DEVELOPMENT AND CHARACTERIZATION OF BIO-COMPOSITES FROM BANANA PEELS BIO-RESIN, PSEUDO-STEM BANANA AND SISAL FIBRES

BY

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DECLARATION

Declaration by the Candidate

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DEDICATION

I hereby dedicate this thesis report to the European Commission and Mobility for Enhancing Training of Engineering Graduates in Africa (METEGA) project for the financial support without which I would not have completed this Masters programme.

ABSTRACT

Composite materials result into lightweight structures with high stiffness and tailored properties for specific applications. Interest in agricultural materials for bio-composites has grown rapidly due to their renewability, biodegradability and eco-friendliness hence an alternative to non-renewable and non-biodegradable synthetic materials. Over 30 million tons of banana peels are thrown away annually worldwide, hence disposed of by burning that is environmentally unfriendly. Banana peels have a potential of development into eco-friendly resins for bio-composite production. Banana pseudo-stems are used for banana fibres though some are thrown away without further value addition. There is also a declining trend of sisal production worldwide due to competition from polypropylene synthetic fibres used in sack making, hence a decline in agricultural employment opportunities. Bio-composites from renewable resources therefore, will reduce waste disposal, promote agricultural value addition and create more employment opportunities. The objectives of this study were to develop, characterize and optimize bio-resin development from raw banana peels. Then surface-treat and characterize pseudo-stem banana and sisal fibres, followed by development, characterization and optimization of the design of bio-composites from banana peels bio-resin, pseudo-stem and sisal fibres. Pureed raw banana peels paste was mixed with various ratios of water and Glycerine at different temperatures and time and the bio-resin characterized for viscosity and density. Pseudo-stem banana and sisal fibres were treated with 4% sodium hydroxide, boiled at 100^0C for 1 hour, dried under the sun and characterized. The fibres were chopped to a critical length of 15mm and bio-composites produced using the hand layup technique and characterized. Using surface response experimental design and regression analysis, effect of fibre volume fraction, bio-resin mass and Glycerine mass on the mechanical properties of the developed bio-composites were studied. The viscosity model exhibited an R^2 value of 0.95 and an optimum viscosity of 242 mPa.s. Percentage contributions of factors affecting viscosity of the bio-resin were water amount at 20% and Glycerine amount (18.6%) among others. Regression analysis for bio-resin density yielded an R^2 of 0.83 with an optimized density of 0.95g/cm^3. Viscosity and density values were in close range with other commercial resins. Treated pseudo-stem banana fibres yielded a linear density of 12.52tex, elongation (0.49%), tenacity (189.5MPa) and Young's modulus (3Gpa). Treated sisal fibres yielded a linear density of 23.84tex, elongation (1.03%), tenacity (217.13MPa) and Young's modulus (5.6Gpa). There was significant improvement in the mechanical properties of treated pseudo-stem banana and sisal fibres than untreated fibres. Treated pseudo-stem banana and sisal fibres were used for bio-composite development using the optimized bio-resin. Sisal and banana bio-composites yielded tensile strengths of 5.2MPa and 4.2MPa respectively, with an R^2 value of 0.93 and fibre volume fraction contributing the highest percentage of 38.11% to the model. The sisal and banana bio-composites also exhibited compressive strengths of 2.9MPa and 2.1MPa respectively with an R^2 value of 0.92 and fibre volume fraction contributing the highest percentage of 42.8% to the model. The optimized bio-composites were comparable to the available commercial composite boards. The developed bio-resin can be used in development of bio-composites for interior applications including partition, ceiling and notice boards as an alternative to non-renewable and non-biodegradable petroleum based materials and solid wood products.

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Chapter 1 : INTRODUCTION

1.0 Introduction

This chapter presented the role of bio-composites in the current century. It highlighted the paradigm shift from non-renewable and non-biodegradable synthetic and solid wood products to eco-friendly materials. It further elaborated on the underlying dangers of petroleum-based resources in relation to advantages accruing to renewable natural resources. The chapter therefore, justified the need for research in bio-composites and the likely positive outcomes. The main and specific objectives and the scope of the study illustrating how these objectives were achieved are outlined.

1.1 Background of the study

Composites often culminate into lightweight structures having high stiffness and tailored properties for specific applications hence saving on weight. Bio-composites are materials made from fibres (natural or synthetic) and petroleum-derived non-biodegradable polymers or bio-polymers. However, bio-composites derived from natural plastics and fibres are more eco-friendly hence among the most desired materials of the 21st century. The non-renewability and non-biodegradability of petroleum resources, depletion of solid wood products, environmental concerns and increasing awareness of the carbon footprint are directing research into natural fibre reinforced composites for new applications. Due to waste disposal problems and strong environmental regulations (European Union (EU) Packaging Directive (1997), EU Landfill Directive (1999) and EU Directive for automotive parts (2000), a great part of scientific research has been directed to bio-degradable eco-composite materials. Europe is the largest region for natural fibre composites for automotive applications and North America is the largest region for

building and construction applications. By 2016, the global market for natural fibre composites was expected to reach 3.8 billion (US Dollars) at a compound annual growth rate of 10% and 11.2% during 2014-2019 (Lucintel, 2011; Research and Markets, 2014).

Agriculture is a major source of raw materials for the natural fibre composites market worldwide. Currently, natural fibres account for over 14% share of the global composites reinforcement projected to rise to 28% by 2020 (Hobson and Carsus, 2011). Banana plants are grown in over 135 tropical and subtropical countries hence over 30 million tons of banana peels are thrown away annually worldwide leading to environmentally unfriendly burning (Lisey, 2013). However, some of the ripe banana peels have been used for production of bio-plastics with a potential for use in insulation and cosmetic prosthetics (Bilgin, 2013). Therefore, banana peels have a potential of conversion into thermoplastic bio-resins for bio-composite development. Banana pseudo-stems are used for paper pulp and banana fibres; some thrown away without further value addition (Alwani et al, 2015). There is also a global declining trend in the sisal industry due to competition from non-biodegradable and non-renewable polypropylene fibres currently being used for sack making. Sisal occupies 6th place among fibre crops, representing about 2% of the world plant fibres production. The world's largest producers are Brazil, China, Mexico, Kenya, Tanzania and Madagascar (Muthangya, 2009).

In recent decades, natural fibres as an alternative reinforcement in polymer composites have attracted the attention of many researchers and scientists due to their advantages over conventional glass and carbon fibres (Malkapuram et al, 2008). Natural fibres including pseudo-stem banana and sisal fibres constitute examples of renewable and sustainable materials hence a continous fibre supply (Arpitha et al, 2014). The interest on these

agricultural fibres has grown rapidly due to their abundance, renewability, biodegradability, low density and non-toxic nature suitable for bio-composites development hence an altenative to non-renewable and non-biodegradable man-made fibres (Oksman et al, 2002). Bio-composites form the basis for a portfolio of industrial, sustainable and eco-efficient products for application in automotives, packaging, building and construction products, electrical and insulated appliances, furniture, consumer and household goods (Mohanty et al, 2005). This research therefore, endeavoured to develop and characterize bio-composites using bio-resin from raw banana peels, pseudo-stem banana and sisal fibres as reinforcement.

1.2 Problem statement

Petroleum based materials are non-biodegradable hence disposed of by incineration that emits toxic gases like dioxin into the atmosphere hence air pollution and global warming. Furthermore, petroleum waste leads to soil fertility poisoning, human health problems and hazards for animals, birds and fish through entrapping, ingestion or intoxication of the pollutants. Therefore, fabrication of alternative bio-composite materials will decrease un-decomposable solid wastes and their negative environmental and eco-life impact. In addition, non-renewability of petroleum resources and depletion of solid wood products is a great threat worldwide and continuous usage will endanger the next generations. Consumption of renewable and sustainable materials like bio-composites therefore, will greatly reduce this catastrophe. Banana plants being global food crops have abundant agro-waste which is difficult to dispose of. Every year, over 30 million tons of banana peels are thrown away worldwide (Lisey, 2013). This sometimes leads to disposal by enviromentally unfriendly burning. There is also a global declining trend of sisal production, a non-food

but cash crop due to competition from non-renewable and non-biodegradable polypropylene fibres currently used for sack making. Therefore, development of these bio-composites will reduce negative environmental impact, control depletion of non-renewable materials, promote agricultural value addition and create employment opportunities for most of the rural population.

1.3 Justification of the study

In a bid to fulfil the United Nations Sustainable Development Goals of 2030, global awareness on eco-friendly materials is taking a paradigm shift. Promoting food security and sustainable agriculture, enhancing sustainable consumption and production and combating climate change and its negative impact are among the key development goals. The growing ecological, social and economic awareness, high depletion rate of petroleum and solid wood resources, concepts of sustainability and new environmental regulations have stimulated the search for bio-composite materials. This would reduce the negative petroleum based environmental and eco-life impact, control depletion of non-renewable materials, promote agriculture and create employment opportunities**.** Furthermore, the global availability of banana agro-waste (pseudo-stems and banana peels) is responsible for the new interest in sustainable technology. Over 30 million tons of banana peels are thrown away globally every year. Also banana pseudo-stems are used for paper pulp and banana fibres, yet some are thrown away without further value addition. These potentially serve as inexpensive sources of key components of bio-composites hence adding value and turning waste into wealth as is the case in Uganda, shown by photos taken in Figure 1.

Figure 1: Photos of lamp shades and fibre board from banana fibres and cornstarch

In addition, there is a global declining trend of sisal production (Wilhelm, 2013) as non-food but cash crops hence need for revitalization of the sisal industry due to increasing demand for eco-friendly composite materials worldwide. More so, agriculture is a major back borne to most African economies hence a source of employment to especially the rural population. Furthermore, the high depletion rates of solid wood products especially in East Africa posses a need for alternative and eco-friendly materials. Currently, non-renewable and non-biodegradable petroleum-based materials claim a major share as wood substitutes. However, bio-composites present a better alternative since renewable resources as their raw materials, are lighter due to their favourable density in comparison with other synthetic and metallic materials. This attribute in combination with other favourable properties are beneficial where lighter materials are required.

1.4 Significance of the study

This research delivered banana and sisal bio-composites for application in ceiling, partition, notice boards and wall hangings from banana agro-waste and sisal fibres that are renewable resources. Since the developed bio-composites were eco-friendly, human health and eco-life would be preserved and conserved. Furthermore, the bio-composites would be

a source of inspiration for further research in green science and technology. Research and development in bio-composites would enhance value addition through conversion of agro-waste to wealth. This would also provide a better solution to agro-waste disposal rather than burning. In addition, development of the bio-composites would attract more people into the agricultural sector and home based cottage industry, hence economic growth and livelihood improvement.

1.5 Objectives of the study

The objectives of the study were categorized as the main and specific objectives.

1.5.1 Main objective

The main objective of the study was to develop and characterize bio-composites from banana peels bio-resin, pseudo-stem banana and sisal fibres.

1.5.2 Specific objectives

The specific objectives of the study were:

Objective 1: To develop and characterize locally made bio-resin from raw banana peels in terms of viscosity and density.

Objective 2: To surface-treat and characterize pseudo-stem banana and sisal fibres in terms of linear density, tenacity, Young’s modulus and elongation.

Objective 3: To develop and characterize banana and sisal bio-composites in terms of tensile strength, Young’s modulus, elongation and compressive strength.

1.6 Scope of the study

Raw banana peels were collected from Naguru market (Kampala–Uganda) and used to develop a bio-resin from Uganda Industrial Research Institute. Glycerine bio-resin plasticizer was purchased from Desbro Uganda Limited. The universal rotatable design and multiple regression analysis were used to characterize and optimize the bio-resin in terms of viscosity and density. Pseudo-stem banana and sisal fibres were purchased from Afri-Banana Limited and Kamwe Business Solutions (Uganda) respectively. The fibres were surface treated with Sodium Hydroxide from Desbro Uganda Limited, characterized and paired T-tests used for fibre analysis. Development of the bio-composites was done at Rivatex, Eldoret Polytechnic, Moi University Mechanical, Textile and Industrial Engineering laboratories. Characterization and optimization of the bio-composites was done using universal rotatable experimental design and multiple regression analysis.

