film formation process of latex occurs in three major steps: first, the polymer particles become into close contact with each other by evaporation of water. Second, as more water evaporates, the particles undergo deformation to form a void-free solid structure which is still mechanically weak. Last, fusion occurs between adjacent particles to generate mechanically strong film. In many applications, the key stage is the transition between wet, dispersed polymer and dry film (Berber, 2013).

VAc copolymers have been developed by using many kinds of comonomers such as ethylene, acrylates, maleates, vinyl chloride and versatic acid esters. VAc is polymerized exclusively via free-radical polymerization. These resins are inherently flexible, tough and clear (http://www.dupont.com/, 2016).

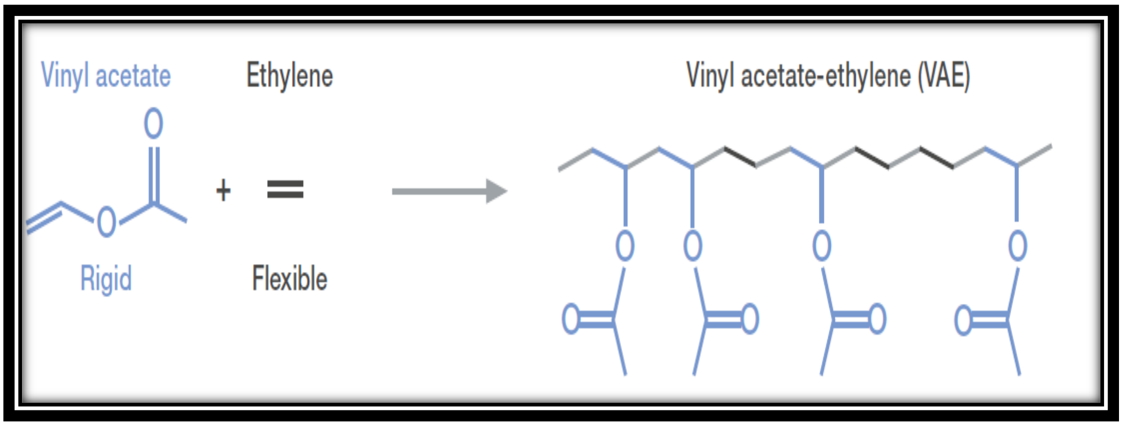


Figure 9: Example of vinyl acetate copolymer (Wacker, 2016)

The most commonly used process in the industrial practice of VAc emulsion polymerization is the delayed addition method in semi-continuous process. In this method, 5-15% of the VAc monomer is added into the reactor with some of the ingredients such as water, emulsifier and initiator at start. After the particle-generating period is completed, the remaining ingredients are added incrementally during the polymerization process (Guo, 2009).

In the emulsion polymerization of VAc, the most commonly used initiators are the water soluble, thermally decomposed, free-radical producing persulfates (peroxodisulfates) such as potassium-, sodium-, and ammonium-persulfate. The emulsion polymerization of VAc monomer, an amorphous, non-crystalline and thermoplastic polymer is obtained. Polyvinyl acetate is soluble in alcohols, ketones, aromatic hydrocarbons and ethers. It can be also solubilized in emulsifier solutions. It absorbs 3 to 6 w/w water between 20 to 70 ^{o}C within 24 hrs. Moreover, in the presence of water, it can hydrolyze to form vinyl alcohol units and acetic acid, or the acetate of the basic cation (Erbil, 2000).

Due to these properties of the Vac homopolymer, VAc is copolymerized with other monomers such as ethylene, n-ethyl acrylate, n-butyl acrylate, 2-ethylhexyl acrylate, methyl methacrylate, vinyl chloride, vinyl propionate, vinyl versatate, maleates (dibutyl malate), fumarates, and acrylonitrile to improve the poor properties of this polymer. Terpolymers of VAc are also widely produced. The selection of comonomers to be used to produce VAc copolymer latexes for any given application depends principally upon the functional suitability of the comonomer and its cost. As well as the VAc homopolymer latex, the VAc based copolymer/terolymer latexes are widely used for exterior and interior architectural coatings, adhesives, textile and paper industry, and numerous other applications (Berber, 2013; USAdhesive.com, 2016).

This study used Synemul TB 341 which is a VAM-Veova Emulsion (Synresins Limited, 2016) as a bonding agent in the production of a nonwoven from *luffa cylindrica* fibres. This is because the emulsion exhibits excellent binding properties coupled with excellent colour holding potential and tough bonding to fabrics when used in textile printing (Synresins Limited, 2016). Upon disposal, the emulsion can partition on exposure to air where it is rapidly degraded without any likelihood of bioaccumulation (The Dow Chemical Company, 2014).

2.3.2.2 Thermal Bonding

The basic idea for thermal bonding was first introduced by Reed in 1942 (Mahmut Kayar, 2014,). Originally, rayon was used as the carrier fibre and plasticized cellulose acetate (PCA) or vinyl chloride (PVC) as the binder fibre. Thermal bonding requires the batt to contain a synthetic bonding fibre in form of bi-component of fibre blend to facilitate bonding upon heating for example polyethylene fibres acting as bonding fibres in blend with polypropylene (Ghosh, 1994). The batt containing the synthetic fibres is compacted and transferred to an oven which softens and melts the fibres to facilitate bonding of the various batt components. The bonded nonwoven is then calendared to the correct thickness, cooled and transported to the slitting and rewinding system. Thermal bonded nonwovens exhibit considerable bursting strength but low elongation at break (A N Desai and N Balasubramanian, September 1994,).Thermal bonding finds wide use in spun bond, melt blown, air-lay, and wet-lay manufacturing as well as with carded-web formation technologies (Michielsen, 2005).

2.3.2.3 Hydrogen-bonding.

Hydrogen bonding is based on the ability of cellulose fibres to bond together when naturally occurring moisture contained in the fibres is removed while the fibres are in close contact. The bonding is achieved with the help of high temperature and pressure. This technique provides the advantage of eliminating the need for synthetic binders often added to the air laid web; hence ensuring minimal changes in the desirable fibre properties.

2.3.2.4 Needle punching

Needle punching technology is the most ideal method for converting un-spinnable fibres like sisal and coir into nonwoven fabrics (Indu & SenthilKumar, 2016). Bonding is achieved through the use of mechanical needling of the fibre web with softer and more absorbent structure which has the ability to retain and release fluid (Andrew Slater and Dr. Andrew Wilkes, 2003,). These properties however depend essentially on needling machine parameters such as needle gauge, punch density and depth needle penetration (Ghali, 2014). In a study involving jute based nonwovens, a needle depth of 10mm, punch density of 250 punches/cm^2 and area density of 700 g/m^2 resulted in optimal mechanical properties of the final jute/polyester composite material (Sengupta, 2008). Higher needle punch penetration depth results in low porosity of the needle punched nonwovens which in turn lead to enhancement of thermal conductivity of the structure (Ghane, 2015).

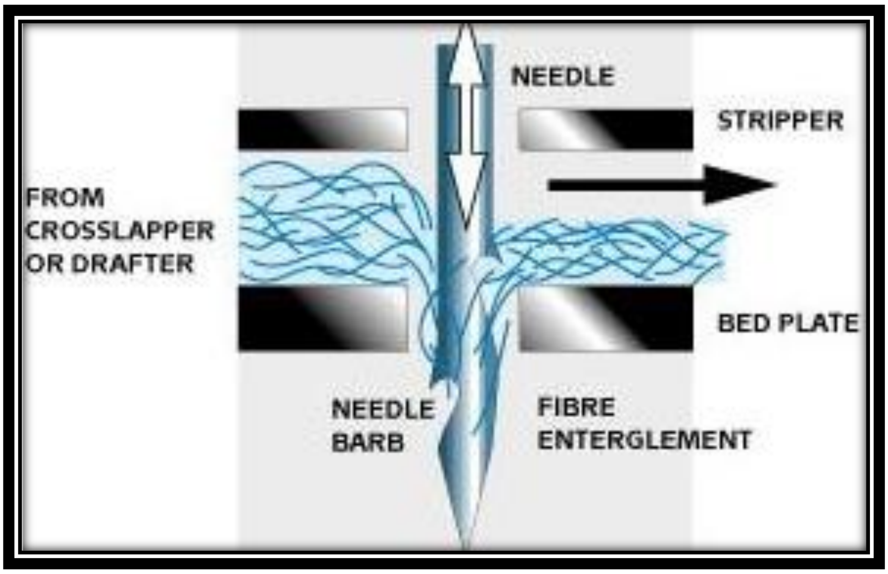


Figure 10: Schematic diagram showing needle punching (http://www.tikp.co.uk, 2016)

2.3.2.5 Multi-bonding

Multi-bonding is a combination of resin and thermal bonding. The web is thermally bonded and a light application of latex is sprayed on both sides of the web to reduce the lint that is often released in high-speed converting operations (Dan-Web, 2016).

2.3.2.6 Hydro-entanglement

Figure 11 shows the hydro-entanglement process of web bonding which involves various fibrous webs being uniformly hydroentangled using a fleissner minijet system equipped with one low water pressure jet head for wetting out the feed material and two high water pressure jet heads. The first jet impacts the substrate material on its top face and the other on its bottom face. The low water pressure head is set to inject the water at 50 bar and the two high water pressure heads are set at 125 bar. The hydroimpacted/entangled material/fabric is dried using a meter-wide, gas-fired fleissner through-air drum dryer and finally wound on to a tube to form a compact roll of at least 50 meters of the fabric (Sawhney, 2012).

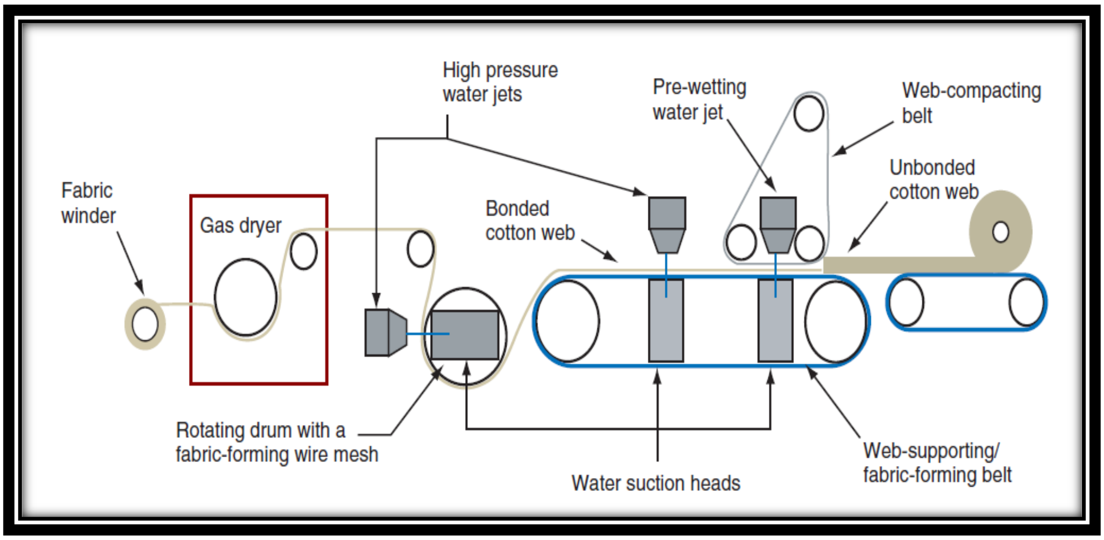


Figure 11: A schematic of the fleissner minijet system (Sawhney, 2012).

2.3.2.7 Ultrasonic bonding

Figure 12 shows an example of ultrasonic sewing machine which can be used for web bonding. The principle involves use of ultrasonic energy to sew two or more webs together into a nonwoven structure. Sewing process can be defined as assembling of cut fabrics by using proper sewing machines to obtain a cloth. Ultrasonic sewing is an effective method to assemble the thermoplastic materials in industry. Ultrasonic assembly technology uses high frequency vibration to join two or more thermoplastic and thermoplastic blended materials. Neither needle nor yarn is required for the ultrasonic sewing process. Assembly process is performed by the melting and bonding of the material (Kayar & Mistik, 2014).

Figure 12: Sonimak ultrasonic sewing machine (Kayar & Mistik, 2014)

2.4 Testing properties of nonwoven fabrics

Testing is the process of verifying conformity to requirements with the help of either artificial or natural means. In this study, testing will mainly refer to the activities of establishing the practicality of the nonwovens performance in relation to what will be expected of it in real applications. For this reason, the nonwoven will be required to conform to acceptable loading strength, bursting strength, resistance to perspiration, and appreciable resistance to abrasive forces. It is thus crucial to review the available and best practice on how to simulate the performance of the nonwoven through these tests so as to avoid cognitive dissonance in the intended market.

2.4.1 Specific requirements for packaging/shopping bag material in Kenya

In order to meet desired performance in the intended market/end-use, shopping bags in Kenya are required to adhere to some minimum standards. Table 1 gives a summary of the three specific requirements set by the Kenya bureau of standards (KEBS) as regards Shopping bags.

Table 1: Specific requirements for paper shopping bags in Kenya

s. no.	**Characteristics**	**Requirements**		
		Class 1	Class 2	Class 3
a.	Grammage g/m^2 ±5%	50	60	70
b.	Bursting strength (kPa min)	90	124	162
c.	Tearing resistance (MD) (mN, min)	320	430	540

Source (Kenya Standard KS 2523:2014)

2.4.2 Mass per unit area and thickness test

ISO 9073-1:1989 specifies a method for the determination of mass per unit area of a nonwoven structure. The principle involves measurement of an area and mass of a test piece and calculation of its mass per unit area in grams per square metre. From each sample, at least three test pieces are cut with an area of 50,000 mm^2, using either the die or the template and a sharp razor blade. In case of insufficient material, a largest possible rectangle is cut and its area determined with the help of a meter rule. The mass per unit area is then determined under standard atmosphere for testing. (Indian Standard, 2011).

ISO 9073-2:1995 specifies a method for the determination of the thickness of both normal and bulky nonwoven structures under specific pressure. The principle involves measuring the distance between the reference plate on which the nonwoven rests and a parallel presser foot that exerts a specified pressure on the area under test. For normal nonwoven structures, the principle involves the use of two circular horizontal plates attached to a stand, comprising an upper plate, or presser-foot, capable of moving vertically and having an area of approximately 2500mm^2, and a reference plate having a plane surface of diameter at least 50mm greater than that of the presser-foot. A measuring device with graduations of 0.01mm is used for measuring the distance between the reference plate and the presser-foot. To obtain results, 10 test pieces are taken and their thickness readings used to calculate the mean thickness of the nonwoven in millimetres, and, the coefficient of variation if required (Indian Standard, 2011).