Chapter 2 : LITERATURE REVIEW

2.0 Introduction

This chapter was a review of related literature by other researchers on bio-composites developed from natural resins and fibre materials. It presented an overview on bio-composites and the need for research into sustainable and eco-friendly materials. It also highlighted the major application areas of composites, the various natural resins and fibres including their properties as employed in bio-composite production.

2.1 Development and characterization of bio-resin from raw banana peels

Bio-composites derived from natural resins and fibres are likely more eco-friendly hence fits perfectly into the design of bio-composites using bio-resin from raw banana peels as the matrix, pseudo-stem banana and sisal fibres as the reinforcements (Netravali and Chabba, 2003).

2.1.1 Development of bio-resins

Thermoplastic materials currently dominate as matrices for bio-fibres used for bio-composites development. The commonly used thermoplastics for this purpose are polypropylene (PP), polyethylene, polyether ether ketone (PEEK) and poly Vinyl Alcohol (PVA). Among these resin materials, PEEK is most widely used in bio-composites development. However, the complete biological degradability, reduction in volume of waste and compostability, mitigation of climate change due to the increasing carbon footprint and increased utilization of agricultural resources for the production of new “green” materials are some of the reasons for public interest in development of materials from renewable sources (Mohanty et al, 2005). Therefore, biodegradable resins are explored as the best forms of polymers for composites apart from their synthetic

alternatives, which are non-renewable. Figure 2 shows the various categories of biodegradable polymers for bio-composites development (Mohanty et al, 2005). Demand for biomaterials is spearheading a paradigm shift from conventional polymers to biopolymer materials. A new biodegradable epoxy resin CHS-Epoxy G520 developed by Spolchemie Limited (Czech Republic) has been discovered to produce stronger bio-composites (33MPa) for automotive instrument panel applications than synthetic epoxy composites (30MPa) (Rwahwiire et al, 2015).

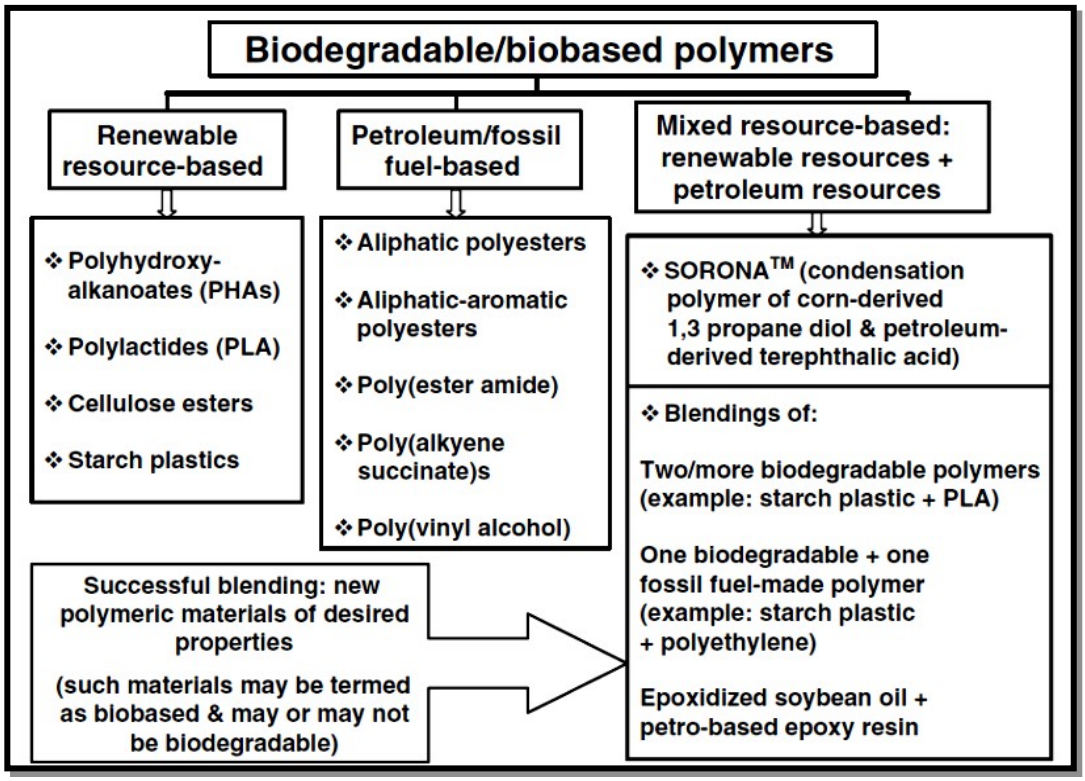


Figure 2: Categories of various biodegradable polymers (Mohanty et al, 2005).

However, the best-known renewable resources capable of making biodegradable plastics are starch. It is one of the least expensive biodegradable materials available in the world market today. It is a versatile biopolymer with immense potential for use in non-food

industries (Narayan, 1998). Unfortunately, these starch sources including potatoes, maize corn and wheat are food items worldwide. However, raw banana fruits possess about 20% starch whereas ripe bananas have starch content between 11-13%. Grade 1 green banana peels possess 3% starch, which reduces to between 1% - 2% in grade 4 ripe banana peels according to the colour guide in Figure 2 showing banana ripening grades (Phatcharaporn et al, 2008). Over 30 million tonnes of banana peels are thrown away globally every year yet are a cheap source of bio-raw materials.

Figure 3: Banana ripening grades hence reducing starch content (Lourdes et al, 2004).

According to Bilgin (2013), ripe banana peels at grade 4 were used in production of bio-plastic as an alternative to petroleum plastics for insulation and cosmetic prosthetic applications. Several studies on biodegradable resins for bio-composites development have also been done (Mohanty et al, 2005; Alvarez et al, 2009; Susheel et al, 2011). However, no literature exists on bio-resins from raw banana peels for bio-composites development. To prepare biodegradable resins, starch granules are mixed with plasticizers or additives

and by gelatinization process, it is possible to obtain thermoplastic starch (TPS). Plasticizers are added to avoid the brittleness of the products and to increase their flexibility and end uses (Susheel et al, 2011). This can be done by application of mechanical, thermal, or thermo-mechanical energy in the presence of water and plasticizers including glycerol, sorbitol and poly(ethylene glycol). Efficient plasticizers generally have low molar mass, a high boiling point and exhibit low viscosities and low temperature coefficients of viscosity (Graaf et al, 2003). Glycerine produces stronger hydrogen bonding with starch, increasing the strength and toughness of the composite materials (Soest et al, 1997). Furthermore, glycerol is a by-product generated in large amounts in the bio-fuel industry and is becoming nowadays a waste product (Yazdani, 2007). According to Curvelo et al (2001) and Wattanakornsiri et al (2012), glycerol content should be in the ranges of 20 to 40%. They noted that lower and higher glycerol content led to samples that were too much brittle or to discharge phenomena of glycerol from the samples respectively.

2.1.2 Characterization and application of bio-resins

According to Satin (2007), starch has two major components: amylose and amylopectin as shown in Table 1. These components are very different structurally, amylose being linear and amylopectin highly branched. The viscosity, shear resistance, gelatinization, textures, solubility, tackiness, gel stability, cold swelling and retro-gradation are all functions of starch amylose to amylopectin ratio. Despite the amylopectin’s high molecular weight, its intrinsic viscosity is very low because of its extensively branched molecular structure (Mohanty et al, 2005).

Table 1: Amylose and Amylopectin in various starch sources (Satin, 2007).

Starch	% Amylose	% Amylopectin
High Amylose Corn	70	30
Maize corn	28	72
Wheat	26	74
Sago	26	74
Arrowroot	21	79
Raw banana	20.7	79.3
Irish Potato	20	80
Rice	19	81
Sweet Potato	18	82
Cassava	17	83

Viscosity is the most important technological characteristic in the processing of polymeric materials. It is the only parameter used for characterization of Newtonian liquid materials. It is the measure of internal friction of a fluid hence the time required for a liquid to drain out of a capillary tube is directly proportional to its viscosity (Stabik et al, 2009). Dynamic (apparent) viscosity is used to characterize liquid products for example molten polymers whereas kinematic viscosity is a measure of the resistance to flow of a fluid under the influence of gravity. Dynamic viscosity is measured in milli-Pascal times second/centipoises or Pascal times second while kinematic viscosity is measured in centistokes (Wypych, 2000; ASTM Standards, 2005). Table 2 represents the pros and cons of viscosity measuring techniques.

Table 2: Pros and cons of viscosity measuring techniques (Stabik et al, 2009).

Viscosity Measuring Technique	Advantages	Disadvantages
Zahn viscosity cup: The cup is filled level full with the liquid under test and the time for the material to flow through one of the standard orifices is measured. For liquids that have viscosity from 20 to 1600 cSt in the range (Stabik et al, 2009)	1. Used to measure viscosity directly in tanks or containers. 2. Several cup nozzles for various viscosities. 3. Easy to use and robust	1. For viscosity control work only within one plant or laboratory. 2. Limited to Newtonian & near Newtonian materials. 3. Lower accuracy & bias than Ford & Brookfield Viscometer
Falling Needle Viscometer: Viscosities of Newtonian, non-Newtonian fluids by measuring the constant velocities of cylindrical needles as they fall through the test liquid under the influence of gravity. (Stabik et al, 2009)	1. Both Newtonian & non Newtonian materials. 2. Due to the simplicity of design, well suited to high temperature viscosity.	1. More expensive than Ford and Zahn cups.
Brookfield Rotational Viscometer: Cover the determination of the apparent viscosity and the shear thinning and thixotropic properties of non-Newtonian materials. Test Method A determines apparent viscosity by measuring the torque on a spindle rotating at a constant speed in material. (ASTM, D2005)	1. Better accuracy & bias than Ford & Brookfield Viscometer. 2. Low temperature viscosities as applies to this research. 3. Availability and accessibility locally.	1. More expensive than Ford and Zahn cups. 2. Limited to Newtonian materials.

The density of starch samples can also be determined using a pycnometer according to ASTM standard D854 - 2010. This is a flask with a close-fitting ground glass stopper with

a fine hole through it, so that a given volume can be accurately obtained. This enables the density of a fluid to be measured accurately, by reference to an appropriate working fluid such as water or mercury, using an analytical balance. If the flask is weighed empty, full of water, and full of a liquid whose specific gravity is desired, the specific gravity of the liquid can easily be calculated. Density is measured grams/cm^3 or kilograms/m^3. Other methods include the densymeter, aerometer and ultrasonic pulse echo method (Kazys and Rekuviene, 2011). Table 3 represents the properties of common thermoplastic and thermoset resins.

Table 3: Properties of some common thermoplastic and thermoset resins

No.	Matrices (Resins)	Viscosity (CPS/MPa.s)	Density (g/cm^3)	References
	Thermosets			
1	Epoxy (Lapox A-31) @ 25^0C	25,000 - 45,000	1.06 – 1.18	(Atur Limited, 2015)
2	Green Epoxy (G520-G530) @25^0C	8,000 – 14,500	-	(Spolchemie Limited, 2014)
3	Polyester Resins	3,000	1.12 - 1.46	(Expert Process Systems, 2014)
4	Phenolic Resins	500 – 40,000	-	(Sumitomo Ltd, 2015)
	Thermoplastics			
1	Urea Formaldehyde Resins	300 – 450	1.0 – 1.3	(Aime et al, 2005)
2	Polypropylene (PP)	-	0.85 – 0.96	(Expert Process Systems, 2014)
3	Poly Vinyl Alcohol (PVA)	65,000	1.3	(Li et al, 2013)
4	Cornstarch	250 – 1,500	1.21	
5	Tapioca pudding @ 113^0C	500 - 1,000	0.7	Expert Process Systems, 2014)

Furthermore, thermoplastic starch is fully biodegradable in a wide variety of environments as it can be hydrolyzed into glucose by microorganisms or enzymes, metabolized into

Carbon dioxide and water (Wattanakornsiri et al, 2012). However, when compared to synthetic biodegradable polymers, thermoplastic starch has disadvantages like strong ability to absorb water and poor mechanical and thermal properties (Alberta et al, 2004). According to Mohanty et al (2005), the performance limitations of biopolymers are major barriers for their widespread acceptance as substitutes for traditional non-biodegradable polymers. The other challenge lies in the fact that biodegradable polymers should be stable during storage or use and only degrade when disposed of after their intended lifetime. However, they noted that biopolymers reinforced with bio-fibres can produce novel bio-composites to replace and substitute glass fibre-reinforced composites in various applications. The reinforcement of the thermoplastic starch matrix with natural ligno-cellulosic fibres seems to be the logical alternative to increase their mechanical performance and to preserve the green character of the final product (Girones et al, 2012). Cellulose fibres commonly used are sisal, banana, wood, cotton, jute, and kenaf (Alvarez et al, 2009; Lamis et al, 2013). Furthermore, Table 4 shows other types of fibres and thermoplastic starch sources employed in bio-composites development.

Table 4: Developed cellulose fibre reinforced thermoplastic starch bio-composites

Starch Type	Plasticizer Ratio	Fibre Type	Fibre Ratio
Corn (Curvelo et al, 2001)	30wt% (glycerol)	Eucalyptus Urongrandis	0 and 16
Wheat (Averous and Boquillon, 2004)	$TPS_{1:}$ 18wt% (glycerol) and 12% (water); TPS_2: 35%wt (glycerol)	Leafwood & paper pulp fibres from broad leaved species	$TPS_{1:}$ 0,15 and 30 TPS_2: 0, 4, 8, 10, 12, 16 and 20.
Cassava (Tapioca) (Wattanakornsiri, et al 2012)	30wt% (glycerol)	Used office paper and newspapers	0, 2, 6, 8

2.2 Surface treatment and characterization of pseudo-stem banana and sisal fibres

According to the study by Alwani et al (2015), pineapple, pseudo-stem banana, sisal and coir fibre overall mechanical properties were higher than the previous studies. Thus, this could help to find out suitable fibres for different composite applications by optimizing the production process and choosing the suitable end use. Pseudo-stem banana and sisal fibres are among the natural fibres employed in bio-composite development (Kim, 2008).

2.2.1 Introduction to pseudo-stem banana fibres

The word ‘banana’ comes from the Arabic language and means “finger”. Bananas (cooking and plantains) with its entire species belong to the genus: *Musa*, order: Zingiberales, family: Musacea*e* (Satish et al, 2014). All varieties of banana plants possess fibres in abundance (Vigneswaran et al, 2015). Banana fibres have been obtained from the pseudo-stem of banana plants *(Musa Sapientum)* (Alwani et al, 2015). The East African highland bananas accounts for majority bananas grown in East Africa, especially Uganda (Vezina et al, 2014). These survive at altitudes between 1,000 to 2,000 metres above sea level (Asten et al, 2010). Bananas require well distributed rainfall of an average of 2,000 to 2,500 mm throughout the year and short dry seasons. Although bananas can be grown on a wide range of soils, deep well drained retentive loam soils, with high humus content are the best (Zake et al, 2000)**.** Uganda is one of the top banana producing countries accounting for up to 11% of the world’s production (UNCST, 2007; Vigneswaran et al, 2015). Figure 4 represents the East African Highland Bananas grown in the East African region.

Figure 4: The East African highland bananas (Vezina et al, 2014).

2.2.2 Introduction to sisal fibres

Agave sisalana (sisal) in Figure 5 belongs to the genus Agave of the order Asparagales and to the Agavaceae family, and more than 200 species plus 47 intra specific categories have been identified (Muthangya et al, 2013). Sisal plant is a perennial crop, which produces a terminal tight rosette of narrow tapering spine after 5–10 years before it flowers and then dies. Sisal can grow well in prolonged drought conditions and can survive at a low annual rainfall of 40–300 cm and temperatures up to 40^{o}C-50^{o}C (Kar, 2008). Currently, sisal represents the first natural fibre in commercial application and a prospective reinforcing material that its use has been more experiential than technical until now (Tara and Jagannata et al, 2011). Presently, world sisal production is declining due to competition from synthetic fibres like polypropylene, (Wilhelm, 2013) as shown in Figure 5.

Figure 5: Photo of sisal plants from a sisal farmland in Kenya.

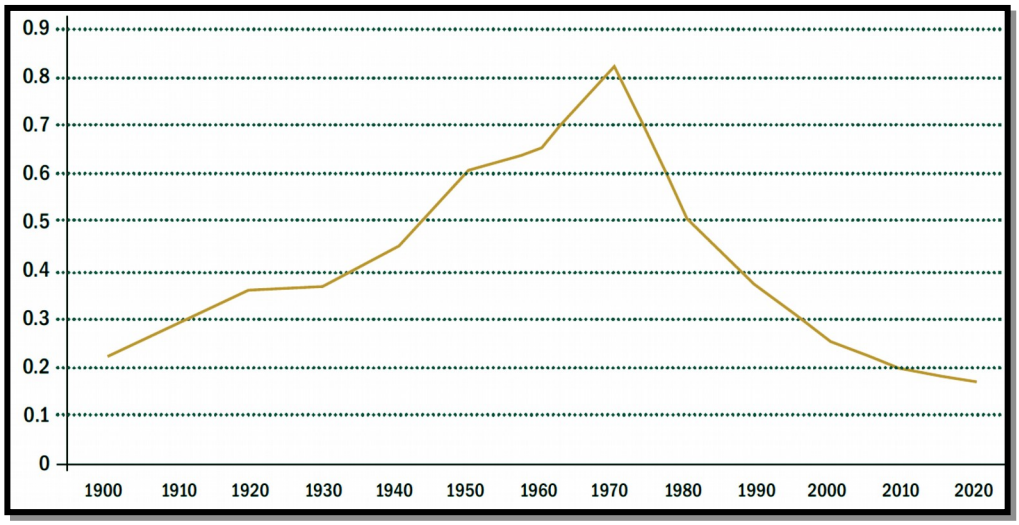


Figure 6: Declining trend of Sisal fibres. (Wilhelm, 2013).

2.2.3 Surface treatment of pseudo-stem banana and sisal fibres

According to Alwani et al (2015), agricultural residue fibres have waxy substances on the outer surface of fibre that cover the reactive functional groups of the fibre and act as a barrier to interlock with the matrix resulting into poor surface wetting. However, surface modifications by different chemical treatments, reactive additives and coupling agents

would optimize the interfacial bonding between the fibre and matrix. Ligno-cellulose fibre surface modification has been reported, involving alkali treatment, silane treatment, acetylation treatment and benzoylation treatment. The simplest chemical modification is alkali treatment of fibres, which has been used to treat almost all natural fibres with successful results (Valadez et al, 1999; Bisanda, 2000). This modification results in an increase in adhesive bonding and thus improves ultimate tensile strength up to 30% (Satish et al, 2014). Sisal fibres conditioned in sodium hydroxide solution increased in their initial strength from 60.9% to 72.7% after 420 days (Tara and Jagannata, 2011). The effect of chemical treatment of natural fibres with sodium alginate and sodium Hydroxide has been reported for coir, banana and sisal fibres. Alkali treatment reduces fibre diameter and thereby increases the banana fibre aspect ratio (Ebisike et al, 2013). According to Alhayat et al (2014), banana fibres were treated with different concentrations of sodium hydroxide of 2.5%, 5%, 10% and 15% at a temperature of 80-100^{0}C for 30 Minutes to 1 hour with a few droplets of a wetting agent. There was weight loss as shown in Table 5 and best results were obtained between 2.5% and 5% concentration of sodium hydroxide (NaOH). Sumaila et al (2013), treated extracted banana fibres with 5% sodium hydroxide (NaOH) solution for four hours, washed in overflowing tap water until neutral pH was attained and dried in an oven for 24 hours at 105^{0}C to remove free water. Ezema et al (2014), noted that the combination of NaOH and Na_2SO_3 in fibre surface treatment indicated better bonding from the Scanning Electron Microscopy results than use of only sodium hydroxide (NaOH). However, this increased the cost of production in terms of chemicals and temperature.

Furthermore, Varughese et al, (2004) examined the effect of NaOH concentrations ranging from 0.5 to 10% in treating sisal fibre-reinforced composites and concluded that the

maximum tensile strength resulted from the 4% NaOH treatment at room temperature. When 25% sisal fibre volume fraction were treated with 4% sodium hydroxide for 1 hour before composite fabrication compared to untreated sisal fibres, there was increase in tensile strength (Romao et al, 2003).

Table 5: Weight Loss: Alkalization increases aspect ratio (Ezema et al, 2014).

No.	NaOH (Treatment)	Total weight before Alkalization (g)	Total weight after Alkalization (g)	Weight loss (%)
1	2.5%	333.1665	324.2286	4.1216
2	5%	338.1665	306.4255	9.3862
3	10%	126.08	111.9938	11.1724
4	15%	126.08	106.1338	15.8203

2.2.4 Linear density of pseudo-stem banana and sisal fibres

According to Kulkarni et al (1983), pseudo-stem banana fibre *(Musa Sapientum)* fineness could be determined using a torsion balance. The results showed that the fineness of banana fibres range between 6.45tex and 7tex with an average of 6.77tex. Mukhopadhyay et al (2008), also noted linear density of pseudo-stem banana fibres as 7tex. However, according to Das et al (2010), banana linear density ranges between 3tex and 12tex for a filament and the density for a bundle is 1.35g/cm^3, while sisal fibres possess a true density of 1.45g/cm^3. On the contrary, four various cultivars studied in Tamilnadu (India) yielded a range of variation from 13.33tex to 24.23tex (Preethi and Murphy, 2013).

2.2.5 Diameter of pseudo-stem banana and sisal fibres

The diameter of pseudo-stem banana fibre varies between 0.05 and 0.3 mm (Geethama et al, 1998). However, Mukhopadhyay et al (2008) noted a range of variation from 0.08mm to 0.32 mm where majority of pseudo-stem fibres were between 0.17 to 0.19mm hence considered for tensile testing. Sisal fibres have a diametre range of 0.1 to 0.3 mm (Das et al, 2010). According to Kulkarni et al (1983), there is no appreciable change in mechanical properties of banana fibres with an increase in diameter of the fibre between 0.5 to 0.25mm. This is contrary to Alwani et al (2015), who noted that mechanical properties of natural fibres showed increasing trends with the decrease of diameter.

2.2.6 Length of pseudo-stem banana and sisal fibres

According to Kumar and Santhanen (2014), better mechanical properties are found for composites reinforced with 10mm fibre length. However, Sreekumar et al (2008) investigated that natural fibre reinforced polymer composites having fibre length of 30mm and a fibre volume content of 40 percent showed maximum tensile strength. In their study, Chandrasekaran and Santhanen (2014) reported that the increase in fibre length attributes toward the increase in fracture toughness value of the composite. However, when the fibre length increases beyond its critical length the fibre acts as continuous fibre. Sumaila et al (2013) and Raghavendra et al (2013), noted that the tensile strength of the composite, Young's modulus and percent elongation had their highest values of 67.2 MPa, 653.07 MPa and 5.9% respectively at 15mm banana fibre length suggesting critical fibre length for effective and maximum stress transfer. According to Ajith et al (2015), tensile strength of banana reinforced phenol formaldehyde composite increased for fibre length of up to 30mm and after that tensile strength value decreased. However, generally pseudo-stem

banana and sisal fibres range between 300mm to 900mm and 500mm to 1,000mm respectively. The ratio between fibre length and width (aspect ratio) is important in determining the strength level of the banana fibres. Higher value represents improved strength, the reverse being true.