2.4.3 Tensile strength and Elongation test

Tensile strength is indicative of the strength derived from factors such as fibre strength, fibre length, and bonding. It may be used to deduce information about these factors, especially when used as a tensile strength index. For quality control purposes, tensile strength has been used as an indication of the serviceability of many nonwovens which are subjected to a simple and direct tensile stress. When evaluating the tensile strength, the stretch and the tensile energy absorption for these parameters can be of equal or greater importance in predicting the performance of nonwovens, especially when that paper is subjected to an uneven stress such as gummed tape, or a dynamic stress such as when a sack full of granular material is dropped. The exposure of the nonwoven fabric to a high relative humidity before preconditioning and conditioning can lead to erratic results varying from a decrease in stretch and tensile to a substantial increase in these properties. Careful protection of the sample from the time of sampling until testing is therefore very important.

ISO 9073-3:1989 Textiles - Test methods for nonwovens. Part 3: Determination of tensile strength and elongation; specifies a method for the determination of the tensile properties of nonwovens by the cut strip method. The principle involves Application of a force longitudinally to a test piece of a specified length and width at a constant rate of extension. Values for breaking strength and elongation are the determined from the recorded force-elongation curve.

Preparation and conditioning of test pieces

Unless otherwise specified, cut five test pieces in the machine direction and five in the cross-machine direction, ensuring that they are all taken at least 100 mm from the edge and are equally distributed across the width and length of the specimen. Cut the test pieces 50 mm±0.5 mm wide and of sufficient length to allow a jaw separation of 200 mm, thus avoiding risks due to local heterogeneity of nonwovens or to undue cutting of long-fibre nonwovens.

Set the jaws of the tensile testing machine 200 mm + 1 mm apart and clamp the test piece between them; straighten out the test piece until the force curve is on the zero line. Apply a constant rate of extension of 100 mm/min and record the force-elongation curve for each test piece. Determine the elongation of the test piece at the maximum breaking strength and express this as a percentage of the nominal gauge length, that is, the original jaw separation. Discard the results from any test piece where the break occurs in the clamp or where any break reaches the jaws at a minimum of one point. Determine the means of the results, expressing the average breaking strength, in newtons, to the nearest 0,l N, and the average percentage elongation at break to the nearest 0,5 %. Calculate the coefficients of variation of the results.

2.4.4 Bursting strength test

Bursting strength is a measure of the strength of the material when a multidirectional force is applied on it (Teli, 2008). Bursting strength thus implies the measure of resistance of a material to rupture (Rashed, 2014) or wear damage of the material (Das & Raghav, 2009). The methods used for determination of bursting strength of textile structure include the ball burst method (Wang, 2011), pneumatic bursting method (Apurba, 2012), and Hydraulic bursting method (Akaydin, 2009). Generally, bursting strength depends upon the kind, proportion, and amount of fibres present in the sheet, their method of preparation, their degree of beating and refining, upon sheet formation, and the use of additives.

ISO 13938-2:1999 describes a pneumatic method for the determination of bursting strength and bursting distension of knitted, woven, nonwoven and laminated fabrics. The principle involves clamping a test specimen over an expansive diaphragm by means of a circular clamping ring. Compressed air pressure is then increased on the underside of the diaphragm causing distension of the diaphragm and the test specimen. The pressure is increased smoothly until the test specimen bursts. The mean bursting strength (KPa) and mean height at burst (mm) are then recorded. The bursting strength and bursting distension are determined (Indian Standard, 2009).

Bursting strength = mean bursting pressure – diaphragm pressure

2.4.5 Tearing strength

Tearing and tensile tests are two main domains of interest of research as regards the physical behaviour of a textile structure. However, only rupture caused by tearing is much more closely related to real life usage of the structures (Kan, 2012). Tearing tests can be conducted using the Trapezoidal method, Elmendorf method, Trouser method or Wing and Tongue tear method. The trouser tear test method is mainly used for evaluating elastomeric materials (Chang, 2002). Elmendorf method is commonly used for testing cotton and cotton blended fabrics (Dhamija & Chopra, 2007). The wing tear method has been used by Beata &Iwona (2012) for determining the static tear resistance of woven fabrics (Witkowska & Frydrych, 2010).

ISO 9073-4:1997 specifies a method for the determination of tear resistance of nonwovens by the trapezoid method. The method involves marking a trapezoid on a test piece, Clamping of the non-parallel sides of the trapezoid in the jaws of a tensile testing machine. Application of a continuously increasing extension to the test piece in such a way that a tear propagates across its width. The average maximum tear resistance is the determined in Newton (Indian Standard, 2011).

2.5 Gaps Which This Study Intends To Fill

Several studies (López–Vásquez, 2012; Acharya, 2015; Adewale, 2013; Barirega & Patrick, 2014) have studied *luffa cylindrica* for various uses and engineering applications. However, it was noted that the studies mostly used the gourds in their natural state or extracted the fibres using mechanical means. This study therefore sought to provide data as regards the effect of water retting and caustic treatment on some mechanical properties of the fibres.

As regards the nonwovens, there was no literature to cite that discussed a fabricated/produced nonwoven structure from *luffa cylindrica* fibres. This study provides an understanding of the effect of different bonding agents and fibre pre-treatments on selected properties of a nonwoven structure from *luffa cylindrica* fibres.

CHAPTER THREE

RESEARCH METHODOLOGY

3.0 Introduction

This chapter covers the procedures, techniques and framework used to knit the study objectives in the process of achieving the project aim. It includes the materials used in the study, methods for characterising *luffa cylindrica* fibres, how the nonwoven structure from *luffa cylindrica* fibres was produced and characterised, and the methods of presentation and analysis of the findings.

3.1 Materials

The materials used for successful completion of this study are subdivided into: fibres, chemicals and equipment. Chemicals are substances which facilitate the necessary modifications on the fibres with the help of equipment in order to achieve the project objectives. The fibres used in the project were extracted from *Luffa cylindrica* mature gourds obtained from Jinja district of Uganda. The chemicals used were; Rwenzori mineral water for water retting because it is ISO 9002 certified, distilled water, Sodium Hydroxide, potassium hydroxide, ethanol, glacial acetic acid, nitric acid, sulphuric acid, synemul TB 341 resin, maize starch and ionic liquid.

The equipment required for this study included: buckets, beakers, conical flasks, burettes and pipettes for measuring and handling chemicals; universal tensile testing machine, bursting strength machine, high precision weighing balance, drying oven and micrometre disc gauge available at Rivatex East Africa Limited laboratory.

3.2 Characteristics of *luffa cylindrica* fibres

Luffa cylindrica fibres used in this study were obtained from Jinja district in Uganda. Over 1000 mature *luffa cylindrica* gourds were collected, cut into quarter pieces and mixed together in order to establish the varies properties of the fibres.

3.2.1 Moisture regain

It is defined as the amount of water present in a specimen expressed as a percentage of its dry mass. The fibre sample was conditioned for 24h at 22±3 ^{o}C and the weight was taken (x). The conditioned fibre sample was dried in oven at 105 ^{o}C for 4h and the weight was taken (y). Moisture regain percentage of the given sample was calculated according to the formula (Nawaz, 2002).Twelve tests were conducted and the average was taken as moisture regain from equation 4.

Moisture regain (%) =$\frac{x-y}{y}\ X\ 100\%$ Equation 2 *(Nawaz, 2002)*

3.2.2 Lignin content

0.5g of *luffa cylindrica* fibres (Mi) was treated with 15 ml of 72% $H_2SO_4$for 2 hours. The material mixture was then diluted to 3% $H_2SO_4$to a volume of 575 ml with distilled water and then boiled for 4 hours. These two steps are intended to dissolve the carbohydrates leaving lignin to float in the acid as a black substance. The lignin was filtered into a pre-weighed crucible, washed with distilled water to remove any remaining acid, dried to a constant weight (Mf) and weighed to determine the amount of lignin is determined as a percentage of the original Mass of material (Klason Procedure) (Ronald & Romualdo, 2005; Fagerstedt, 2015).Seven tests were conducted and the average was taken to give the lignin content from equation 5.

Lignin% = $\frac{Mi}{Mf}\ X\ 100$ Equation 3 (*Fagerstedt, 2015)*

3.2.3 Cellulose content

The cellulose determination was made according to the Kurschner and Hoffer method: 1g of *luffa cylindrica* fibres (M1) were treated with 100 ml of a 1:4 (v/v 72% nitric acid: 96% ethanol) mixture (Brauns, 2013), and then increased to boiling for 1 hour. Nitric acid hydrolyses, oxidises and dissolves lignin and hemicellulose while cellulose is protected by ethanol. (Chen, 2015)The solution was filtered and the insoluble residue was retreated twice again using the previous process. After 3 treatments, the solid was washed with distilled water and hot ethanol to neutral. The solid residue was oven dried at 105^{o}C to constant weight (M2) to determine the percentage of cellulose (Ouensanga, 1989; Bremer, 2013).Seven tests were conducted and the average was taken as cellulose content from equation 6.

Cellulose content% = $\frac{M2}{M1}\ X\ 100$ Equation 4 *(Bremer, 2013)*

3.2.4 Hemicellulose content

1g of sample (W1) was weighted and 24% KOH was added to the sample and allowed to stand for 2hours. The mixtures were filtered and washed with additional 24% KOH solution and the filtrate was further precipitated by the addition of ethanol. The precipitated hemicellulose was filtered with Whitman filter paper and the residue was washed with ethanol before oven drying to constant mass at 105°C. After the treatment, the hemicellulose was transferred into desiccators and allowed to cool for 30minutes after which the weight was taken (W2)(Cox & Webster, 1960; Oladele, 2010). Seven tests were conducted and the average was taken as the hemicellulose content from equation 7.

Hemicellulose % = $\frac{W2}{W1}\ X\ 100$ Equation 5 *(Oladele, 2010)*

3.2.5 Effect of gauge length, water retting and Sodium Hydroxide on *Luffa cylindrica* fibres

Preparation in this case refers to the processes that the materials underwent in order to be suitable for producing the nonwoven fabric which was assessed for suitability of shopping bags on the Kenyan market. Water retting also known as degumming was conducted by immersing the gourds into water over a period ranging from 2 weeks to 8 weeks. The gauge length was varied by adjusting the distance between jaws of the tensile testing machine to subject varying length of the *luffa cylindrica* fibres to the tensile force in order to establish the optimal effective length for the mechanical properties. The concentration of Sodium Hydroxide was varied from 0.5% to 16.0% to establish the endurance of *luffa cylindrica* fibres to both low and high concentrations of Sodium Hydroxide. The summary of these factors is shown in Table 2: Experimental design for *luffa cylindrica* fibres.

Table 2: Experimental design for *luffa cylindrica* fibres

Factors	**Levels**						
Degumming duration (W)	2 weeks	4 weeks	8 weeks				
Gauge Length of the fibres (L)	5 mm	10 mm	20 mm				
Concentration of NaOH (C)	0.0 %	0.5 %	1.0 %	2.0 %	4.0 %	8.0 %	16.0 %

3.2.5.1 Water retting procedure

The mature dry gourds were obtained from Jinja district in Eastern Uganda. The fully opened gourdes were each split into four equal proportions and mixed before placing them in water retting buckets as shown in Figure 15. Rwenzori mineral water (ISO 9002 Certified) obtained from Uganda was then poured into the buckets containing the dry gourds. The retting duration was for two weeks, four weeks and eight weeks to allow for the decomposition of the lignin for easy extraction of the fibres. After extraction, the fibres were air dried for one week to remove excess moisture.

Figure 13: Water retting of *luffa cylindrica* fibres

3.2.5.2 Caustic treatment procedure

15 grams of the extracted fibres were sampled from the 2 weeks (2w), 4 weeks (4w) and 8 weeks (8w) and placed in beakers. Sodium Hydroxide solutions were prepared based on a concentration of 2^{n-1} per cent from n = 0 to n = 5 as elaborated below.

Table 3: Caustic concentrations used for delignification of *luffa cylindrica* fibres

n – value	**(2^{n-1})%NaOH**	**%NaOH**
n = 0	$2^{0-1} = 2^{-1} = 0.5$	0.5%
n = 1	$2^{1-1} = 2^{0} = 1.0$	1.0%
n = 2	$2^{2-1} = 2^{1} = 2.0$	2.0%
n = 3	$2^{3-1} = 2^{2} = 4.0$	4.0%
n = 4	$2^{4-1} = 2^{3} = 8.0$	8.0%
n = 5	$2^{5-1} = 2^{4} = 16.0$	16.0%

$$\%\text{NaOH} = \frac{grams\ of\ NaOH}{300\ ml\ of\ distilled\ water}\ x\ 100\% \qquad \text{Equation 6}(\textit{Paschal, 2015})$$

Required grams of NaOH = $\frac{\%\text{NaOH x 300 ml of distilled water}}{100}$ grams of Sodium Hydroxide.

For example to get 0.5%NaOH,

Required grams of NaOH = $\frac{0.5*300}{100} = \frac{150}{100} = 1.5$g of NaOH.

300 ml of distilled water was therefore used to dissolve 1.5g, 3g, 6g, 12g, 24g, and 48g of Sodium Hydroxide to give 0.5%, 1%, 2%, 4%, 8%, and 16% respectively. 0%NaOH was used as a control to judge the effect of alkalisation on the *luffa cylindrica* fibres. The fibres were then immersed in the prepared caustic solutions and allowed to stay for 45 minutes with some intermittent mechanical stirring to ensure effective treatment. After 45 minutes, the treated fibres were removed from caustic solutions and thoroughly rinsed with *water* containing mild Acetic acid to remove any residual Sodium Hydroxide. The rinsed fibres were then oven dried for 30 minutes at 80 ^{o}C to remove excess water and moisture before transferring them to a conditioning lab for further testing analysis. Caustic treatment resulted in a total of 21 samples since for each week of degumming, seven treatments were made as shown in table 5 (Valcineide, 2014; Paschal, 2015).

Table 4: Matrix for alkalisation of *luffa cylindrica* using Sodium Hydroxide

	2 weeks (2w)	**4 weeks (4w)**	**8 weeks (8w)**
0.0 grams of NaOH (0g)	2w0g	4w0g	8w0g
1.5 grams of NaOH (1.5g)	2w1.5g	4w1.5g	8w1.5g
3.0 grams of NaOH (3g)	2w3g	4w3g	8w3g
6.0 grams of NaOH (6g)	2w6g	4w6g	8w6g
12.0 grams of NaOH (12g)	2w12g	4w12g	8w12g
24.0 grams of NaOH (24g)	2w24g	4w24g	8w24g
48.0 grams of NaOH (48g)	2w48g	4w48g	8w48g

3.2.5.3 Determination of Breaking load and Elongation

This testing was done in accordance to ISO 5079:1995(E) – Textile Fibres – determination of breaking force and elongation at break of individual fibres. A universal tensile testing machine set at a speed of 100 mm/minute was used to conduct tests on the 21 fibre specimen from Table 5 at gauge length of 5 mm, 10 mm and 20 mm to ascertain the effect of gauge length on mechanical properties of *luffa cylindrica* fibres. The procedure involved setting the gauge length of the machine to either 5 mm, 10 mm or 20 mm followed by clamping the fibres into the jaws of the machine. For the 21 fibre samples derived from table 5, 20 specimen tests were made on each of the samples amounting and the averages of tensile strength and elongation were recorded in Newton and millimetres respectively. To convert from Newton to centinewton, the values were multiplied by 100 as shown in equation 9. Percentage elongation was obtained from the division of elongation at break by the set gauge length as shown in equation 10.