2.2.7 Tensile properties of pseudo-stem banana and sisal fibres

Mechanical behaviour of natural fibres is influenced by conditions such as; history (specie, growing, retting conditions), materials (crystallinity, micro-fibril angle) and measurement conditions (moisture, temperature) (Stamboulis et al, 2001; Osorio et al, 2010). Tensile tests are a well-adopted way to investigate the mechanical properties of elementary and bundle of plant fibres (Baley, 2002). Properties of banana pseudo-stem fibres have been studied over the past few years (Jayaprabha, 2011; Mukhopadhyay, 2009). Banana fibre, obtained from the pseudo-stem of banana plant, has relatively good mechanical properties compared to other nature fibres (Kulkarni et al, 1982; Samrat, 2008). Among various natural fibres, banana fibre is of particular interest because its composites have high tensile strength, Young's modulus and low elongation at break beside its low cost and availability (Chandrasekaran and Santhanen, 2014).

Pseudo-stem banana fibres have an average tensile strength of 941.05 MPa (Rwawiire et al, 2014). This is supported by Alwani et al (2015) who stated that the physical and chemical composition of different agricultural fibres show high variability in properties even for the same type of fibres. In their study, Mukhopadhyay et al (2008) obtained pseudo-stem banana fibre tenacity in the ranges of 146.2MPa to 167.2MPa as a result of variation in strain rates and gauge length. Furthermore, Preethi et al (2013) obtained an average tenacity of 8.5g/tex (8.34cN/tex) from various cultivars of pseudo-stem banana

fibres. Ebisike et al (2013) tested the tensile properties of banana fibres according to ASTM 638 - 2014 using a tensile strength test machine.

Sisal fibres have good tensile strength ranging between 347-378MPa and modulus of elasticity of 15 GPa (Tara and Jagannata, 2011). After alkali treatment of sisal fibres, tensile strength of 34.27MPa as opposed to 31.12MPa were obtained. Furthermore, elongation of untreated sisal fibres was 2% and opposed to 1% in the case of treated fibres (Pavithran et al, 1996). According to Silva etal (2008), sisal fibres possess an elastic modulus of 19GPa and tensile strength of 400MPa, respectively. Young's modulus and ultimate tensile strength are not influenced by gauge length. The strain-to-failure decreases from approximately 5.2% to 2.6% when the gauge length is increased from 10 mm to 40 mm. The strength of sisal fibres is not uniform along the length of the fibre bundle because the probability of finding significant defects is much larger in a sisal technical fibre than in a single fibre. In addition, the load distribution is much more inhomogeneous in technical fibres (Oksman et al, 2002). Table 6 shows the properties of some common natural fibres.

Table 6: Properties of selected natural fibres (Das et al, 2010).

No.	Physical and Mechanical Properties	Banana fibres	Sisal fibres
3	Aspect Ratio (Length/Width)	100	150
4	Filament Fibre Length (mm)	300 - 900	500 – 1,000
5	Filament Fibre Width (µm)	80 - 250	100 - 300
6	Density (g/cm^3)	1.35	1.45
8	Tensile Strength (MPa)	355 - 790	347 - 800
9	Filament Tenacity (g_f/Tex)	30 - 40	40 - 45
10	Young's Modulus (MPa)	8 - 32	9 - 28
11	Filament Elongation (%)	1.0 – 3.5	2.5 – 4.5

2.3 Development and characterization of banana and sisal bio-composites

2.3.1 Development of banana and sisal bio-composites

Bio-composites consist of reinforcing bio-fibres and matrix polymer systems. Some of the growing areas of applications for bio-composite materials are in automotive parts, housing products and packaging. The challenge in replacing conventional glass-reinforced plastics with bio-composites is to design materials that exhibit structural and functional stability during storage and use, yet are susceptible to microbial and environmental degradation upon disposal without any adverse environmental impact (Mohanty et al, 2005). A three-cornered approach in designing bio-composites of superior and desired properties as shown in Figure 7 include efficient but low-cost natural and bio-fibre treatment, matrix modification through functionalization and blending, and selection of appropriate and efficient processing techniques. Since the significant attraction of natural fibres is their low cost, inexpensive yet effective surface treatments that avoid organic solvents are logical ways of making a reactive natural fibre surface (Drzal et al, 2001). Furthermore, studies indicate that fibre volume fraction is one of the main parameters in the determination of the natural fibre composite's mechanical properties hence the need to determine its exact value (Gibson et al, 2002; Madsen, 2004). Generally, fibre volume fraction is calculated according to the formulae shown in Eqn. 1:

$$V_f = (\rho_m x w_f) / (\rho_m x w_f + \rho_f x w_m) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.1$$

Where; V_f = Fibre volume fraction, W_f = Weight of fibres, W_m = Weight of the matrix,

ρ_f = Density of fibres, and ρ_m = Density of matrix.

In his review, Satish et al (2014) noted that the utilization and application of cheaper goods in high performance appliance is possible with the help of composite technology. Combining properties of two different materials, versatility and usefulness in various fields makes bio-composites the most wanted technology in the fast growing current trend.

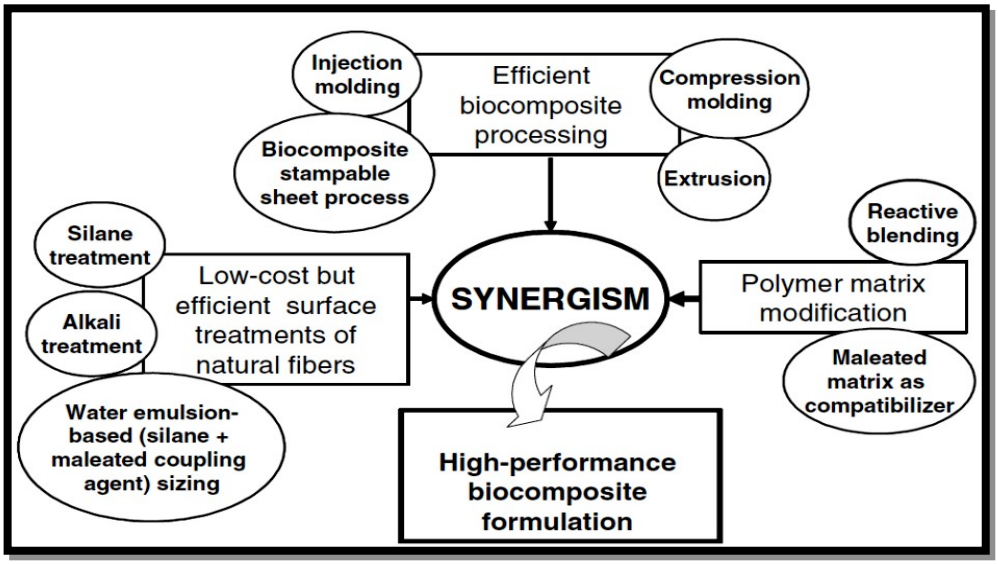


Figure 7: Design and engineering of bio-composites (Drzal et al, 2001).

When a biodegradable thermoplastic polymer is blended with natural fibres, good dispersion and distribution of the fibres are necessary (Alvarez et al, 2009). Several techniques used in fabricating composites are categorized into three main groups by Suong and Hoa (2009) and Ashwani and Depark (2013): Open mould process, Closed mould and Continuous process. Open mould process involves Hand layup, Spray up, Filament winding, Sheet moulding, Contact moulding and Expansion to moulding. Closed mould process is achieved by compression moulding, Injection moulding, Resin transfer

moulding (RTM),Vacuum bagging, Autoclave and Pressure bag. Finally, continuous process also known as Pultrusion method. Hand-lay-up techniques, Resin Transfer Moulding, Reaction Injection Moulding, compression moulding are the techniques mostly used to fabricate bio-composites from bio-fibres and liquid-based resins as shown in appendix A. The hand layout process of manufacturing is one of the simplest and easiest methods for manufacturing composites. However, this research concentrated on a very simple, hand layup fabrication process due to lack of equipment.

2.3.2 Characterization of banana bio-composites

ASTM D638-2014 is a test method that covers the determination of the tensile properties including tensile strength, Young's modulus and elongation of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens when tested under defined conditions of pre-treatment, temperature, humidity, and testing machine speed. This test method is applicable for testing materials of any thickness up to 14 mm (0.55 in.) Measure the width and thickness of each specimen to the nearest 0.025 mm (0.001 in.) Measure the width and thickness of flat specimens at the centre of each specimen and within 5 mm of each end of the gauge length. Place the specimen in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. Set the speed of testing at the proper rate as required and start the machine. Record the load-extension curve of the specimen and the load and extension at rupture. Three specimens were recommended for testing each sample. The tensile strength of banana fibre reinforced bio-composite laminate was determined as 6.5MPa (Olusegun et al, 2012). According to Lamis et al (2013), banana fibre reinforced cornstarch bio-composites at 50% fibre volume fraction yielded an

ultimate tensile strength of 30GPa. This was different from tensile strength of 3.56MPa obtained at 35% fibre volume fraction (Guimaraes et al, 2010). Furthermore, Lamis et al, (2013) reported a Young's modulus of 4.6GPa for banana fibre reinforced cornstarch bio-composites at 50% fibre volume fraction. This was different from Young's modulus of 74.35MPa obtained at 35% fibre volume fraction (Guimaraes et al, 2010).

In addition, Ajith et al (2015) studied the tensile properties of banana reinforced phenol formaldehyde composite of gauge length ranging between 1mm to 4mm; tensile strength ranged between 1.98MPa to 4.58MPa, Young's modulus between 2GPa and 9.39GPa and elongation ranged between 1.72% to 2.65%. The banana reinforced phenol formaldehyde composite had a better load carrying capacity and was more flexible than plywood of the same thickness hence recommended for lighter applications.

ASTM D695-2010 is a test method that covers the determination of the mechanical properties of unreinforced and reinforced rigid plastics, including high-modulus composites, when loaded in compression at relatively low uniform rates of straining or loading. Compression tests provide information about the compressive properties of plastics when employed under conditions approximating those under which the tests are made. Compressive properties include modulus of elasticity, yield stress, deformation beyond yield point, and compressive strength. The width and thickness of the specimen are measured to the nearest 0.01 mm (0.001 in.) at several points along its length. The cross sub sectional area is measured and the minimum value recorded. The length of the specimen is measured and recorded. The test specimen is placed between surfaces of the compression tool. The speed control is set at 1.3 mm/min (0.050 in./min) the machine is started. Record the maximum load carried by the specimen during the test (usually this will

be the load at rupture). In a study to determine the mechanical properties of banana bio-composite laminates for engineering applications, the compressive strength was determined as 16.75MPa (Olusegun, 2012).

2.3.2 Characterization of sisal bio-composites

Tensile properties of sisal bio-composites including tensile strength, Young's modulus and elongation are determined using ASTM D638-2014 and following the previous procedures. According to Kuruvilla etal (1999), six (6) mm random sisal fibre reinforced polypropylene composites yielded tensile strength ranging between 29MPa to 33.84MPa for a fibre volume fraction between 10% and 30%. Similarly, tensile strength of sisal fibre reinforced low density polyethylene composites increased from 10.8MPa to 14.7MPa for the same range of fibre volume fraction. This was different from the tensile strength of sisal fibre reinforced bio-composite laminate that was determined as 5.4MPa (Olusegun et al, 2012). In addition, untreated sisal fibre reinforced epoxy composite exhibited a tensile strength of 45.1MPa compared to the composite with treated sisal fibres at 49.85MPa. 25% sisal fibre volume fraction was treated with 4% sodium hydroxide for 1 hour before composite fabrication (Romao et al, 2003). Six (6) mm random sisal fibre reinforced polypropylene composites yielded Young's modulus between 605MPa to 940MPa for a fibre volume fraction between 10% and 30%.