1 Newton (N) = 100 centinewton (cN) Equation 7 (*ISO 5079:1995(E))*

Percentage elongation = $\frac{elongation\ at\ break}{gauge\ length}$ X 100 % Equation 8*(ISO 5079:1995(E))*

3.2.5.4 Determination of linear density for *Luffa cylindrica* fibres

This test was carried out using the Gravimetric method described by ISO 1973:1995 (E) textile fibres – Determination of linear density – Gravimetric method and Vibroscope method. The Tex system of linear density was used. From the 21 variants from Sodium Hydroxide treatment in table 5, 100 individualised single fibres were measured and their total length as a bundle was obtained. The bundle of 100 fibres was then weighed using a high precision balance machine to obtain the total weight. Tex being the grams of material in 1000 meters, the obtained bundle weight was divided by total bundle length and multiplied by 1000 to obtain the linear density in Tex as shown in Linear density = $\frac{observed\ weigth\ (g)}{observed\ length\ (m)}\ x\ 1000\ Tex$ Equation *9*.

Linear density = $\frac{observed\ weigth\ (g)}{observed\ length\ (m)}\ x\ 1000\ Tex$ Equation 9*(ISO 1973:1995 (E)))*

To express in decitex, 1 Tex = 10 Decitex. Equation 10*(ISO 1973:1995 (E))*

3.2.5.5 Determination of fibre tenacity

Tenacity is defined as the maximum breaking force applied to a test specimen carried to rupture, divided by the linear density, expressed as centinewton (cN) per Tex (Hannel S. Sankari, 2000).

Tenacity = $\frac{breaking\ strength\ of\ fibre}{Tex\ of\ fibre}$ Equation 11(Fathima, 2006)

3.3 Production and Testing of the Nonwoven Structure

3.3.1 Production of the nonwoven structure

3.3.1.1 Preparation of the materials

The materials for the production of the nonwoven structure were; *luffa cylindrica* fibres, ionic liquid, maize starch, Synemul TB 341 resin, a woven fabric screen for laying the nonwoven structure. First the woven fabric screen was prepared by nailing a screen mesh onto a 50 cm x 30 cm wooden frame. The water retted *luffa cylindrica* fibres were then treated with pure ionic liquid and sodium hydroxide at concentrations of 2% (w/v), 4% (w/v), and 8% (w/v) and neutralised with mild acetic acid to remove Sodium Hydroxide before rinsing with distilled water.

Table 5: Summary of preparation of *luffa cylindrica* fibres for different webs

Batt Prefix	**Treatment media**
IL	Ionic liquid
2	2% NaOH
4	4% NaOH
8	8%NaOH

3.3.1.2 Production of the web

The treated fibres were then dry-laid as shown in Figure 15 by hand on the previously formed screens and allowed to settle overnight. Four kinds of webs were dry-laid according to (Tanchis, 2008) for ionic starch bonding and three webs for synemul TB 341 resin. These included three webs treated with Sodium Hydroxide at 2%, 4% & 8% used for both ionic starch bonding and synemulTB 341 resin. one web was made from *luffa cylindrica* fibres boiled ionic liquid for one hour in order investigate the total effect of ionic liquid on the properties *luffa cylindrica* nonwoven structure.

Figure 14: The random dry-laid web from *luffa cylindrica* fibres

3.3.1.3 Web bonding

Figure 16 shows an example of the dry-laid webs after impregnation with bonding agents. Bonding agents used were made of maize starch boiled in ionic liquid and synemul TB 341 resins as summarised in Table 7. The produced nonwoven structures were allowed to dry until they were free from tackiness and completely solid for one week. For easy identification, the structures were given codes instead of the complete descriptive names. Batt code represents the combination of the batt prefix explained in the previous section and the initials of the bonding agent employed. For example, 2IS has prefix 2 which implies 2% NaOH and suffix IS which implies ionic liquid/starch adhesive.

Figure 15: The adhesively bonded web from *luffa cylindrica* fibres

Table 6: summary of web bonding adhesive to produce nonwoven structures

Batt Code	**Treatment media**	**Bonding agent**
IL	Ionic liquid	Ionic Starch
2IS	2% NaOH	Ionic Starch
4IS	4% NaOH	Ionic Starch
8IS	8%NaOH	Ionic Starch
2S	2% NaOH	Synemul TB 341
4S	4% NaOH	Synemul TB341
8S	8%NaOH	Synemul TB341

Source (primary data)

3.3.1.4 Finishing of the nonwoven

The dry nonwoven structures were then finished by passing through pressing rollers as shown in figure 17 to consolidate the structure before conditioning it for tensile strength, percentage elongation, bursting strength and tearing strength testing. The pressing rollers were used to make the nonwoven more compact and stronger (Desai & Balasubramanian, 1994).

Figure 16: Consolidating the nonwoven structure from *luffa cylindrica* fibres

3.3.2 Testing of the produced nonwoven structure from *luffa cylindrica* fibres

All the testing was done under a conditioned room at temperature of 20±2^{o}C and 65% RH.

3.3.2.1 Mass per unit area of the nonwoven structure

This was determined according to ISO 9073-1:1989 textiles – test methods for nonwovens - part 1 determination of mass per unit area. The structure samples were cut into rectangular shape and their length and width were obtained using a meter rule. The obtained length and width was used to calculate the area by multiplying the length by width. The same sample was then weighed using a high precision weighing balance and the weight was recorded. The mass per unit area was determined by dividing the sample mass by calculated area as show in equation below. For each nonwoven structure, 5 specimens were evaluated and the average reading was recorded as the mass per unit area as shown in Appendix XI: Mass per unit area and thickness of nonwoven from *luffa cylindrica* fibres.

$$Mass\ per\ unit\ area = \frac{sample\ mas\ in\ grams}{sample\ area\ in\ sq.meters}$$ Equation 12*(ISO 9073-1:1989)*

3.3.2.2 Thickness of the nonwoven structure

ISO 9073-2:1995 specifies a method for the determination of the thickness of both normal and bulky nonwoven structures under specific pressure. The technique for determining thickness of normal nonwoven structures was employed in this study. The nonwoven structures were pressed under a constant pressure and the thickness was measure using a Vanier calliper. For each nonwoven structure, ten specimens reading were conducted and the average computed thickness was recorded as the thickness of the nonwoven structure in Appendix XI.

3.3.2.3 Tensile strength and elongation of the nonwoven structure

The cut strip method from ISO 9073-3:1989 Textiles — Test methods for nonwovens — Part 3: Determination of tensile strength and elongation was used to determine breaking load and elongation of the produced nonwoven. To achieve results with minimal error, 6 test specimens were cut from the longitudinal and crosswise directions to obtain the average of each of the 7 fabric samples as recorded in Appendix IX: Tensile strength of nonwoven from *luffa cylindrica* fibres.. The nonwoven dimensions were set at 50±0.5 mm wide with sides parallel within 0.1 mm and 100 ± 5 mm long gauge length to facilitate easy clamping of the fabrics in the machine jaws. The fabric samples were checked for any abnormalities, creases and wrinkles that may interfere with the accuracy of the findings.

3.3.2.4 Bursting strength of the nonwoven structure

ISO 13938-2:1999 textiles-bursting properties of fabrics. Determination of bursting strength and bursting distension: Part 2 pneumatic method was used to determine the bursting strength of the nonwoven structures from *luffa cylindrica* fibres. Ten specimens were used for each reading by obtaining the average reading for five tests on each fabric surface i.e. five tests were done on one side to obtain the average reading before turning to the other side to obtain the average of five tests.

3.3.2.5 Tearing strength of the nonwoven structure

ISO 9073-4:1997 method for the determination of tear resistance of nonwovens by the trapezoid method. The samples were cut according to the template shown in Figure 18.

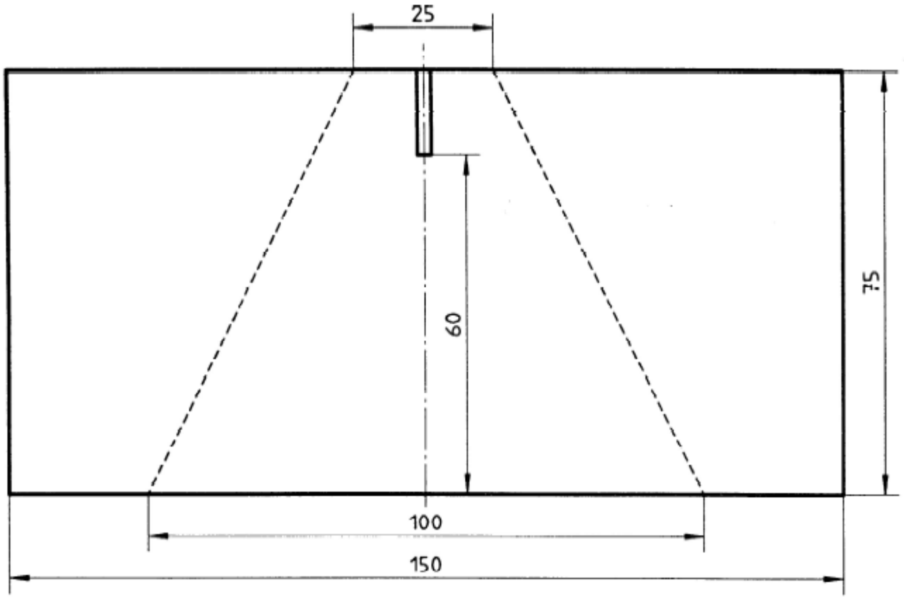


Figure 17: Template for trapezoidal testing of bursting strength (ISO 9073-4:1997).

The samples were cut from regions with minimal to no imperfections and conditioned for a minimum of 24 hours at 20±2^{o}C and 65% RH.

The machine jaws were adjusted to an initial length of 25 mm and the sample piece was clamped along the dotted lined shown in Figure 18. The tearing strength was then read from the peaks of the graphs plotted by the machine on a monitor. Ten tests were conducted for each sample, five for each perpendicular direction to obtain average for both directions of the structure as outlined in ISO 9073-4:1997. The averages of the tearing strength computed as ts_x (longitudinal tearing strength) and ts_y (crosswise tearing strength) were used for the analysis in chapter four.

3.4 Data Collection Methods

Untreated samples of luffa were used as controls when testing for the effect of; degumming duration, alkali concentration, and gauge length of the fibres on the strength properties of the fibres before producing the web that was used for the nonwoven fabric. The tests on the strength of the fibre materials were performed from the Moi University facility at Rivatex East Africa limited in sets of 20 to obtain the average under standard conditions of 22 ± 2^oC temperature and 65±2 RH % humidity.

As regards the nonwoven structure, all the tests were done according to the specified standards.

3.5 Analysis of Findings

The results obtained from the surveys and experiments were analysed using professional computer software for data analysis. Some of this software was Ms Excel and Minitab with consultation from a professional statistician.

3.5.1 Effect of degumming duration, fibre length and alkali concentration on the mechanical properties of *luffa cylindrica* fibres.

Both graphical and regression analysis were used to present and analyse the findings. Bar charts and line plots with percentage error bars generated by the software from input data were used in graphical analysis. Regression a highly useful statistical technique was used to develop a quantitative relationship between the dependent variable (response) and one or more independent variables (factors) (Lazic, 2004). Since all the experiments are based on a full factorial design, the following linear regression model was used to screen the interactions between the effect of degumming duration, fibre length and concentration of Sodium Hydroxide on strength and elongation properties of the fibres.

$Y = \beta_0 + \beta_1 W + \beta_2 l + \beta_3 C + \beta_4 Wl + \beta_5 WC + \beta_6 lW + \beta_7 WlC + \varepsilon$ Equation 13*(Lazic, 2004)*

Where: Y is for either tensile strength, Elongation at break, and tenacity; W is for retting duration, C is for concentration of Sodium Hydroxide; l is for gauge length; and their interaction is represented by Wl, WC, lM and ClW. The effects W, C and l are the main effects while Wl, WC, lM and ClW are called interaction effects. These effects are the sources for the variation of Y.

3.5.2 Analysis of the nonwoven structure properties

The results from testing the nonwoven structure from *luffa cylindrica* fibres were analysed using Ms excel and presented using bar charts with percentage error bars generated by the software from input data.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

This chapter covers the outcomes from the quest of this study as guided by the procedures discussed in chapter three. It includes results from the characterisation of *luffa cylindrica* fibres and results from the characterisation of the nonwoven structures from *luffa cylindrica* fibres.

4.1 *Luffa cylindrica* Fibre Properties

4.1.1 Moisture regain

The moisture content of *luffa cylindrica* fibres was found to be 9.74±1.1%. Whereas the moisture regain was 10.81% ±1.34%. The observed moisture content was almost double (4.79±0.02%) that was reported by Smole (2013). The raw data is given in APPENDICES

Appendix I: Raw data for moisture regain and moisture content *of luffa* cylindrica fibres.

4.1.2 Lignin content

The lignin content was found to be 12.03%± 2.34%. This was comparable to Smole (2013) value of 15.46%±0.02% but far from 1.6% reported by Seki(2011).The raw data is given in Appendix II: Raw data for lignin content of *luffa cylindrica* fibres.

4.1.3 Cellulose content

The cellulose content *luffa cylindrica* from Jinja Uganda was found to be 65.69%±3.77%. This value was comparable to 66.59%±0.61% reported by Smole (2013) and 63.0% reported by Seki (2011). The raw data is given in Appendix IV: Raw data for cellulose content of *luffa cylindrica* fibres.

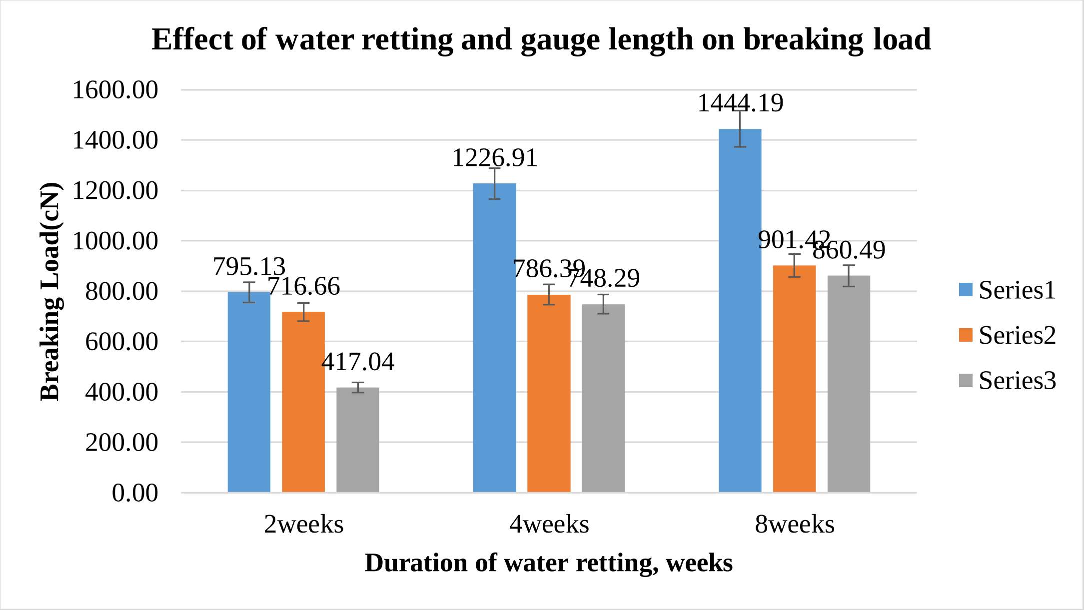
4.1.4 Hemicellulose content

The hemicellulose from Jinja Uganda was found to be 19%±3%.this was slightly higher than 14.4% reported by Seki (2011). The raw data is given in Appendix III: Raw data for hemicellulose content of *luffa cylindrica* fibres

4.1.5 Mechanical Properties of *luffa cylindrica* fibres

4.1.5.1 Breaking load of *luffa cylindrica* fibres

As shown in Figure 25 and Figure 26, the tensile strength is higher at a gauge length of 5 mm for each of the sodium hydroxide concentrations and durations of water retting. This can be associated with presence of fewer imperfections at shorter length (Pardini , 2002). In Figure 26, the strength appears to be divisible into three sections with similar trends considering a gauge length of 20mm between concentrations 0.0% to 0.5%, 1.0% to 4.0% and 8% to 16%. The extra drop in strength at 16% concentration of sodium hydroxide can be associated with the hydrolysis of some cellulose components of the *luffa cylindrica* fibres. Considering a fibre at 8 weeks water retting duration, gauge length of 20 mm and initial strength at 0% NaOH as control level, the effect of NaOH treatment resulted in 2% increase in breaking load at 0.5% NaOH, 15% increase at 1.0%NaOH, 7% reduction at 2%NaOH, 16% increase at 4%NaOH, and 35% reduction at 8%NaOH and 16% NaOH. These results are similar to those obtained by (Paschal, 2015) in the study to establish the effect of Sodium Hydroxide treatment on the tensile properties of *luffa cylindrica* composites. As regards water retting shown in Figure 26, the fibres subjected to 8 weeks of water retting exhibited higher breaking loads at all the gauge length of testing. As regards gauge length in Figure 27, 10 mm shows less variability of the results as compared to 5 mm and 20 mm for the three durations of water retting.



Key: series 1, 2, and 3 represent Gauge length 5 mm, 10 mm and 20 mm, respectively

Figure 18: Effect of water retting on breaking load of *luffa cylindrica* fibres

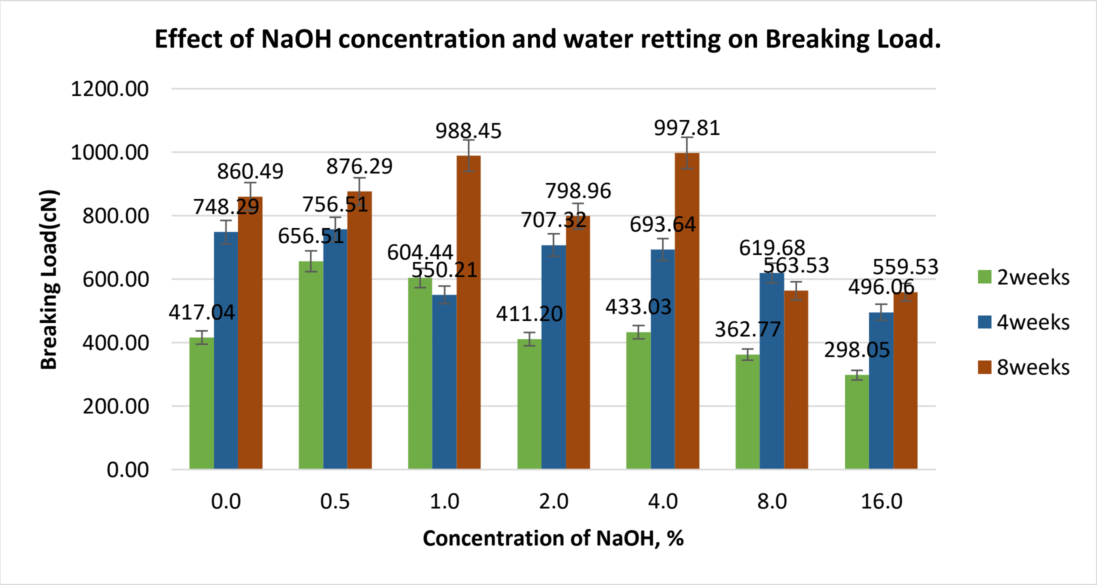


Figure 19: Effect of NaOH concentration on breaking load of *luffa cylindrica* fibres

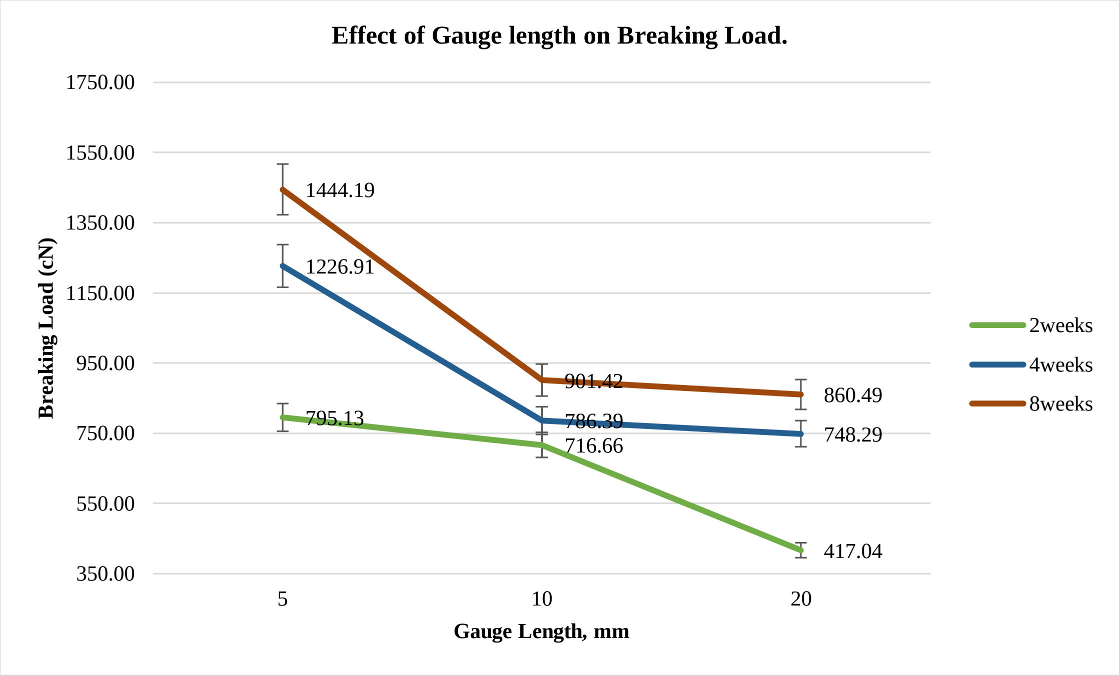
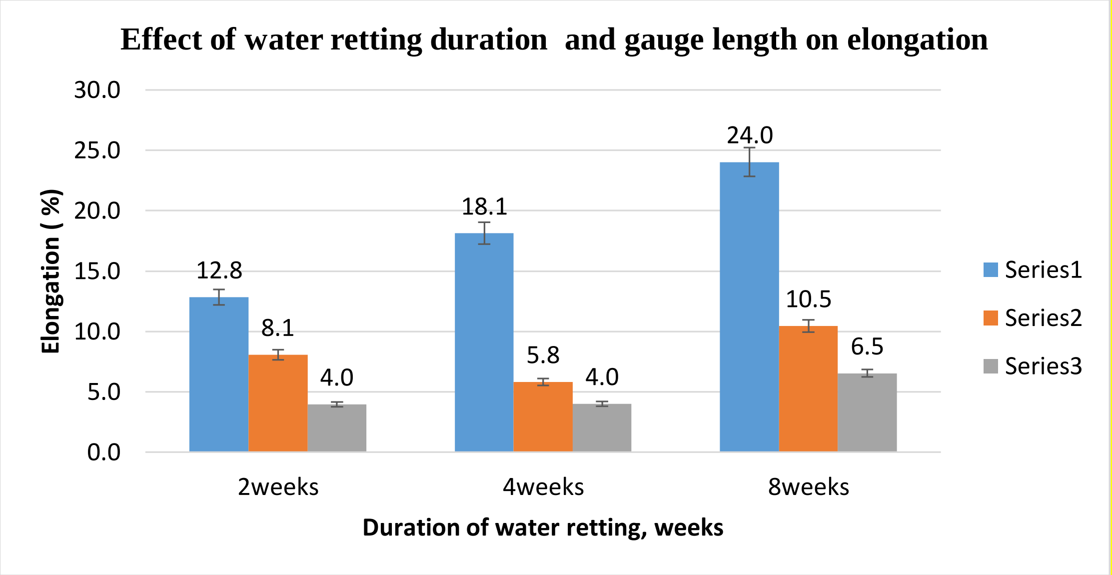


Figure 20: Effect of gauge length on breaking load of *luffa cylindrica* fibres

4.1.5.2 Elongation of *luffa cylindrica* fibres

As can be seen in Figure 29, considering 8 weeks of water retting and gauge length of 20mm, the percentage elongation appears to increase with concentration of sodium hydroxide up to 8% when it drastically drop at 16% sodium hydroxide. From 0%NaOH to 0.5% NaOH the increment was 37%, 1% NaOH resulted in a decrease of 19% of the original control value at 0%NaOH. At 2%NaOH, the elongation reduced by 21% before increasing again at 4%NaOH by 27%. Further increase of sodium hydroxide concentration at 8% resulted in a decrease of 30% and a further decrease of 10% at 16% NaOH. Therefore, a treatment with 0.5% Sodium Hydroxide is sufficient for higher observable elongation while a treatment at 8% Sodium Hydroxide showed the highest percentage decrease in elongation. As regards the effect of gauge length as shown in Figure 30, there was more variability in the results at 5mm as compared to 10mm and 20mm for the respective durations of water retting. 8 weeks of water retting produced higher percentage elongation without any sodium hydroxide treatment. The raw data is given in Appendix VI: Elongation (mm) of *luffa cylindrica* fibres.



Key: series 1, 2, and 3 represent Gauge length 5 mm, 10 mm and 20 mm, respectively

Figure 21: Effect water retting duration on percentage elongation of *luffa cylindrica* fibres

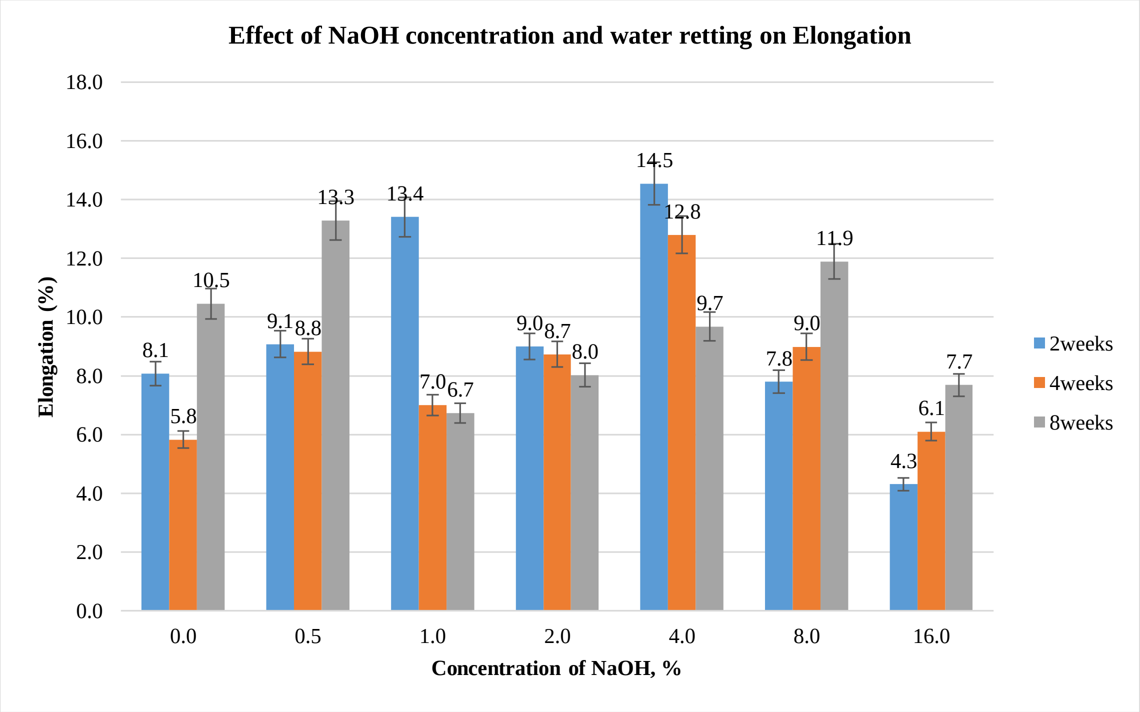


Figure 22: Effect of sodium hydroxide on percentage elongation of *luffa cylindrica* fibres

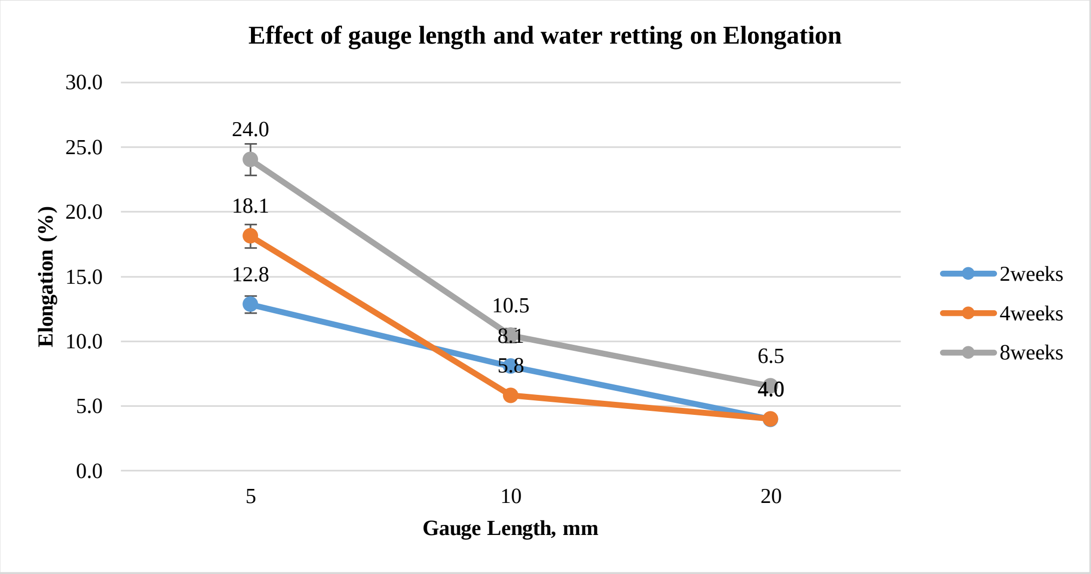


Figure 23: Effect of gauge length on percentage elongation of *luffa cylindrica* fibres

4.1.5.3 Linear density of *luffa cylindrica* fibres

As shown in Figure 31 and Figure 32, there was a general reduction in linear with increase duration of water retting weeks and increase in Sodium Hydroxide concentration. From 2 weeks to 8 weeks of retting, the linear density decreased by 17.7% at 0%NaOH. The linear density of *luffa cylindrica* fibres reduced by 27%, 25% and 18% from the treatment with 16% Sodium Hydroxide after 2 weeks, 4 weeks and 8 weeks of water retting respectively. This can be attributed to the fact that at 8 weeks of water retting, the fibres are more eroded by water hence resulting in a less significant effect as observed at 2 weeks of water retting. This also greatly implies that the linear density of *luffa cylindrica* fibres is highly dependent on the level of surface erosion treatments. The raw data is given in Appendix VII: Linear density (dTex) of *luffa cylindrica* fibres.