Furthermore, Young's modulus of sisal fibre reinforced low-density polyethylene composites increased from 324MPa to 781MPa for the same range of fibre volume fraction (Kuruvilla etal, 1999). Untreated sisal fibre reinforced epoxy composite exhibited Young's modulus of 4.87MPa compared to the composite with treated sisal fibres at 6.51MPa (Romao et al, 2003).

When randomly arranged sisal fibre reinforced polypropylene composites were produced, they exhibited a percentage elongation of 8% to 8.5% for a fibre volume fraction of 10% to 30%. However, percentage elongation of sisal fibre reinforced low-density polyethylene composites decreased from 27% to 7% for the same range of fibre volume fraction (Kuruvilla etal, 1999). This was also in agreement with (Romao et al, 2003), where percentage elongation decreased from 1.07% for untreated sisal fibre reinforced epoxy composite to 0.97% of the composite with treated sisal fibres.

Compressive strength of sisal bio-composites is determined in using previous procedures according to ASTM D695-2010 standard. According to (Olusegun et al, 2012), the compressive strength was determined as 42MPa.

Chapter 3 : METHODOLOGY

3.0 Introduction

This chapter presented the methodological process for the development of bio-composites from raw banana peels bio-resin, pseudo-stem banana and sisal fibres. The development process including the experimental design technique and characterization were presented. Furthermore, pseudo-stem banana and sisal fibres were presented in terms of surface treatment and characterization to prepare them for use as reinforcement during the bio-composite development. The chapter also discussed the manufacture of the bio-composites, their characterization and analysis. Figure 8 showed the methodological process that was followed to achieve the study objectives.

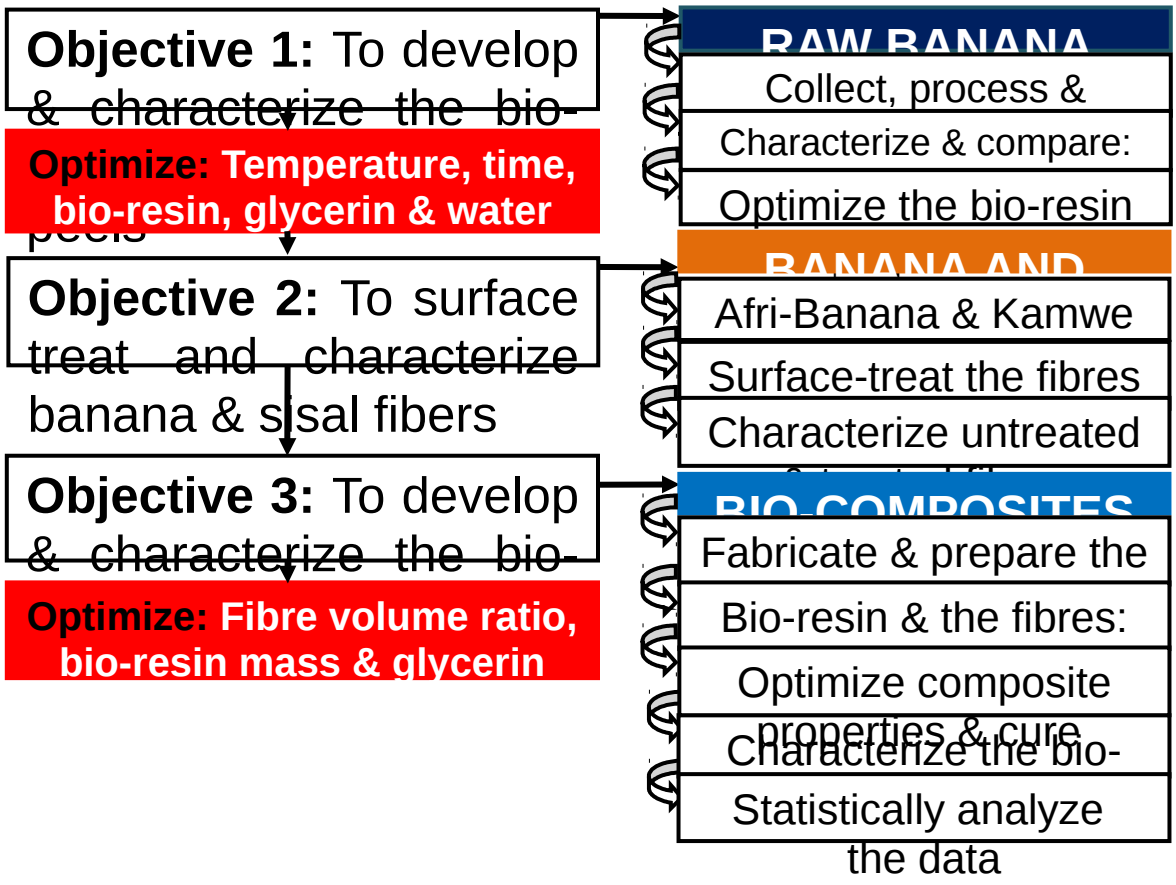


Figure 8: Methodological process relating to the research objectives

3.1 Development and Characterization of bio-resin from raw banana peels

Based on objective one (1), locally made bio-resin from raw banana peels was developed and characterized in terms of viscosity and density based on universal rotatable experimental design for data collection. The quest for use of banana peels for bio-resin development culminates from increased public interest for the utilization of agricultural resources for production of new “green” materials. Banana peels are also waste material and a non-food source of starch unlike corn, rice, wheat and potatoes. Furthermore, raw banana peels were considered based on their higher percentage of starch content compared to ripe banana peels. Although several studies on biodegradable resins for bio-composites development exist, there is limited literature on bio-resins from raw banana peels for bio-composites production.

3.1.1 Development of bio-resin from raw banana peels

Three (3) kilograms of raw banana peels were obtained from Naguru market (Kampala-Uganda). The peels were washed, boiled, drained and allowed to cool. The peels were thereafter chopped into smaller pieces, placed into an electric blender and pureed to obtain banana peels fluid paste as shown in Figure 9 For every 500grams of raw banana peels, 250milli-litres of water were added for easy pureeing. These measurements were selected based on the amount of chopped banana peels that could fit in the blender at a time. Five litres of the fluid paste obtained was stored in a jerrican for testing. The fluid paste was treated with glycerine supplied by Desbro Uganda limited. Glycerine was preferred over other plasticizers because it is a by-product waste material in the bio-fuel industry, added to avoid brittleness and increase flexibility of the final bio-product.

Figure 9: Banana peels fluid paste for characterization

3.1.2 Experimental design and optimization of bio-resin from raw banana peels

Design of experiments refers to planning, designing and analysing an experiment so that valid and objective conclusions can be drawn effectively and efficiently. The central rotatable composite experimental design is used during optimization of new experimental methods (Araujo and Breveton, 1996). The effects of several variables on a given response outlined in the experimental design can be investigated using regression models, a well-established statistical tool (Bowerman and O'Connel, 2001). Previous studies reveal that modern design of experiments, regression analysis and optimization of various responses can be achieved through computer software programs including Matlab, SAS, Design Expert, Monte Carlos and Minitab (Kundan et al, 2015; Meira et al, 2013; Alwani et al, 2015; Mburu et al, 2015). However, Minitab software is user friendly and readily accessible compared to other software mentioned. Data can be imported from Microsoft Excel to Minitab for analysis and exported back to Excel. Multiple regression and paired T-

Tests can be used for material analysis using Minitab. Using Minitab 17.01 Software, Surface Response Design (Central Rotatable Composite Design) using 5 factors at 5 levels were considered with 3 replicates and 32 base runs to yield a total of 96 runs under a total block of 1. Two level factorial, half fraction indicated 48 cube points involved hence, an alpha value of 2 was obtained. Three runs were performed for each experimental setup and the average recorded. Table 7 determined the relationship between factors and levels as input data.

Table 7: Relationship between factors and levels for the banana peels bio-resin

Factors		Levels				
		-α	Low	Medium	High	+α
Coding		-2	-1	0	1	2
Temperature (^{0}C)	X_1	25	40	60	80	100
Time (min)	X_2	20	30	40	50	60
Resin (mls)	X_3	20	40	60	80	100
Glycerine (mls)	X_4	0	10	15	20	25
Water (mls)	X_5	0	10	15	20	25

This experimental design was chosen because of the optimization of a new experimental method required. Unlike the Box Behnken, the Central Rotatable Composite Design was also capable of presenting factor values at five levels. A second order polynomial regression shown in Eqn. 2 was used to fit the model (Araujo and Breveton, 1996).

$$Y = b_0 + b_1 x_1 + \ldots b_5 x_5 + b_6 x_1 x_1 + \ldots b_{10} x_5 x_5 + b_{11} x_1 x_2 + \ldots b_{20} x_4 x_5 \quad \ldots\ldots\text{Eqn. 2}$$

Where; Y = Yield, b_0 = Constant, b_1 to b_{20} = Coefficients and X_1 to X_5 = Factors.

The test samples were subjected to different ratios of temperature (X_1), Time (X_2), Resin (X_3), Glycerine (X_4) and Water (X_5) as the input to study their effect on viscosity (Y_V) and density (Y_D) yields of the bio-resin. Central Rotatable Composite Design was used to

identify the five-parameter combination sets that produced the most optimized yield. Modelling of the influence of the above factors and sensitivity analysis on the bio-resin properties was done using regression analysis. During multiple regression analysis, standardization of the data was effected. The stepwise regression procedure was used by adding terms to maintain a hierarchical model at each step. Analysis of Variance and Variance Inflation Factors were checked and verified to ensure model accuracy.

3.1.3 Characterization of bio-resin from raw banana peels

Various resin, glycerine and water ratios were mixed in glass containers of 85mm diameter and 200ml filling volume. An oven set at various temperatures was used for the prepared test specimens at different time intervals. Viscosity of the samples was determined according to ASTM D2196 - 2005. The Visco Basic Plus Rotational Viscometer (VBCR 320810) shown in Figure 10 with over eight rotational speeds and a set of seven spindles was employed. Viscosity was measured in mPa.S (centipoises) basing on test method A of ASTM D2196, at a constant speed of 100RPM for all the measurements. Three readings per experiment were taken and the average viscosity considered.

The pycnometer was used according to ASTM standard D854 – 2010 standard for density characterization. The pycnometer and glass stopper were thoroughly cleaned with soap and water and then rinsed with a small amount of acetone. The dry flask was weighed with the stopper on a Mettler Toledo analytical balance shown in Figure 11. The volume of the pycnometer was determined by filling it fully with distilled water, inserting the stopper, and tapping the sides gently to remove the air bubbles. The sides were dried and the full pycnometer weighed on the balance. A 25mls density bottle at a temperature of 27^0C was

used for the density measurements. Three readings per experiment were taken and the average viscosity considered.

Figure 10: Visco Basic Plus Rotational Viscometer for bio-resin characterization

Figure 11: Determining bio-resin density: A pycnometer and mettler toledo balance

3.2 Surface treatment and characterization of pseudo-stem banana and sisal fibres

According to objective two (2), pseudo-stem banana and sisal fibres were surface-treated and characterized in terms of linear density, tenacity, Young's modulus and elongation. These natural fibres were considered in this study based on their global significance and availability. Sisal is also currently experiencing a declining global trend as a non-food crop that needs reverting. Furthermore, natural fibre properties in comparison to other synthetic fibres predict a positive trend in bio-composites development.