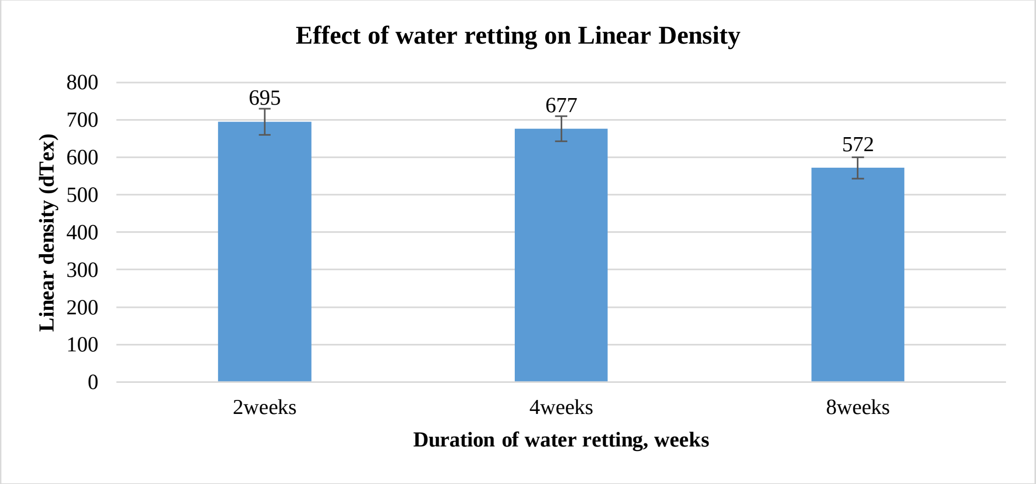


Figure24: Effect of water retting on linear density of *luffa cylindrica* fibres

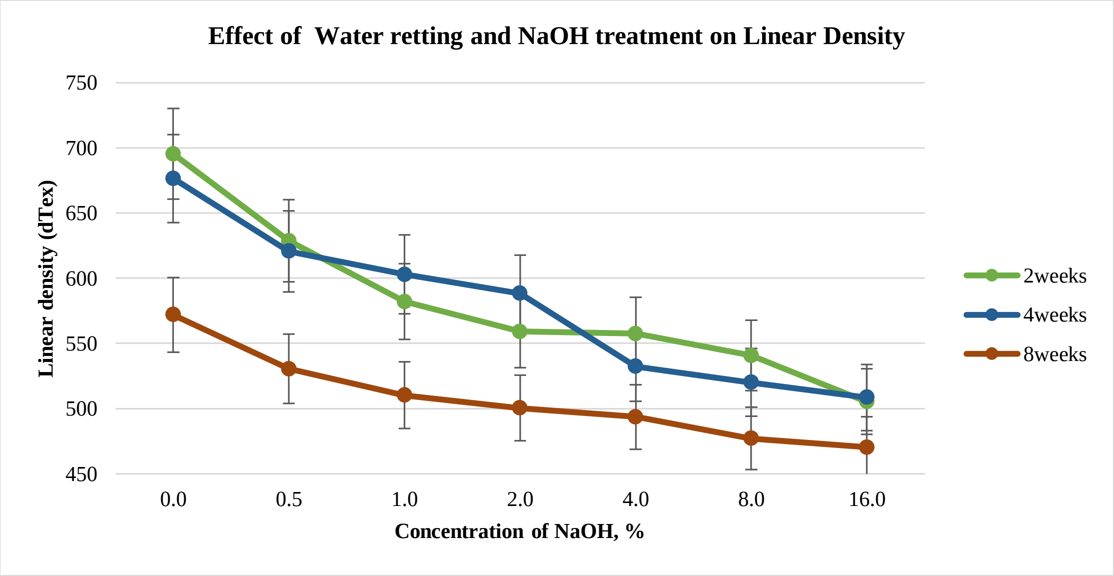


Figure 25: Effect of NaOH concentration on linear density of *luffa cylindrica* fibres

4.1.5.4 Tenacity of *luffa cylindrica* fibres

As shown in Figure 33, retting for 8 weeks resulted in 121% higher than at 2 weeks retting tenacity performance; which can be attributed to more uniform lignin removal. In Figure 34 considering retting of 4 weeks, the tenacity appears to be less sensitive to Sodium Hydroxide treatment (0% to 16%) with a loss of 46% as compared to 48% at 2 weeks and 53% at 8 weeks. Figure 35 shows that the tenacity values of *luffa cylindrica* fibres are less spread at gauge length of 10 mm as compared to gauge length of 5 mm and 20 mm. The raw data is given in

Appendix VIII: Tenacity (cN/Tex) of *luffa cylindrica* fibres.

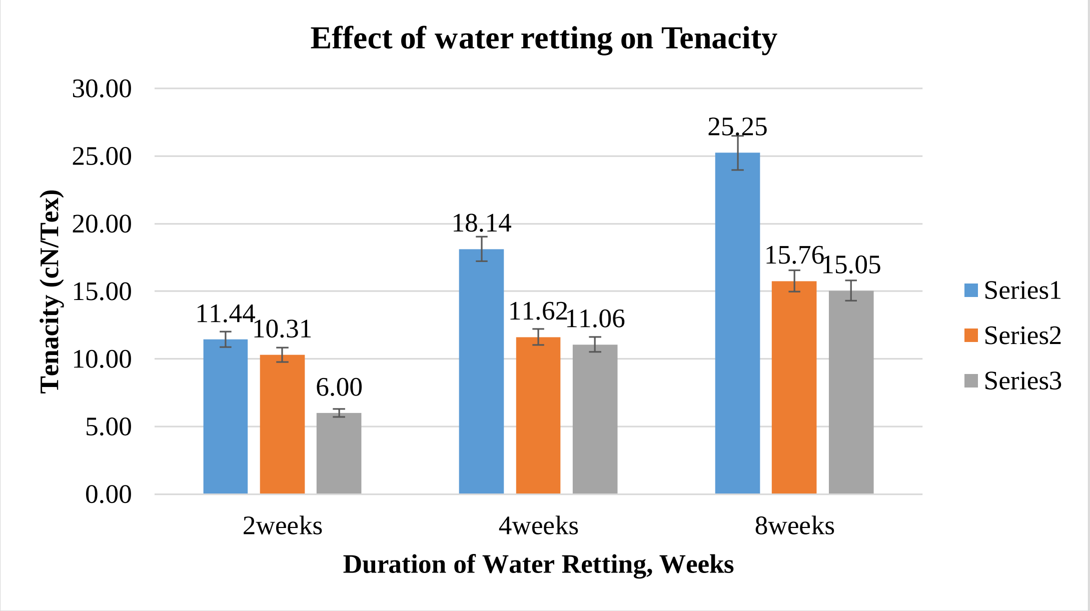


Figure 26: Effect of water retting duration on tenacity of *luffa cylindrica* fibres

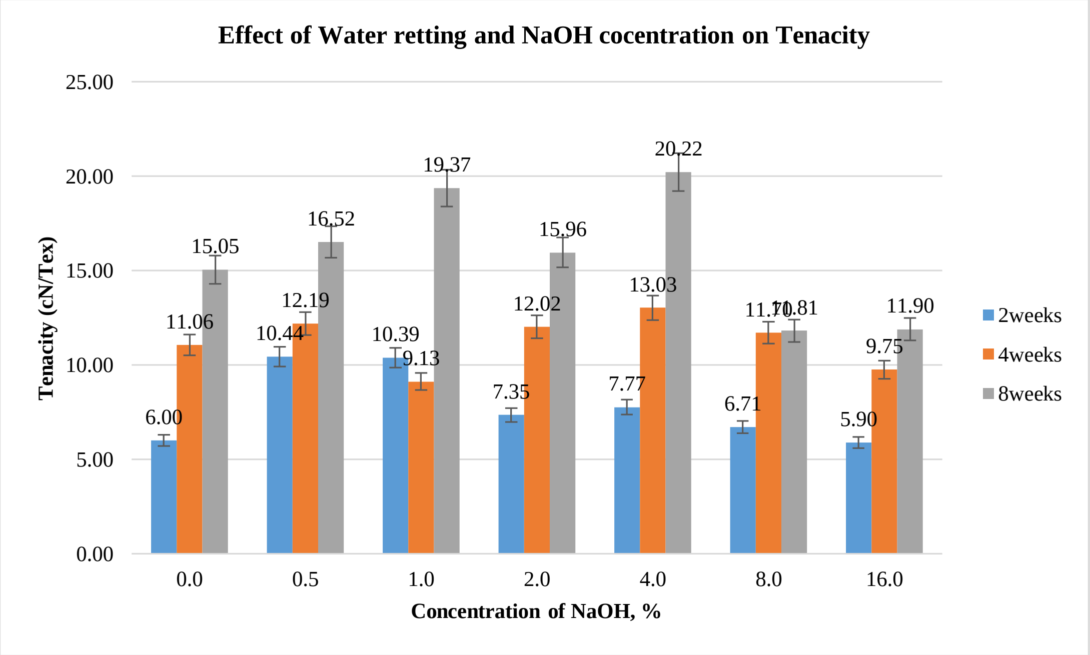


Figure 27: Effect of NaOH concentration on tenacity of *luffa cylindrica* fibres

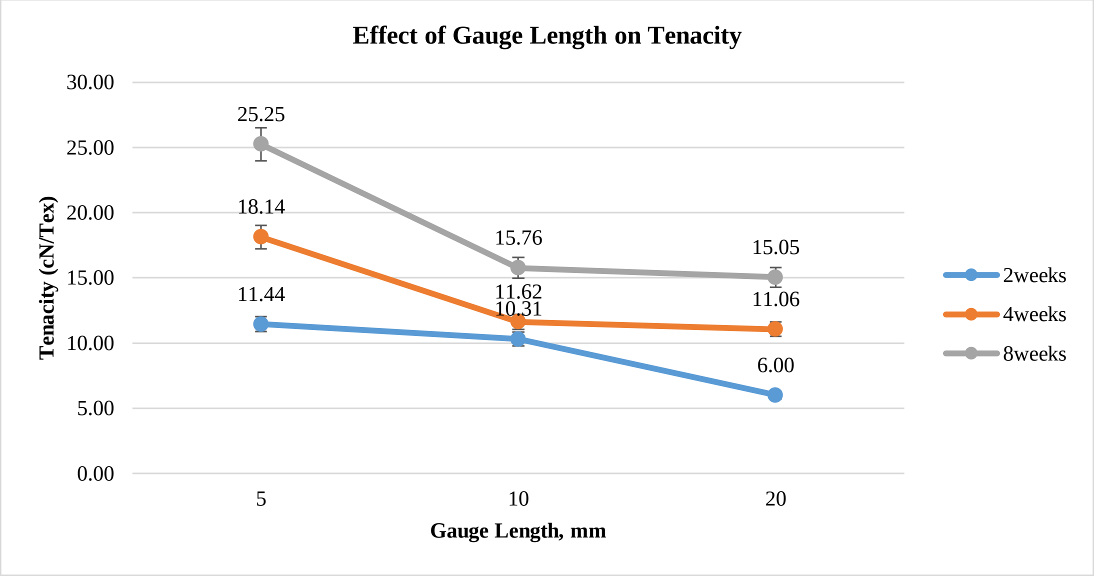


Figure 28: Effect of gauge length on the tenacity of *luffa cylindrica* fibres

4.1.5.5 Regression analysis of *luffa cylindrica* fibres

4.1.5.5.1 Breaking load of *luffa cylindrica* fibres

$$S = 767 - 47.9\ L + 156.6\ W - 42.7\ C + 1.074\ L^2 - 8.34\ W^2 + 1.035\ C^2 + 0.926\ L*C - 1.84\ W*C \qquad \text{Equation 14}$$

S – Breaking load, W – Weeks of degumming, L – Gauge length, C – NaOH concentration

The relationship between S and W, L, C is statistically significant with a p-value < 0.01. 84.81% (R.sq. value) of the variation in S can be explained by the regression model while 15.19% can be attributed to factors beyond the scope of this study.

Table 7: Optimal setting for maximisation of strength of *luffa cylindrica* fibres

Goal: Maximize S		Solution: Optimal Settings	
Predicted S	1273.35	L	5 mm
95% PI	(1044.3, 1502.4)	W	8 weeks
		C	0%

4.1.5.5.2 Elongation of *luffa cylindrica* fibres

$E = 26.97 - 2.485\ L + 0.272\ C + 0.0717\ L^2 - 0.0279\ C^2$ Equation 15

E – Percentage elongation of *luffa cylindrica* fibres, W – Weeks of degumming, L – Gauge length, C – NaOH concentration

The relationship between E and W, L, C is statistically significant with a p-value < 0.001. 72.43% (Rsq. Value) of the variation in E can be explained by the regression model.

Table 8: Optimal settings for maximisation of elongation of *luffa cylindrica* fibres

Goal: Maximize E		Solution: Optimal Settings	
Predicted E	16.9983	L	5 mm
95% PI	(11.037, 22.959)	C	4.8%

4.1.5.5.3 Linear density of luffa cylindrica fibres

$D = 626.1 + 13.57\ W - 24.85\ C - 2.888\ W^2 + 0.927\ C^2 + 0.678\ W*C$ *Equation16*

D – Linear density of *luffa cylindrica* fibres, W – Weeks of water retting, C – NaOH concentration

The relationship between D and W, C is statistically significant with a p-value < 0.1. 85.21% (Rsq. Value) of the variation in D can be explained by the regression model.

Table 9: Optimal settings for maximisation of linear density of *luffa cylindrica* fibres

Goal: Maximize D		Solution: Optimal Settings	
Predicted D	642.081	W	2.3 weeks
95% PI	(591.35, 692.81)	C	0%

4.1.5.5.4 Tenacity of *luffa cylindrica* fibres

$$T = 12.05 - 0.686\ L + 2.025\ W - 0.250\ C + 0.0184\ L^2 - 0.0288\ L*W + 0.01324\ L*C - 0.0430\ W*C$$ Equation 17

T – Tenacity of *luffa cylindrica* fibres, W – Weeks of degumming, L – Gauge length

C – NaOH concentration

The relationship between T and W, L, C is statistically significant with a p-value < 0.1. 86.87% (Rsq. Value) of the variation in T can be explained by the regression model.

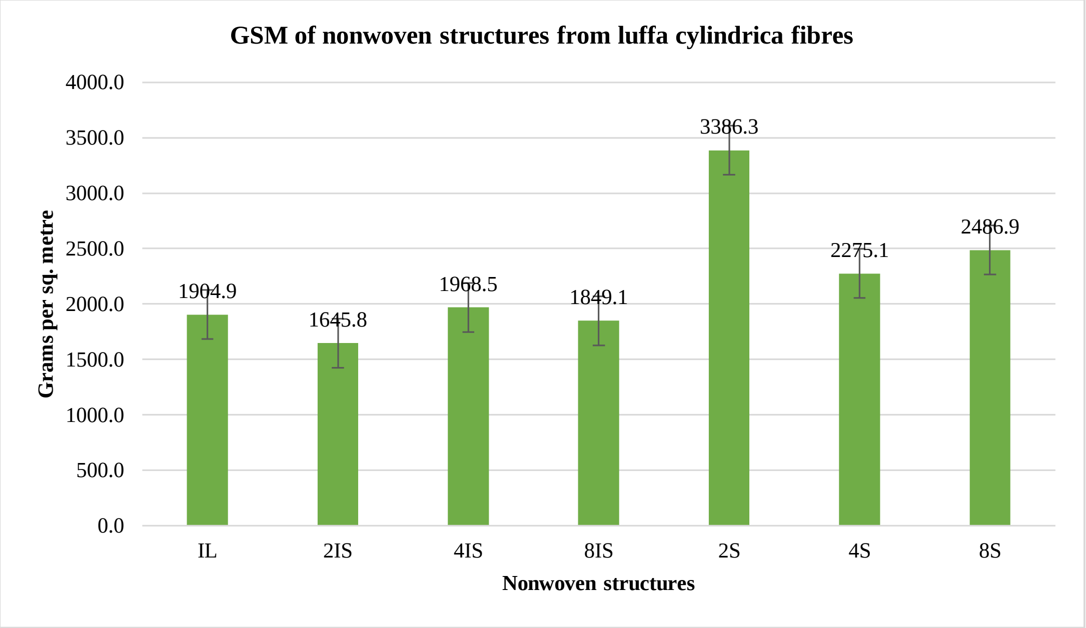
Table 10: optimal settings for maximisation of tenacity of *luffa cylindrica* fibres

Goal: Maximize T		Solution: Optimal Settings	
Predicted T	24.1316	L	5 mm
95% PI	(20.075, 28.188)	W	8 weeks
		C	0%

4.2 Nonwoven structure from *luffa cylindrica* fibres

4.2.1 Mass per unit area

As shown in Figure 36, the mass per unit area of the nonwoven structures bonded with the synemul TB 341 adhesive is higher than that of the structures bonded with ionic liquid/starch adhesive. For the same fibre treatment of 2% NaOH and approximate thickness of 1.5 mm, the nonwoven structure from synemul TB 341 weighed 51.4% more than the nonwoven structure from ionic liquid/starch adhesive.



Key:

Abbreviation	Meaning
IL	Nonwoven structure from fibres treated with ionic liquid and bonded with ionic liquid/starch adhesive.
2IS	Nonwoven structure from fibres treated with 2%NaOH and bonded with ionic liquid/starch adhesive.
4IS	Nonwoven structure from fibres treated with 4%NaOH and bonded with ionic liquid/starch adhesive.
8IS	Nonwoven structure from fibres treated with 8%NaOH and bonded with ionic liquid/starch adhesive.
2S	Nonwoven structure from fibres treated with 2%NaOH and bonded with synemul TB 341 adhesive.
4S	Nonwoven structure from fibres treated with 4%NaOH and bonded with synemul TB 341 adhesive.
8S	Nonwoven structure from fibres treated with 8%NaOH and bonded with synemul TB 341 adhesive.

*this key applies to all Figure s with similar abbreviations

Figure 29: Shows the variation of grams per square metre of different nonwoven structures from luffa cylindrica fibres.

4.2.2 Thickness

As shown in Figure 37, the thickness of the nonwoven structures was consolidated to 1.63±0.14mm. There was a variation of 6.25% in the thickness of the nonwoven structures bonded by ionic liquid/starch adhesive. Synemul TB341 adhesive bonded structures exhibited a thickness variation of 16.67%. This can be attributed to the observed plasticisation effect of sodium Hydroxide on the resin since higher concentrations resulted in higher viscosity.

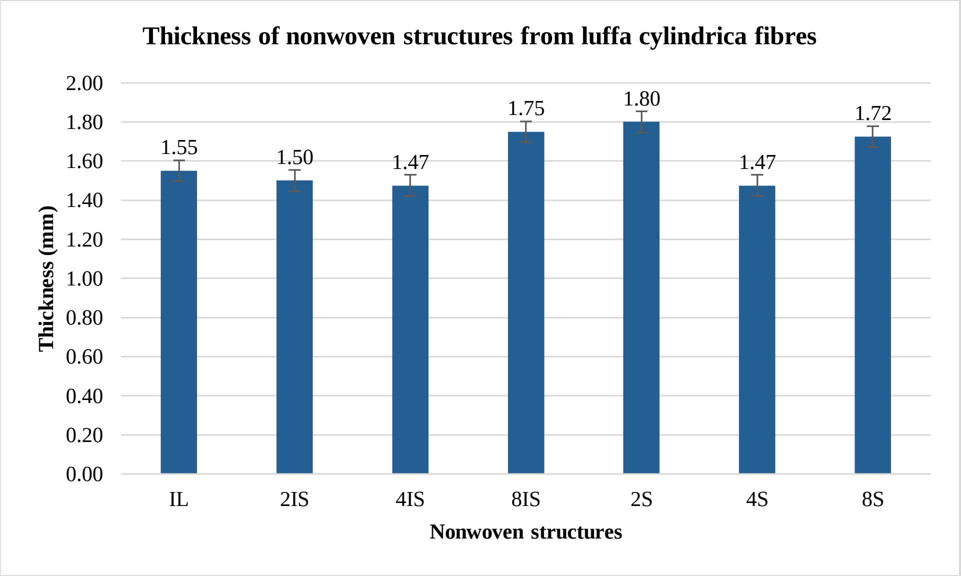


Figure 30: Shows the thickness of different nonwoven structures from *luffa cylindrica* fibres

4.2.3 Tensile strength

As shown in Figure 38,the tensile strength of the nonwoven structures seems vary with the pre-treatment given to the fibres more than the orientation of the fibres in the nonwoven structures. Nonwoven structure from *luffa cylindrica* Fibres treated with ionic liquid exhibited the second lowest strength only 36.67% and 39.13% better than the nonwoven structure from the fibres treated with 8%NaOH in the longitudinal and crosswise directions respectively. The strength percentage range for fibres treated with Sodium Hydroxide and bonded with ionic liquid/starch adhesive was 69.84% and

80.28% in the longitudinal and crosswise directions respectively. The strength difference between orientations of the different nonwoven structures was 20.00±6.05% which is lower than the effect of pre-treatment used implying that nonwoven structures were fairly random laid.

Figure 39 shows the tensile behaviour of *luffa cylindrica* random laid nonwoven structures bonded with synemul TB 341 adhesive. It shows that the tensile strength of the nonwoven structures were highly dependent on the pre-treatment given to *luffa cylindrica* fibres before laying. The strength reduction from 2%NaOH to 8%NaOH was 78.33% and 78.54% in the longitudinal and crosswise direction respectively. This high but close reduction in the strength of the nonwoven structures bonded with the synemul TB 341 adhesive also reveals that the structures were isotropic in nature – that is, the probability of a fibre segment in any direction between 0 and π is the same (= $1/\pi$) (Subhash Kumar Batra, 2012).

As regards the effect of bonding agent, nonwoven structures bonded with the synemul TB 341 exhibited much higher tensile strength of up to 97.28% for same pre-treated *luffa cylindrica* fibres. The strength difference made it unsuitable to plot the two together hence the Figure 38 and Figure 39.

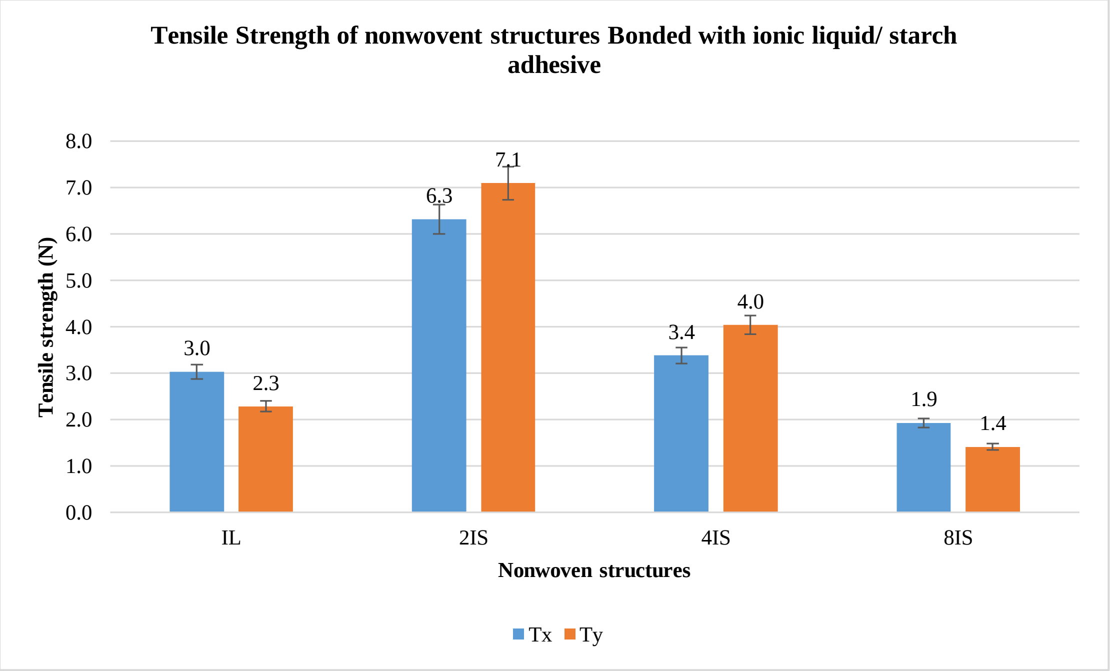


Figure 31: Tensile strength nonwoven structures from *luffa cylindrica* fibres Bonded with ionic liquid/ starch adhesive

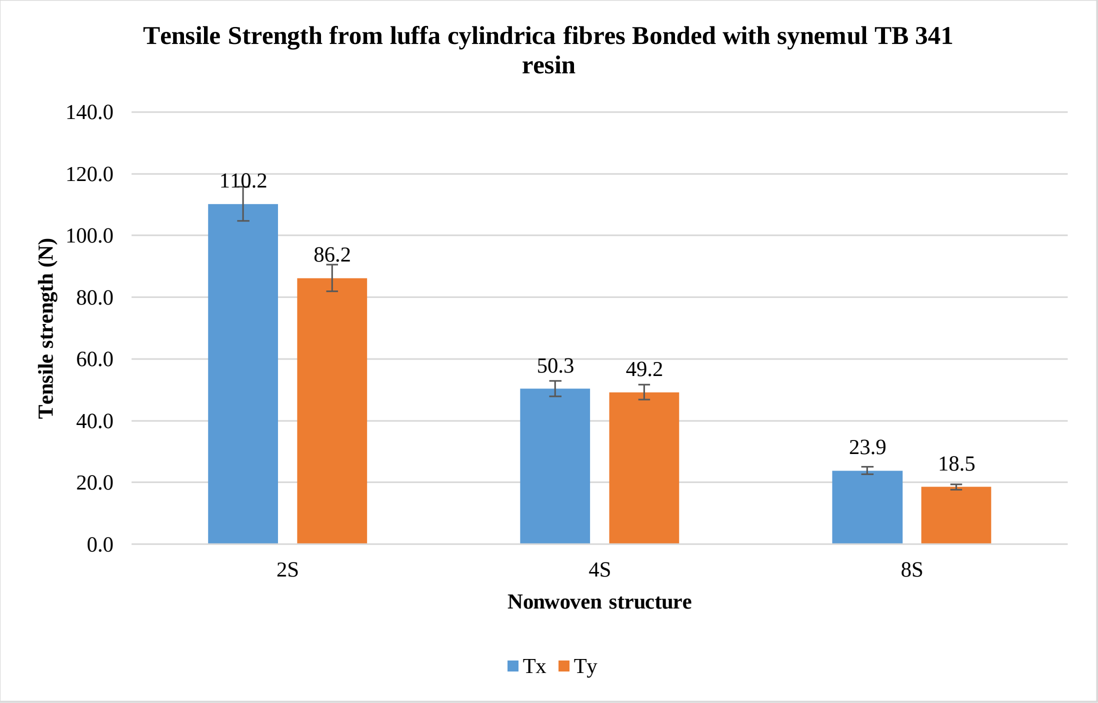


Figure 32: Tensile strength nonwoven structures from *luffa cylindrica* fibres Bonded with synemul TB 341 resin

4.2.4 Elongation

As shown in Figure 40, the percentage elongation of the nonwoven structures seems vary with the pre-treatment given to the fibres more than the direction of the nonwoven structures considering the 4IS structure. Nonwoven structure from *luffa cylindrica* Fibres treated with ionic liquid exhibited the highest percentage elongation in the crosswise (E_y) direction of up to 6.6% which was 57.58% greater than the lowest percentage elongation (exhibited by 4IS). The elongation percentage range for fibres treated with sodium hydroxide and bonded with ionic liquid/starch adhesive was 33.33% and 46.15% in the longitudinal and crosswise directions respectively. The strength difference between orientations of the different nonwoven structures was up to 0.00% (4IS) which is lower than the effect of pre-treatment used implying that nonwoven structures were fairly random laid and isotropic.

Figure 41 shows the percentage elongation properties of *luffa cylindrica* random laid nonwoven structures bonded with synemul TB 341 adhesive. It shows that the percentage elongation of the nonwoven structures were highly dependent on the pre-treatment given to *luffa cylindrica* fibres before laying with a gradual decline from 2S to 8S structures. The reduction in percentage elongation from 2%NaOH to 8%NaOH was 33.33% and 0.00% in the longitudinal and crosswise direction respectively. The 0.00% difference for the structures 2IS and 8IS implies that the percentage elongation in nonwoven structures bonded by ionic liquid/starch adhesive was independent of the pre-treatment given to *luffa cylindrica* fibres.