3.2.1 Surface treatment of pseudo-stem banana and sisal fibres

Alkali, silane, acetylation and benzoylation treatment have been reported as methods for the treatment of the organic (banana and sisal) fibres. The simplest chemical modification is alkali treatment, which has been used to treat almost all natural fibres with successful results (Valadez et al, 1999; Bisanda, 2000). Surface treatment was achieved by treating the pseudo-stem banana and sisal fibres as shown in Figure 12 with 4% weight per volume of sodium hydroxide (NaOH) at a temperature of 100^0C for 1 hour (Romao et al, 2003; Alhayat et al, 2014). The fibres were rinsed in water, dried, weighed and tested for their tensile properties. Untreated and treated pseudo-stem banana and sisal fibres were characterized and linear density, tenacity, Young's modulus, percentage elongation determined. Pseudo-stem banana fibres were characterized in terms of linear density, tenacity, Young's modulus and elongation at break. The pseudo-stem banana fibres were conditioned at $21+1^0$C and 65+2% for 8 hours according to ASTM D1776 – 2004 before testing. However, the obtained sisal fibres from Kamwe Business Solutions Limited (Kampala-Uganda) were already characterized.

Figure 12: Surface treatment of pseudo-stem banana and sisal fibres

3.2.2 Characterization of Pseudo-stem banana fibres

Linear density was determined according to ASTM D1577 - 2001 (Standard test methods for linear density of fibres). Random fibre samples were obtained from two fibre bundles (treated and untreated fibres), then prepared to a length of 300mm as the gauge length. Thirty (30) individual pseudo-stem banana fibres were obtained from each bundle, a number above the proposed 20 test fibre specimens. Sufficient number of fibres was weighed on a Mettler Toledo balance; model THB - 300 CAP with a capacity of 300grams and a sensitivity of 0.005grams to determine the weight and linear density. From the measured fibre weight, length and number of specimen, linear density was calculated using the standard formula.

Tensile properties of pseudo-stem banana fibres including tenacity, Young's modulus and elongation were carried out according to ASTM D3822M - 2014 (standard test methods for tensile properties of single fibres). A Universal tensile testing, TP2730 model machine as shown in Figure 13 at a gauge length of 300mm and a speed of 5mm/min was employed at Rivatex East Africa Limited (Kenya) to determine the tensile strength. Tenacity was

determined by dividing the breaking force by the linear density. Young's modulus and Percentage elongation were determined from the tensile tests carried out using the stress - strain curves obtained.

Figure 13: Universal tensile testing machine for fibre tensile properties at Rivatex

3.2.3 Characterization of sisal fibres

Linear density was determined according to ASTM D1577 - 2001 (Standard test methods for linear density of fibres) using the same procedures as for pseudo-stem banana fibres. Random fibre samples were obtained from only treated fibres as untreated fibres were already characterized.

The ASTM D3822M - 2014 (standard test methods for tensile properties of single fibres) was used to determine the tensile properties including tenacity, Young's modulus and elongation. The Universal tensile testing machine shown in Figure 13, at a gauge length of 300mm and a rate of 5mm/min was employed at the Textile Testing Laboratory at Rivatex East Africa Limited (Kenya) to determine the tensile strength. Tenacity was determined by dividing the breaking force by the linear density. Young's modulus and percentage elongation was determined from the tensile tests carried out using the stress - strain curves obtained.

3.3 Development and characterization of the developed bio-composites

According to the third objective, bio-composites designed from raw banana peels bio-resin, pseudo-stem banana and sisal fibres using an experimental design for data collection and analysis were developed.

3.3.1 Development and optimization of banana and sisal bio-composites

The bio-composites were fabricated using the hand layup method, treated pseudo-stem banana and sisal fibres as the reinforcement and raw banana peels bio-resin combined with glycerine plasticizer as the matrix. Male and female metallic moulds shown in Figure 14 were employed to exert pressure on the wet composite before drying. The moulds of dimensions of 310mm X 310mm X 10mm were employed for bio-composites development. Aluminium foil sheets were laid on the female mould and a gel coat sprayed onto the mould for ease of bio-composite removal. When the gel coat cured, pseudo-stem banana, and sisal fibres and the bio-resin were applied using a brush. According to Kuruvilla etal (1999), randomly aligned sisal fibre reinforced polypropylene composites for a fibre volume fraction between 10% and 30% yielded; tensile strength ranging

between 29MPa to 33.84MPa, Young's modulus between 605MPa to 940MPa and percentage elongation of 8% to 8.5%. This was in agreement with Romao et al (2003), where randomly aligned sisal fibres were reinforced with epoxy for composites production. This research used randomly aligned fibres during bio-composites development. A manual roller was used to remove entrapped air, compact the composite, and thoroughly wet the reinforcement with the bio-resin. Additional layers of fibres and banana peels bio-resin were introduced for the required thickness. 20 sample bio-composites of banana and sisal fibres each were developed and characterized.

Figure 14: Metallic mould and hand roller used during bio-composites development

These were cut according to the ASTM D2584 - 2010 standard and available machine requirements for testing and fibre weight used in the bio-composite determined. Table 8 showed the relationship between factors and levels relating to the experimental design set up for the bio-composites.

Table 8: Relationship between factors and levels for the bio-composites

Factors		Levels				
		$-\alpha$	Low	Medium	High	$+\alpha$
Coding		-1.682	-1	0	1	1.682
Fibre volume fraction (%)	X_1	20	30	40	50	60
Bio-resin Mass (grams)	X_2	60	76	100	124	140
Glycerine Mass (grams)	X_3	0	2	4.3	6	8

The overall fibre weight required in the development of 20 bio-composites from the experimental design in Table 9 was 2,082 grams (approximately 2.1 kilograms). Using Minitab 17.01 Software, Surface Response Design (Central Rotatable Composite Design) using 3 factors at 5 levels was considered with 1 replicate and 20 base runs to yield a total of 20 runs. A total block of 1.8 cube points with 6 centre points in the cube and 6 axial points were involved in the design hence, an alpha value of 1.682 was obtained. Each experiment was performed three times and the average recorded. This experimental design was chosen due to optimization of a new experimental method required. Furthermore, unlike the Box Behnken the Central Rotatable Composite Experimental responses of tensile strength, compressive strength, Young's modulus and percentage elongation were considered to predict the optimum and interaction effects using regression analysis. A second order polynomial regression Eqn. 2 was used to fit the regression models.

Table 9: Central composite rotatable experimental design for the bio-composites

Run	X_1	X_2	X_3
1	0.000	0.000	-1.682
2	1.000	-1.000	1.000
3	0.000	0.000	0.000
4	0.000	-1.682	0.000
5	-1.000	-1.000	1.000
6	1.682	1.682	1.682
7	1.000	1.000	-1.000
8	0.000	1.682	0.000
9	0.000	0.000	0.000
10	1.000	1.000	1.000
11	-1.000	1.000	-1.000
12	-1.682	-1.682	-1.682
13	0.000	0.000	0.000
14	-1.682	0.000	0.000
15	0.000	0.000	0.000
16	0.000	0.000	1.682
17	-1.000	1.000	1.000
18	1.682	0.000	0.000
19	1.000	-1.000	-1.000
20	-1.000	-1.000	1.000

Predictive multiple regression models for tensile strength, Young's modulus, elongation and compressive strength of the developed pseudo-stem banana and sisal fibre reinforced bio-composites were obtained and analyzed. From design of experiments, an experimental datasheet at 3 factors, 5 levels and 20 experimental runs were obtained where each run was performed 3 times and the average recorded. Data obtained from pseudo-stem banana and sisal bio-composites was combined into a single data sheet for analysis.

Test samples were composed of different ratios of fibre volume fraction (X_1), Bio-resin mass (X_2) and Glycerine mass (X_3) as input data to study their effect on tensile strength (Y_T), Young's modulus (Y_Y), percentage elongation (Y_E), and compressive strength (Y_C) of the developed bio-composites as yields (responses). The Central Rotatable Composite

Design was used to identify the three-parameter combination sets that produced the most optimized responses. Modelling of the influence of the above factors and sensitivity analysis on the bio-resin properties was done using multiple regression analysis. Various second order polynomial regression equations were used to generate optimal data values and sample points with predicted response values closest to the optimal solution. These values were evaluated alongside alternative solutions closest to the optimum settings to determine if any were adequate. Standardization of the data was effected using backward elimination regression technique to remove insignificant terms during regression to maintain a hierarchical model at each step. Analysis of variance (P - Values) and variance inflation factors were checked and verified to ensure model accuracy.

3.3.2 Characterization of the banana bio-composites

Tensile strength tests, including Young's modulus and percentage elongation were determined using a universal material tester shown in Figure 15 from Eldoret Polytechnic (Kenya), model type WP 310 and Serial number 3578343387 with a maximum capacity of 50 Kilo Newton according to ASTM D638–2014. The pseudo-stem banana and sisal bio-composite boards of varying thickness (0.1cm to 1cm) were cut into 16.5cm by 1.9cm as recommended by the standard using a gelatine metal sheet cutter. The specimens were placed in the grips of a universal material tester by aligning the long axis of the grips with an imaginary line joining the points of attachment to the machine. Using a testing speed of 100mm/min, testing gauge length of 10cm and force in kN. The tensile stress in N/mm^2 (MPa) and percentage elongation at the yield and rupture points were recorded by the computerized data recording system.

Banana bio-composite boards of varying thickness (0.1cm to 1cm) were cut into 16.5cm by 1.9cm as recommended by the standard using a gelatine metal sheet cutter. The specimens were placed in the grips of a universal material tester as shown in Figure 15, using a testing speed of 100mm/min, testing gauge length of 10cm and force in kN. The tensile stress in N/mm^2 (MPa) was recorded by the computerized data recording system. Young's modulus was calculated using strain-stress curves obtained from the tensile test. The percentage elongation (deformation of the specimen due to tensile stress) was obtained from the results of the tensile test. This research aimed at establishing the percentage elongation of pseudo-stem banana bio-composites as there was limited literature on elongation.

Figure 15: Universal material tester used for banana and sisal bio-composites tests

The pseudo-stem banana and sisal bio-composite boards of varying thickness (0.1cm to 1cm) were cut into 7.94cm by 1.9cm as recommended by ASTM D695 - 2010 using a gelatine metal sheet cutter. The specimens were placed between the compression surfaces

of a universal material tester shown in Figure 3.8 using a test speed of 1.3mm/min, gauge length of 10cm and a maximum force of 10kN. The compressive strength in N/mm^2 (MPa) and percentage elongation at the yield and rupture points were recorded by the computerized data recording system.

3.3.3 Characterization of sisal bio-composites

Compressive and tensile strength tests, including Young's modulus and percentage elongation were determined using a universal material tester shown in Figure 3.8 from Eldoret Polytechnic (Kenya), model type WP 310 and Serial number 3578343387 with a maximum capacity of 50 Kilo Newton according to ASTM D638–2014. The same procedure as in the case of banana bio-composites above were used.

Tensile strength tests, including Young's modulus and percentage elongation were determined using a universal material tester shown in Figure 15 from Eldoret Polytechnic (Kenya) as explained in previous sections according to ASTM D638–2014. Sisal bio-composite boards of varying thickness (0.1cm to 1cm) were cut into 16.5cm by 1.9cm as recommended by ASTM D638 using a gelatine metal sheet cutter. The specimens were placed in the grips of a universal material tester. Using a testing speed of 100mm/min, testing gauge length of 10cm and force in kN. The tensile stress in N/mm^2 (MPa) was recorded by the computerized data recording system. Young's modulus was calculated using strain and stress values obtained from the tensile test. The percentage elongation (deformation of the specimen due to tensile stress) was obtained from the results of the tensile test. The same machinery in previous and procedures used for banana bio-composites were the same used for sisal fibre reinforced banana peels bioresin bio-composites.

Chapter 4 : RESULTS AND DISCUSSION

4.0 Introduction

Bio-resin from raw banana peels was obtained, characterized for viscosity and density and findings reported. In this chapter, results were analyzed and interpreted based on the experimental design data from the development process of the bio-resin. It also analyzed and interpreted results from surface treatment and characterization of pseudo-stem banana and sisal fibres. Tensile properties (tensile strength, Young's modulus, percentage elongation and compressive strength) were determined. Analysis and interpretation of results from development and characterization of the bio-composites was carried out. All results obtained were related to previous studies to enhance the relevance of this research in bio-composites development.