As regards the effect of bonding agent, nonwoven structures bonded with the synemul TB 341 exhibited much higher percentage elongation of up to 73.91% for same pre-treated *luffa cylindrica* fibres. The elongation difference made it unsuitable to plot the two together hence the Figure 40 and Figure 41.

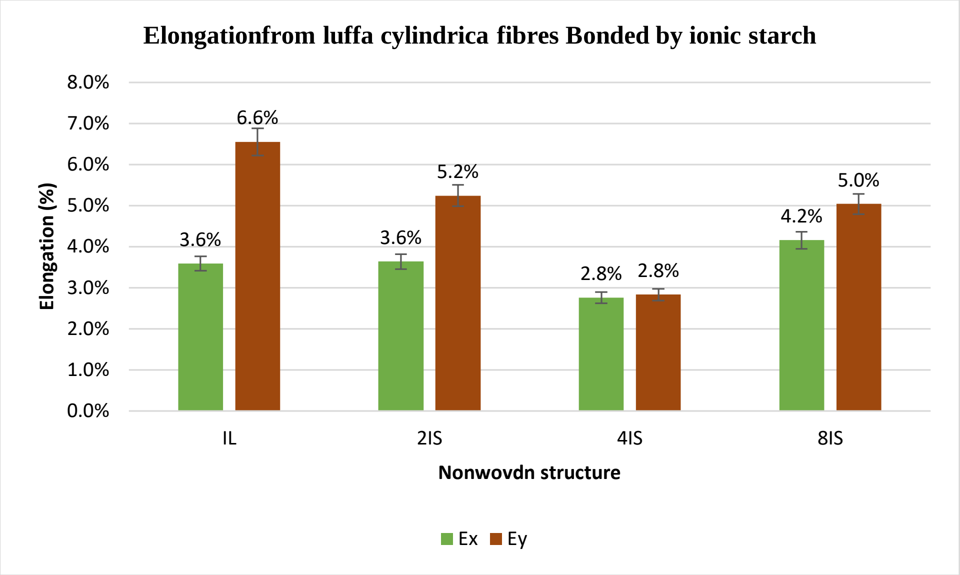


Figure 33: Percentage elongation of nonwoven structures from *luffa cylindrica* fibres Bonded by ionic starch

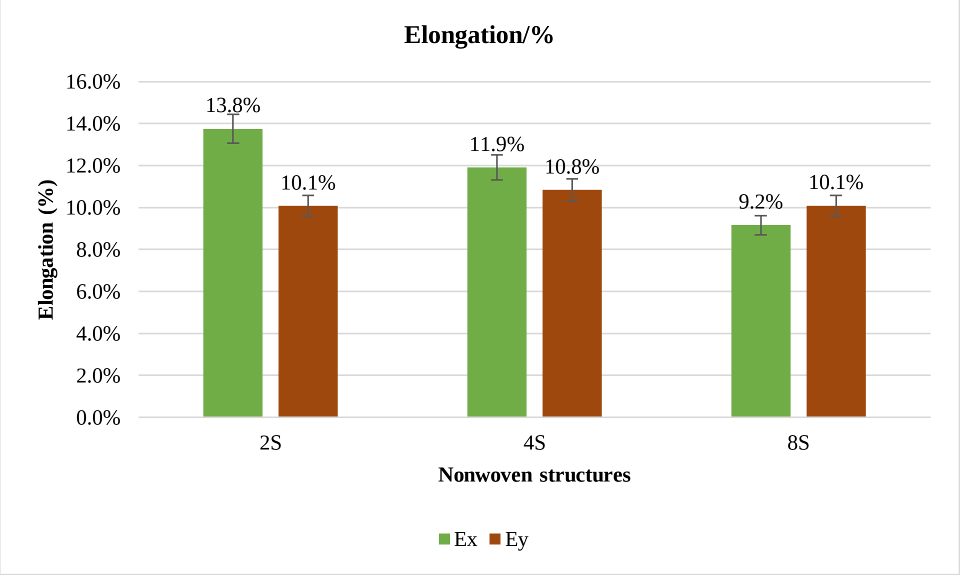


Figure 34: Percentage elongation of nonwoven structures from *luffa cylindrica* fibres Bonded by synemul TB 341

4.2.5 Tearing strength

As shown in Figure 42, the tearing strength of the nonwoven structures seems vary with the pre-treatment given to the fibres more than the direction of the nonwoven structures. Nonwoven structure from *luffa cylindrica* Fibres treated with ionic liquid exhibited the lowest strength in the longitudinal (ts_x) direction of 2293 mN which was 82.97% lower than the exhibited maximum by 2IS nonwoven structure. The tearing strength had percentage range for fibres treated with Sodium Hydroxide and bonded with ionic liquid/starch adhesive of 66.17% and 48.74% in the longitudinal and crosswise directions respectively. The strength difference between orientations of the different nonwoven structures was up to 1.52% (4IS) which is lower than the effect of pre-treatment used implying that nonwoven structures were fairly random laid isotropic in nature.

Figure 43 shows the tearing strength behaviour of *luffa cylindrica* random laid nonwoven structures bonded with synemul TB 341 adhesive. It shows that the tensile strength of the nonwoven structures were dependent on the pre-treatment given to *luffa cylindrica* fibres before laying especially in the longitudinal (ts_x) direction. The tearing strength reduction from 2%NaOH to 8%NaOH was 65.73% and 76.63% in the longitudinal and crosswise direction respectively. This high reduction in the strength of the nonwoven structures bonded with the synemul TB 341 adhesive also reveals that the structures were isotropic in nature. This is because when compared to 8.19% difference between ts_x and ts_y of 8S nonwoven structure except for ts_y for 4S nonwoven structure which shows a ts_x 65.01% greater than ts_y. This can be attributed to some inevitable errors which may result from accidental orientation of the fibres during consolidation causing the internal fibres to realign more in one direction leaving the other direction dependent on the adhesive which has lower tearing strength.

As regards the effect of bonding agent, nonwoven structures bonded with the synemul TB 341 exhibited much higher tearing strength of up to 73.19% (ts_y 2) for same pre-treated *luffa cylindrica* fibres. This tearing strength difference made it illogical to plot the two structures together hence the Figure 42 and Figure 43.

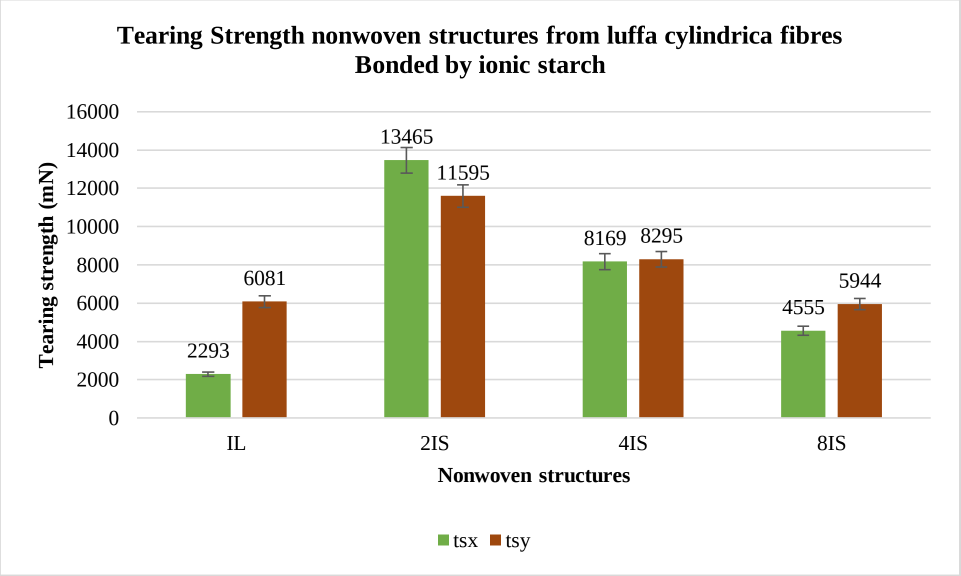


Figure 35: Tearing strength nonwoven structures from *luffa cylindrica* fibres Bonded by ionic starch

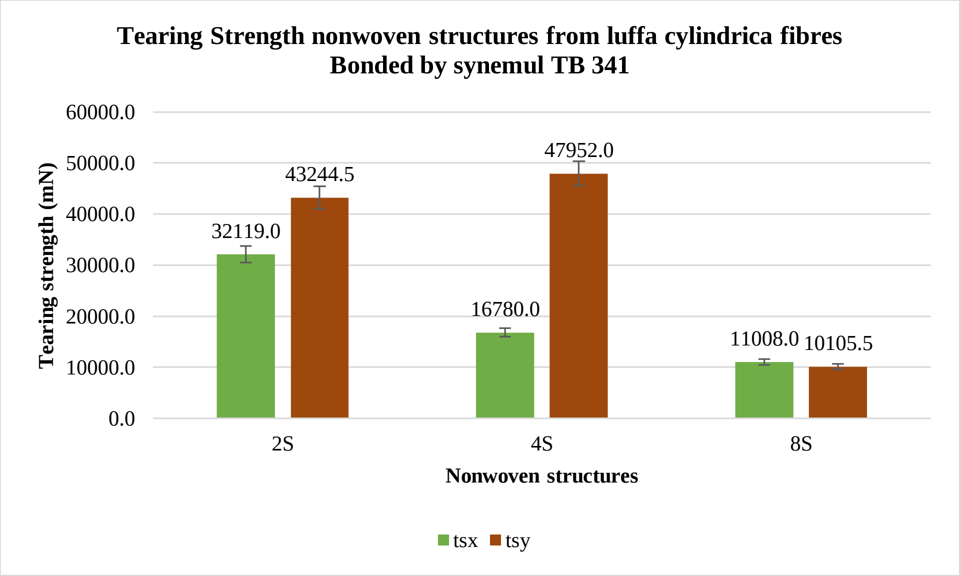


Figure 36: Tearing strength nonwoven structures from *luffa cylindrica* fibres Bonded by synemul TB 341

4.2.6 Bursting strength

As shown in Figure 44, the bursting strength increases with concentration of Sodium Hydroxide used in pre-treatment as observed in a 45.39% increase from 2IS to 8IS. However when synemul TB 341 was used, the bursting strength appears to decrease by 58.66% from 2S to 8S nonwoven structures. As much as the bursting strength of synemul TB 341 bonded nonwoven structures decreased, 8S nonwoven structure was only 3.85% weaker than 8IS. Therefore overall, synemul TB 341 bonded nonwoven structures exhibited superior bursting strength as compared nonwoven structures bonded with ionic liquid/starch adhesive.

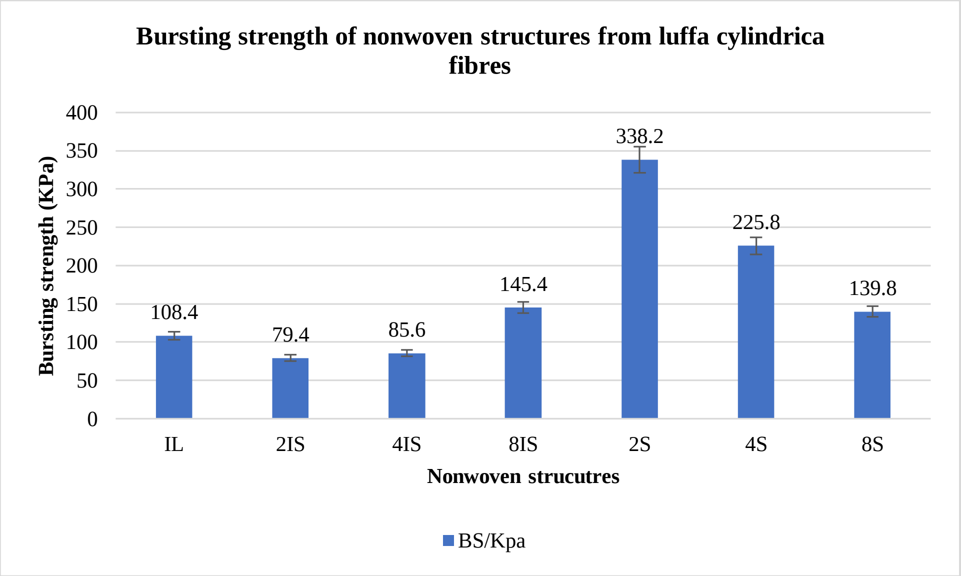


Figure 37: Bursting strength of nonwoven structures from luffa cylindrica fibres

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

This chapter discusses the conclusions and recommendations from the characterisation of *luffa cylindrica* fibres; and the conclusions and recommendations for the nonwoven structure that was produced from *luffa cylindrica* fibres.

5.1 Mechanical properties of *luffa cylindrica* fibres

5.1.1 Conclusion based on properties of *luffa cylindrica* fibres

Luffa cylindrica fibres can withstand sodium hydroxide concentrations above 13% without considerable loss in strength. The regression analysis proved that the strength of *luffa cylindrica* fibres is independent of the caustic treatment. This implies that *luffa cylindrica* fibres can be applied in composites and textile structures intended for use in highly alkaline environments. Since the optimal maximum breaking load based on the regression model was at 8 weeks of retting, it can be concluded retting at 8 weeks is sufficient for degumming. As regards elongation of *luffa cylindrica* fibres, it was observed to increase with concentration of sodium hydroxide due to the tendency of the fibres to fibrate and slide past each other at high caustic concentrations. The tendency to fibrillate can further be observed in the considerable reduction in linear density of the fibres as the concentration of sodium hydroxide increases.

5.1.2 Recommendations for *luffa cylindrica* fibres

In line with the aim of this study, the mechanical properties of *luffa cylindrica* avail great possibility of producing durable nonwoven structures. The fibrillation contributes to increase in contact surface area which results in improved bonding and strength and in the nonwovens and composites. This also implies that with proper equipment, *luffa* *cylindrica* fibres can be used in nano-textiles with a vast range of applications across the spheres of science.

Therefore, *luffa cylindrica* obtained from Uganda can provide a great source of textile fibres which can be used in a wide range of textile applications. With more research, entrepreneurs can be encouraged into exploiting fibres from this plant to produce marketable products. This will result in high demand for this plant translating into more income for the farmers.

5.2 Nonwoven from *luffa cylindrica* fibres

5.2.1 Conclusion based on tensile properties of nonwoven fabric from *luffa cylindrica* fibres

From the tests conducted on the nonwoven structure, it was evident that the nature of bonding has significant effect on the mass per unit area, tensile strength and elongation, tearing strength and bursting strength of the nonwoven made from *luffa cylindrica* fibres.

The mass per unit area of the nonwoven structures ranged from 1645.85 g/m^2 to 3386.26 g/m^2 with an average thickness ranging from 1.5mm to 1.8mm.

The tensile strength in the longitudinal direction was found to be considerably greater than the crosswise tensile strength. The ranges for were T_x = 3.0N - 1.9N and T_y = 2.3N – 1.4N for ionic starch bonded nonwoven structures. Synemul TB 341 bonded structures tensile strength was T_x = 110.2N – 23.9N and T_y = 86.2N – 18.5N. The percentage elongation was in the range of 3.6% - 4.2% in Ex and 6.6% - 5.0% in Ey.

The tearing strength was ranging from 32119 mN to 4555 mN in longitudinal direction and 47952 mN to 5944 mN in the crosswise direction which satisfies the range of 320 mN to 540 mN requirements for shopping bags in Kenya specified by KEBS (Kenya Standard, 2014).

The bursting strength was in the range of 79.4 KPa to 338.2 KPa which satisfies the range of 90 KPa to 162 KParequirements for shopping bags in Kenya specified by KEBS (Kenya Standard, 2014).

5.2.2 Recommendations for the nonwoven structure from *luffa cylindrica* fibres

Since the nonwoven from ionic liquid/starch bonding agent was fairly strong but relatively stiff, this material can be used as filler in packaging fragile objects as a biodegradable substitute to some plastics which are not environmentally friendly.

The nonwoven produced from ionic liquid pre-treated fibres and ionic liquid/starch bonding agent was relative weak but it can find good use in packaging light items which do not require excessive handling.

The nonwoven structure developed with Synemul TB-341 resin very good mechanical properties which satisfied most of the requirements for shopping bags on the Kenyan market.

There is opportunity of blending *luffa cylindrica* fibres with other fibres for in order to avail more potential alternatives as regards substitutes to polythene bags on the Kenyan market as shown in section 5.3.1.

5.6 Further Studies

The current study did not explore the nature and mechanism of bonding in the nonwoven structure produced. This should be studied in future to provide a scientific base of the good properties obtained in the current study.

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APPENDICES

Appendix I: Raw data for moisture regain and moisture content of *luffa cylindrica* fibres

S.no	Oven dry mass (I)	Final mass (F)	I-F	Moisture content	Moisture regain
1	1.903	2.105	0.202	9.60%	10.61%
2	2.536	2.801	0.265	9.46%	10.44%
3	2.26	2.481	0.221	8.91%	9.78%
4	1.7	1.865	0.165	8.85%	9.71%
5	1.304	1.423	0.119	8.36%	9.13%
6	1.815	1.967	0.152	7.73%	8.37%
7	2.27	2.542	0.272	10.70%	11.98%
8	1.977	2.21	0.233	10.54%	11.79%
9	1.907	2.148	0.241	11.22%	12.64%
10	2.088	2.34	0.252	10.77%	12.07%
11	3.551	3.962	0.411	10.37%	11.57%
12	4.96	5.537	0.577	10.42%	11.63%
Average				**9.74%**	**10.81%**
Standard deviation				**1.10%**	**1.34%**

Appendix II: Raw data for lignin content of *luffa cylindrica* fibres

S.no.	**i**	**a**	**b**	**a-b**	**lignin%**
1	0.5	0.543	0.501	0.042	8.40%
2	0.5	0.563	0.495	0.068	13.60%
3	0.5	0.64	0.587	0.053	10.60%
4	0.5	0.708	0.632	0.076	15.20%
5	0.5	0.974	0.921	0.053	10.60%
6	0.5	24.347	24.278	0.069	13.80%
7	0.5	24.18	24.12	0.06	12.00%
Average					**12.03%**
Standard deviation					**2.34%**

Key

i - initial mass of fibre sample

a – mass of fibre sample and drying material

b. – mass of drying empty drying material

a-b – mass of lignin

lignin % = $\frac{a-b}{i} X\ 100\ \%$

Appendix III: Raw data for hemicellulose content of *luffa cylindrica* fibres

S.no.	**i**	**a**	**b**	**a-b**	**Hemicellulose %**
1.	1	1.758	0.965	0.793	21%
2.	1	1.748	0.948	0.8	20%
3.	1	1.768	0.942	0.826	17%
4.	1	1.744	0.953	0.791	21%
5.	1	1.759	0.973	0.786	21%
6.	1	1.793	0.948	0.845	16%
7.	1	1.78	0.961	0.819	18%
Average					**19%**
Standard deviation					**3%**

Key

i - initial mass of fibre sample

a – mass of fibre sample and drying material

b. – mass of drying empty drying material

a-b – mass of Hemicellulose

Hemicellulose % = $\frac{a-b}{i}\ X\ 100\ \%$

Appendix IV: Raw data for cellulose content of *luffa cylindrica* fibres

S.no.	**i**	**a**	**b**	**Cellulose %**
1.	1	0.985	0.358	62.70%
2.	1	1.025	0.354	67.10%
3.	1	0.958	0.321	63.70%
4.	1	1.084	0.458	62.60%
5.	1	1.293	0.616	67.70%
6.	1	1.257	0.529	72.80%
7.	1	0.981	0.349	63.20%
Average				**65.69%**
Standard deviation				**3.77%**

Key

i - initial mass of fibre sample

a – mass of fibre sample and drying material

b. – mass of drying empty drying material

Cellulose % = $\frac{a-b}{i} X \, 100 \, \%$

Appendix V: Breaking load (N) of *luffa cylindrica* fibres.

Conc./%	Gauge/mm	2weeks	stdev	4weeks	stdev	8weeks	stdev
0.0	5	**7.951**	2.60	**12.269**	2.59	**14.442**	2.18
	10	**7.167**	1.59	**7.864**	2.12	**9.014**	2.94
	20	**4.170**	1.36	**7.483**	1.29	**8.605**	2.98
0.5	5	**7.801**	2.82	**13.418**	3.84	**13.884**	2.73
	10	**6.565**	1.93	**9.591**	3.46	**11.425**	4.21
	20	**6.565**	2.34	**7.565**	2.49	**8.763**	2.88
1.0	5	**7.558**	2.47	**9.169**	1.91	**11.788**	2.78
	10	**7.213**	3.45	**7.423**	2.99	**11.050**	3.16
	20	**6.044**	2.01	**5.502**	2.71	**9.885**	3.29
2.0	5	**6.541**	2.18	**7.663**	1.24	**10.732**	3.31
	10	**6.532**	2.17	**7.585**	1.66	**8.944**	3.08
	20	**4.112**	2.10	**7.073**	1.50	**7.990**	3.18
4.0	5	**6.397**	3.09	**7.203**	1.96	**10.731**	4.66
	10	**4.522**	1.22	**7.064**	1.84	**10.633**	2.54
	20	**4.330**	1.31	**6.936**	1.62	**9.978**	2.58
8.0	5	**5.532**	1.28	**7.083**	2.03	**10.383**	3.40
	10	**5.425**	1.92	**6.751**	2.06	**8.335**	1.85
	20	**3.628**	1.66	**6.197**	2.52	**5.635**	1.79
16.0	5	**3.989**	1.43	**5.827**	2.73	**6.954**	1.41
	10	**3.836**	1.98	**5.493**	2.52	**5.836**	1.40
	20	**2.980**	2.08	**4.961**	1.95	**5.595**	2.36

Appendix VI: Elongation (mm) of *luffa cylindrica* fibres.

Conc./%	Gauge/mm	2weeks	stdev	4weeks	stdev	8weeks	stdev
0.0	5	**0.642**	0.32	**0.906**	0.28	**1.201**	0.31
	10	**0.808**	0.29	**0.583**	0.32	**1.045**	0.30
	20	**0.793**	0.22	**0.801**	0.35	**1.309**	0.46
0.5	5	**0.715**	0.28	**0.857**	0.26	**1.185**	0.23
	10	**0.908**	0.32	**0.883**	0.37	**1.329**	0.43
	20	**1.318**	0.50	**0.782**	0.32	**1.787**	0.48
1.0	5	**0.919**	0.24	**0.833**	0.33	**0.656**	0.25
	10	**1.341**	0.53	**0.701**	0.27	**0.673**	0.31
	20	**1.355**	0.27	**0.954**	0.44	**1.056**	0.46
2.0	5	**0.587**	0.26	**0.755**	0.28	**0.619**	0.26
	10	**0.900**	0.49	**0.873**	0.35	**0.802**	0.36
	20	**0.909**	0.38	**1.243**	0.42	**1.040**	0.37
4.0	5	**0.954**	0.34	**1.178**	0.75	**0.790**	0.38
	10	**1.455**	0.63	**1.280**	0.54	**0.968**	0.26
	20	**1.953**	0.55	**1.467**	0.49	**1.656**	0.44
8.0	5	**0.512**	0.40	**0.871**	0.33	**0.985**	0.28
	10	**0.780**	0.27	**0.899**	0.43	**1.189**	0.49
	20	**0.654**	0.48	**1.365**	0.72	**0.921**	0.38
16.0	5	**0.611**	0.35	**0.585**	0.17	**0.651**	0.22
	10	**0.431**	0.26	**0.610**	0.25	**0.769**	0.29
	20	**1.011**	0.38	**0.900**	0.43	**1.181**	0.61

Appendix VII: Linear density (dTex) of *luffa cylindrica* fibres.

		Tex			dTex		
conc./%	**gauge/mm**	**2weeks**	**4weeks**	**8weeks**	**2weeks**	**4weeks**	**8weeks**
0.0	5	70	68	57	695	677	572
	10	70	68	57	695	677	572
	20	70	68	57	695	677	572
0.5	5	63	62	53	629	621	530
	10	63	62	53	629	621	530
	20	63	62	53	629	621	530
1.0	5	58	60	51	582	603	510
	10	58	60	51	582	603	510
	20	58	60	51	582	603	510
2.0	5	56	59	50	559	588	500
	10	56	59	50	559	588	500
	20	56	59	50	559	588	500
4.0	5	56	53	49	557	532	494
	10	56	53	49	557	532	494
	20	56	53	49	557	532	494
8.0	5	54	52	48	541	520	477
	10	54	52	48	541	520	477
	20	54	52	48	541	520	477
16.0	5	51	51	47	505	509	470
	10	51	51	47	505	509	470
	20	51	51	47	505	509	470

Appendix VIII: Tenacity (cN/Tex) of *luffa cylindrica* fibres.

		F/cN			tex			tenacity cN/tex		
conc./%	**gauge/mm**	**2week**	**4week**	**8week**	**2week**	**4week**	**8week**	**2week**	**4week**	**8week**
0.0	5	795.1	1226.9	1444.19	69.53	67.65	57.19	11.44	18.14	25.25
	10	716.6	786.39	901.42	69.53	67.65	57.19	10.31	11.62	15.76
	20	417.0	748.29	860.49	69.53	67.65	57.19	6.00	11.06	15.05
0.5	5	780.0	1341.7	1388.39	62.87	62.06	53.05	12.41	21.62	26.17
	10	656.5	959.07	1142.53	62.87	62.06	53.05	10.44	15.45	21.54
	20	656.5	756.51	876.29	62.87	62.06	53.05	10.44	12.19	16.52
1.0	5	755.7	916.89	1178.81	58.19	60.29	51.02	12.99	15.21	23.11
	10	721.2	742.32	1105.05	58.19	60.29	51.02	12.39	12.31	21.66
	20	604.4	550.21	988.45	58.19	60.29	51.02	10.39	9.13	19.37
2.0	5	654.1	766.34	1073.18	55.91	58.84	50.05	11.70	13.02	21.44
	10	653.1	758.46	894.37	55.91	58.84	50.05	11.68	12.89	17.87
	20	411.2	707.32	798.96	55.91	58.84	50.05	7.35	12.02	15.96
4.0	5	639.7	720.27	1073.09	55.75	53.24	49.35	11.47	13.53	21.74
	10	452.20	706.39	1063.27	55.75	53.24	49.35	8.11	13.27	21.54
	20	433.03	693.64	997.81	55.75	53.24	49.35	7.77	13.03	20.22
8.0	5	553.17	708.35	1038.29	54.07	52.94	47.71	10.23	13.38	21.76
	10	542.51	675.15	833.55	54.07	52.94	47.71	10.03	12.75	17.47
	20	362.77	619.68	563.53	54.07	52.94	47.71	6.71	11.70	11.81
16.0	5	398.87	582.68	695.43	50.53	50.85	47.04	7.89	11.46	14.78
	10	383.62	549.34	583.55	50.53	50.85	47.04	7.59	10.80	12.41
	20	298.05	496.06	559.53	50.53	50.85	47.04	5.90	9.75	11.90

Appendix IX: Tensile strength of nonwoven from *luffa cylindrica* fibres.

Sample	**Tensile strength/N**	
	T_x	T_y
IL	3.0	2.3
2IS	6.3	7.1
4IS	3.4	4.0
8IS	1.9	1.4
2S	110.2	86.2
4S	50.3	49.2
8S	23.9	18.5

Appendix X: Percentage elongation of nonwoven from *luffa cylindrica* fibres.

Sample	**Elongation/mm**		**Elongation/%**	
	E_x	E_y	E_x	E_y
IL	3.6	6.6	3.6%	6.6%
2IS	3.6	5.2	3.6%	5.2%
4IS	2.8	2.8	2.8%	2.8%
8IS	4.2	5.0	4.2%	5.0%
2S	13.8	10.1	13.8%	10.1%
4S	11.9	10.8	11.9%	10.8%
8S	9.2	10.1	9.2%	10.1%

Appendix XI: Mass per unit area and thickness of nonwoven from *luffa cylindrica* fibres

Sample	Length	Width	Area/cm^2	Mass	g/m^2	Thickness/mm
IL	12.5	6.5	81.3	15.5	1904.9	1.6
2IS	15.9	5.1	81.4	13.4	1645.8	1.5
4IS	12.9	6.7	85.8	16.9	1968.5	1.5
8IS	13.0	6.8	87.8	16.2	1849.1	1.8
2S	15.0	6.5	97.5	33.0	3386.3	1.8
4S	14.9	7.0	104.3	23.7	2275.1	1.5
8S	15.8	7.0	110.8	27.6	2486.9	1.7

Appendix XII: Tearing strength of nonwoven structure from *luffa cylindrica* fibres

Sample	Tearing strength/N		Tearing strength/mN	
	ts_x	ts_y	ts_x	ts_y
IL	2.3	6.1	2292.5	6080.5
2IS	13.5	11.6	13464.5	11594.5
4IS	8.2	8.3	8169.0	8294.5
8IS	4.6	5.9	4555.0	5944.0
2S	32.1	43.2	32119.0	43244.5
4S	16.8	48.0	16780.0	47952.0
8S	11.0	10.1	11008.0	10105.5

Appendix XIII: Bursting strength of the nonwoven structure from *luffa cylindrica* fibres

Sample	**BS /bar**	**BS/KPa**
IL	1.084	108.4
2IS	0.794	79.4
4IS	0.856	85.6
8IS	1.454	145.4
2S	3.382	338.2
4S	2.258	225.8
8S	1.398	139.8

Key

BS – Bursting Strength

KPa – Kilopascal