4.1 Characterization of the bio-resin from raw banana peels

4.1.1 Viscosity (Y_V) of the bio-resin developed from raw banana peels

The viscosity regression model (Y_V) in Eqn. 3, exhibited a coefficient of determination (R^2) of 0.95. From Analysis of Variance (ANOVA) the P-value (0.0001) of the general model obtained was less than the Alpha (α) Value ($P < 0.05$) hence the viscosity model was significant.

$$Y_V = 203.4 - 1.689\,X_1 - 6.514\,X_2 + 3.168\,X_3 + 0.74\,X_4 - 3.146\,X_5 + 0.00786\,X_1X_1 + 0.0511\,X_2X_2 - 0.00990\,X$$

Eqn. 3

Table 10 showed the Analysis of Variance (ANOVA), factor contributions and Variance Inflation Factors (VIF) for viscosity of the bio-resin. The P-values for the estimated coefficients, curvilinear and interaction effects were less than 0.05 hence significant in the

model. Percentage contributions of various factors were also outlined, with resin amount making the highest contribution of 41% to the model, water amount at 20% and glycerine amount at 18.6%.

Table 10: ANOVA, factor contributions and VIF for viscosity of the bio-resin

Source	Analysis of Variance (P-Value)	Factor Contributions (%)	VIF
Regression	0.000	95.03	
X1	0.000	3.96	1.21
X2	0.024	1.17	1.35
X3	0.000	41.04	1.38
X4	0.000	18.61	1.66
X5	0.000	20.00	2.77
X1*X1	0.016	0.61	1.55
X2*X2	0.000	2.07	1.56
X3*X3	0.001	0.65	1.43
X4*X4	0.022	0.04	2.81
X1*X2	0.000	2.32	3.29
X1*X3	0.000	4.54	1.36
Error		4.97	
Lack-of-Fit	0.000	4.4	
Pure Error		0.57	
Total		**100.00**	

Temperature and time contributed 4% and 1.2% respectively. Curvilinear and interaction effects revealed that interacting temperature with resin amount (X_1*X_3) contributed a higher percentage of 4.5% to the regression model compared to other effects. Variance Inflation Factors (VIF) below 5 in Table 10, proved that there was no multi-colinearity. The viscosity regression model was used to design a prediction and optimization report for the developed banana peels bio-resin. The goal of this analysis was to maximize viscosity yield in the bio-resin hence optimal settings yielded maximum viscosity of 242.01 mPa.s (0.242 Pa.s) for this banana peels bio-resin.

However, at 95% confidence interval (CI) a viscosity range was also determined between 229.5 and 254.52 and the predicted interval (PI) was 217.55 and 266.77. Maximizing viscosity could be attributed to high viscosity yields relating to better bio-resin mechanical properties. Maximization of viscosity is evidenced by most of the commercial resins including the recently developed biodegradable epoxy resin (CHS-Epoxy G520: 12 – 14.5 Pa.s) that had high viscosity values (Rwahwiire et al, 2015). The obtained viscosity was in close proximity to some commercial resins including urea formaldehyde (300 - 450 MPa.s) and maize cornstarch (250 - 1,000 MPa.s) which suggested the banana peels bio-resin viability (Aime et al, 2005; Li et al, 2013; Expert Process Systems 2014). Table 11 showed the optimum settings required to obtain maximum viscosity at 95% confidence interval. X_1 to X_5 represent the factors including temperature, time, bio-resin quantity, glycerine quantity and water amount respectively. Therefore, optimum conditions for maximum bio-resin viscosity of 242.01MPa.s were; 100grams of resin (X_3), 4.3grams of glycerine (X_4), minus additional water (X_5) and at room temperature of 25^0C (X_1) for 20minutes (X_1).

Table 11: Prediction, optimization and settings for bio-resin viscosity

Goal: Maximized viscosity (MPa.s)		Solution: Optimal settings			
Predicted viscosity (MPa.s)	242.01	X_1	25	X_4	4.3
95% Confidence Interval	(229.50, 254.52)	X_2	20	X_5	0
95% Predicted Interval	(217.55, 266.77)	X_3	100		

X_1 = Temperature X_2 = Time X_3 = Resin X_4 = Glycerine X_5 = Water

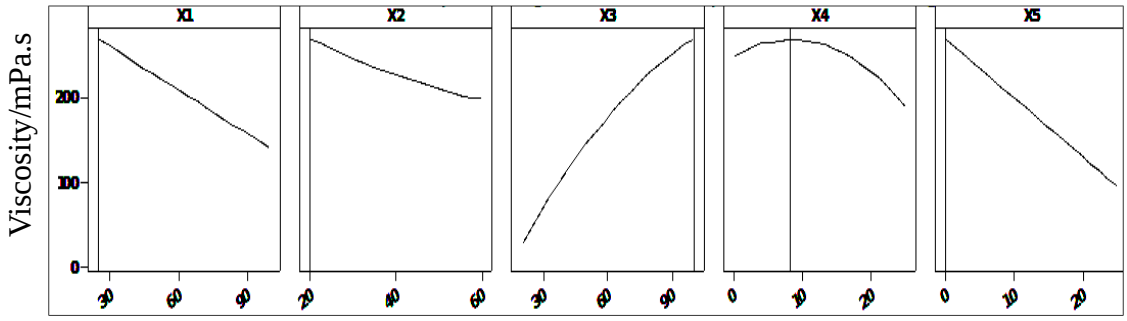
However, Table 12 presented top five alternative settings with corresponding viscosity values that could be used in case optimum settings were not practically applicable.

Table 12: Values close to optimum viscosity settings for banana peels bio-resin

X1	X2	X3	X4	X5	Predicted viscosity
25	20	100	0	0	240.468
100	60	100	0	0	161.611
40	50	80	20	10	104.262
60	60	60	15	15	97.554
25	40	60	15	15	95.822

X_1 = Temperature *X_2 = Time* *X_3 = Resin* *X_4 = Glycerine* *X_5 = Water*

From the viscosity model (Eqn. 3) generated, it was evident that resin quantity (X_3) contributed the highest percentage towards the model. This was also evidenced by Figure 16 that determined the sensitivity analysis for the optimum solution whereby increase in resin concentration (X_3) resulted into increase in viscosity (Y_V). This was due to the amylose and amylopectin ratios in the bio-resin. High bio-resin concentration implies high levels of amylose content that is responsible for high viscosity levels in starch compounds. This was in agreement with Mohanty et al, (2005) who stated that despite the amylopectin's high molecular weight, its intrinsic viscosity is very low because of its extensively branched molecular structure unlike amylose. Bananas are among the starch sources with relatively high amylose content of 20.7% as noted by Lourdes et al, (2004). Glycerine quantity (X_4) had a positive influence on the viscosity up to an optimum level according to Figure 16, beyond which it operated with a negative influence. According to Curvelo et al (2001) and Wattanakornsiri et al (2012), glycerol content in the ranges of 20 to 40% or 20 to 35% without added water has a positive effect on viscosity including improvement of strength and toughness of the resultant composite materials.



X_1 = Temperature/^{0}C X_2 = Time/min X_3 = Resin/grams X_4 = Glycerine/grams X_5 = Water/mls

Figure 16: Settings and sensitivity for optimal viscosity solution

However, further increase had detrimental effect by reducing the viscosity as evidenced by the results. This was also confirmed by Graaf et al (2003), who stated that plasticizers generally have low molar mass, a high boiling point and exhibit low viscosities and low temperature coefficients of viscosity hence capable of reducing resin viscosity.

Temperature (X_1), time (X_2) and water (X_5) all had a negative effect on the viscosity yield. The results showed that increase in temperature led to decrease in viscosity. This was most probably because temperature increases the kinetic energy of the resin molecules hence increasing their mobility and flow. Intermolecular forces holding the bio-resin molecules together are weakened by increase in temperature hence decrease in viscosity. This concurs with a study on preparation and properties of cornstarch adhesives whereby viscosity decreased with increase in temperature (Li et al, 2013). Furthermore, increase in time in relation to gradual temperature rise contributed to continual decrease of viscosity. Addition of water into the bio-resin also decreased bio-resin viscosity due to low viscosity of water molecules hence lowering the viscosity of the consequent bio-resin. Consideration of viscosity as an important factor in characterization of the banana peels bio-resin was

supported by Stabik et al (2009) who stated that viscosity is the only parameter used for characterization of Newtonian liquid materials.

4.1.2 Density (Y_D) of bio-resin developed from raw banana peels

According to Eqn.4, the multiple regression model exhibited a coefficient of determination (R^2) of 0.834, lower than the R^2 (0.95) obtained for viscosity of the bio-resin. The density regression model was used to design a prediction and optimization report for density of the developed banana peels bio-resin to minimize density yield. Therefore, optimum conditions for maximum bio-resin density of 0.834g/cm^3 were; 100grams of bio-resin (X_3), 25ml of water (X_5) and at a temperature of 76.5^{0}C (X_1) for 60minutes (X_1). A bio-resin with optimum properties would be termed as one with high viscosity range of values and relatively low-density range of values.

$$Y_D = 1.0566 - 0.000479\,X_1 - 0.005639\,X_2 - 0.001164\,X_3 + 0.00699\,X_4 + 0.01604\,X_5 + 0.000010\,X_1X_1 + 0.000$$

……...Eqn. 4

Table 13: Prediction and optimization report for bio-resin density

Goal: Minimize density yield (Y_D)		Solution: Optimal settings			
Predicted density yield	0.834	X_1	76.5	X_4	0
95% Predicted Interval	(0.796, 0.872)	X_2	60	X_5	25
		X_3	100		

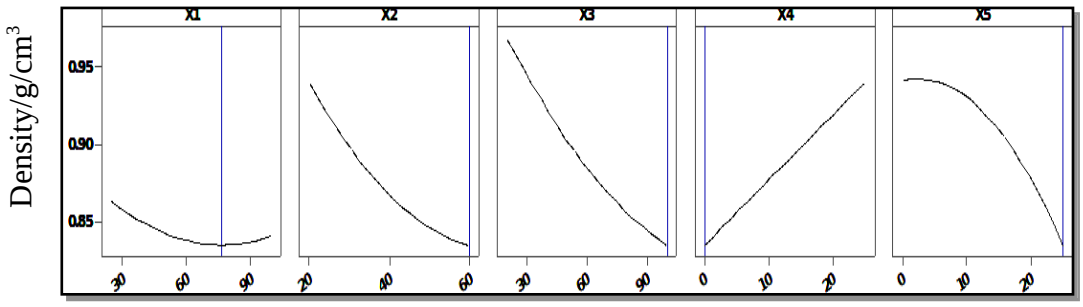
X_1 = Temperature X_2 = Time X_3 = Resin X_4 = Glycerine X_5 = Water

Table 14: Top alternative solutions close to optimal density settings of the bioresin

X_1	X_2	X_3	X_4	X_5	Predicted Y_D
60	40	60	15	25	0.915
80	30	30	20	20	0.925
80	50	80	20	20	0.929
80	30	80	10	20	0.932
40	50	80	10	120	0.933

X_1 = Temperature X_2 = Time X_3 = Resin X_4 = Glycerine X_5 = Water

From Table 13 and Table 14, optimal settings required in obtaining the minimum density for this banana peels bio-resin, which was 0.834g/cm^3 was presented alongside the top five predicted alternatives.



X_1 = Temperature/^{0}C X_2 = Time/min X_3 = Resin/grams X_4 = Glycerine/grams X_5 = Water/mls

Figure 17: Settings and sensitivity for optimum density of banana bio-resin

The alternatives could be considered in case the optimal settings were not practically applicable. From the predictive model, it was evident that to obtain the density objective of yield minimization, temperature (X_1), time (X_2) resin (X_3) and Water (X_5) quantities had to be increased up to the optimal values. However, glycerine quantity (X_4) required to be eliminated from the model since increase leads to increase in density as shown in Figure 17. It was discovered that the optimal settings of bio-resin density were different from

those of viscosity and the bio-resin viscosity predictive model was stronger than that of density. Therefore, the viscosity predictive model (Eqn. 3) was used to predict the required density at the obtained bio-resin viscosity optimal settings.

Table 15: Prediction of bio-resin density based on optimum viscosity settings

Goal: Predict density yield (Y_D)		**Solution: Density optimal settings**			
Predicted Y_D	0.95	X1	25	X4	4.3
95% CI	(0.94, 0.96)	X2	20	X5	0
95% PI	(0.93, 0.96)	X3	100		

X_1 = Temperature *X_2 = Time* *X_3 = Resin* *X_4 = Glycerine* *X_5 = Water*

The predicted value of bio-resin density was 0.95g/cm^3, within a confidence interval of 0.93 g/cm^3 to 0.96 g/cm^3 that fall in the range of high-density polypropylene thermoplastic resins[CITATION Exp14 \l 1033]. Polypropylene has been used in natural fibre including pseudo-stem banana fibre reinforced composites (Malkapuram et al, 2008; Venkateshwaran, 2010). The density value obtained is also in agreement with the top five density alternative solutions with values close to the optimal settings. Unlike viscosity whose objective was to maximize yield, the objective of density was to minimize yield. This was attributed to high viscosity yields relating to better resin mechanical properties while lower density yields relate to reduction in final product density and costs (Abu and Zahra 2002; Kazys, 2011).

4.2 Surface treatment and characterization of pseudo-stem banana and sisal fibres

Physical and mechanical properties of treated and untreated pseudo-stem banana fibres were obtained and the results analyzed using T-test statistical techniques as shown in Table

16. The paired T-Test was used because of the same fibre samples treated under two various conditions.

Table 16: Paired T-Test analysis of treated and untreated banana fibre properties

Pseudo-stem Banana Fibre Responses	Mean	Confidence Interval	T – Value	P – Value
Linear density (Tex) - Treated fibres	12.52	(-19.33, -5.33)	-3.6	0.001
Linear density (Tex) - Untreated fibres	24.85			
Linear density difference	-12.33			
Elongation (%) - Treated fibres	0.4947	(0.1851, 0.3556)	6.48	0.0001
Elongation (%) - Untreated fibres	0.2243			
Elongation difference	0.2704			
Tenacity (MPa) - Treated fibres	189.5	(110.8, 249.5)	5.31	0.0001
Tenacity (MPa) - Untreated fibres	9.3			
Tenacity difference	180.2			
Young’s Modulus (MPa) - Treated fibres	3,074	(1966, 2966)	10.08	0.0001
Young’s Modulus (MPa) - Untreated	609			
Young’s Modulus difference	2,465			

4.2.1 Characterization of pseudo-stem banana fibres

Linear density of untreated pseudo-stem banana fibres was higher at 24.85tex as compared to 12.52tex for the treated fibres. From Table 16, the confidence interval for the mean difference between treated and untreated banana fibres does not include zero, which suggested a difference between them. The small (P–Value, 0.001) further suggested that the two fibres do not perform equally. This T- test therefore, suggested a significant difference between treated and untreated pseudo-stem banana fibres. According to Ebisike et al (2013), alkali treatment reduces fibre diameter and thereby increases the banana fibre aspect ratio and tenacity. According to Satish et al (2014), fibre surface modification results in an increase in adhesive bonding and thus improves ultimate tensile strength up to 30% However, linear density values obtained in this research were lower compared to

those presented by Kulkarni et al, (1983) of 6.77tex and Mukhopadhyay et al (2008) of 7 tex respectively. According to Das et al (2010) pseudo-stem banana filament fibre linear density ranges between 3tex and 12tex. Various cultivars studied in Tamilnadu (India) yielded a range of variation from 13.33tex to 24.23tex (Preethi et al, 2013). Therefore, previous studies present the same range of linear density as that obtained. Better linear density without affecting fibre strength is obtained between 2.5% - 5% sodium hydroxide concentration (Alhayat et al, 2014). This implied that treatment of the banana fibres with 4% sodium hydroxide reduced the linear density of the fibres.

Tensile properties included tenacity, Young's modulus and percentage elongation. Tenacity of treated pseudo-stem banana fibres were higher at 189.5MPa than values for the untreated fibres at 9.3MPa. The confidence interval for the mean difference between treated and untreated banana fibres was above zero, suggesting a significant difference between the fibres. Since the P–value (0.0001) was less than α - value ($P < 0.05$), the alternative hypothesis was acceptable indicating a significant difference in tenacity of the treated and untreated pseudo-stem banana fibres. Banana fibres were of particular interest because their composites have high tensile strength, Young’s modulus and low elongation at break (Chandrasekaran et al, 2014). The tenacity of untreated fibres was low at 9.3MPa compared to treated fibres at 189.5MPa. Treated fibres also had a better tenacity range compared to the range of 146.2MPa to 167.2MPa studied by Mukhopadhyay et al (2008) while varying strain rates against gauge length. This variation was supported by Alwani et al (2015) who stated that physical and chemical composition of different agricultural fibres show high variability in properties even for the same type of fibres. Young’s modulus obtained at 608.62 MPa represented untreated fibres while 3.074GPa was for treated fibres.

From Table 16, the confidence interval for the mean difference between treated and untreated banana fibres did not include zero, which suggested a difference between these fibres. The small (P–Value, 0.0001) further suggested that the two fibres do not perform in the same way. This T-test therefore, suggested a significant difference between modulus of treated and untreated pseudo-stem banana fibres. Young's Modulus range values for untreated and treated fibres were lower than those proposed (8 - 32GPa) by Das et al (2010) and Sumaila et al (2013). However, there was great improvement in the modulus for the treated banana fibres in comparison to the range of the untreated fibres.

Untreated pseudo-stem fibres exhibited a lower percentage elongation at break of 0.22% against 0.49% of the treated fibres as shown in Table 16. The confidence interval for the mean difference between treated and untreated banana fibres did not include zero, which suggested a difference between the fibres. The P–Value, 0.0001 being less than the alpha value ($P < 0.05$) indicated rejection of the null hypothesis and acceptance of the alternative hypothesis that proposed a significant difference in elongation of the treated and untreated pseudo-stem banana fibres. However, obtained values did not fall in the banana fibres elongation range of 1.0 to 3.5 as reported by (Das et al, 2010). This could be due to variations in gauge length used in other studies compared to this research and origin of the fibres used as proposed by (Alwani et al, 2015).

4.2.2 Characterization of sisal fibres

Three (3) Kgs of characterized sisal fibres were obtained from Kamwe Business Solutions (Uganda). The sisal fibres were characterized for tenacity (MPa), percentage elongation, Young's modulus (MPa) and linear density (tex).

Linear density of untreated sisal fibres was 46tex as compared to treated sisal fibres at 23.82tex as shown in Table 17. Alkali treatment reduced fibre diameter and thereby increased the banana fibre aspect ratio and tenacity (Ebisike et al, 2013).

Tenacity of untreated sisal fibres was 108MPa as compared to 217.13MPa of the treated sisal fibres as shown in Table 17. Young's modulus of untreated sisal fibres was 4GPa as compared to 5.76GPa of treated sisal fibres, which were in close range of 8 - 32GPa with those proposed by (Sumaila et al, 2013). Percentage elongation of untreated sisal fibres exhibited was 1.85% and after treatment, the elongation reduced to 1.03%. Percentage elongation was in close range with values proposed by (Das et al, 2010). Elongation values obtained in this research were comparable to untreated sisal fibres with 2% and treated fibres with 1% (Pavithran et al, 1996).

Table 17: 2 sample T-Test of treated pseudo-stem banana and sisal fibre properties

Treated banana & sisal fibre responses	Mean	Confidence Interval	T - Value	P – Value
Linear density (Tex) - Treated sisal fibres	23.82	(9.98, 16.65)	4.7	0.0001
Linear density (Tex) - Treated banana fibres	12.52			
Treated fibre linear density difference	11.3			
Elongation (%) - Treated sisal fibres	1.026	(0.3401, 0.7227)	5.63	0.0001
Elongation (%) - Treated banana fibres	0.495			
Treated fibre elongation difference	0.531			
Tenacity (MPa) - Treated sisal fibres	217.13	(64.0, 145.1)	5.21	0.0001
Tenacity (MPa) - Treated banana fibres	112.7			
Treated fibre tenacity difference	104.43			
Young's Modulus (MPa) - Treated sisal fibres	5,763	(1249, 4129)	3.78	0.001
Young's Modulus (MPa) - Treated banana	3,074			
Treated fibre Young's modulus difference	2,689			

4.3 Development and characterization of the bio-composites

4.3.1 Development and analysis of the bio-composites

20 bio-composite samples of pseudo-stem banana and sisal fibres as shown in Figure 18 of 310mm X 310mm X 10mm were produced as specimen samples for the required tests.

Figure 17: Pseudo-stem banana (a) and sisal fibre (b) reinforced bio-composites

4.3.2 Characterization of the banana bio-composites

Multiple regression analysis of tensile strength (Y_T) exhibited a model with an R^2 value of 0.929 and a P-value of 0.0001 hence significant. Table 18 was a summary of analysis of variance (ANOVA) and variation inflation factors (VIF) statistics generated by the model.

$$Y_T(Banana) = 7.32 - 0.2107\,X_1 + 0.091\,X_2 + 0.001604\,X_1X_1 + 0.000231\,X_2X_2 \ldots Eqn.5$$

The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects.

Table 18: ANOVA and VIF for tensile strength of the banana bio-composites

Source	ANOVA (P-Value)	VIF
Regression	0.000	
X_1	0.000	1.00
X_2	0.000	1.01
X_1*X_1	0.000	1.05
X_2*X_2	0.020	1.05
X_1*X_2	0.000	1.00

X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams)

This was because all the VIF values presented in Table 18 were below 5. The developed regression model was used to design a prediction and optimization report for tensile strength of the developed bio-composites. Optimum settings yielded maximum tensile strength of 4.2MPa in a confidence interval range of 3.5MPa to 4.9MPa. This tensile strength was close to the one obtained by Olusegun et al (2012) of 6.5 MPa. It was also comparable to that of banana reinforced phenol formaldehyde composite ranging from 1.98MPa to 4.58MPa with a better load carrying capacity than plywood of the same

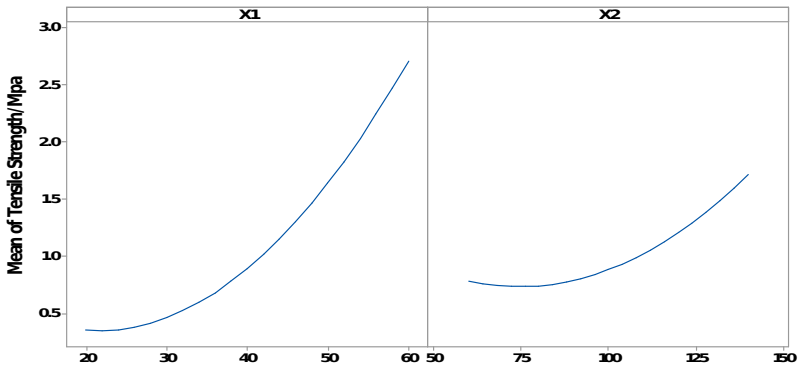
thickness (3mm), recommended for lighter applications (Ajith et al, 2015). Furthermore, the tensile strength of 4.2MPa was above the required standard value for commercial medium density fibreboards of thickness, 10mm to 21mm and tensile strength of 1.15MPa (EWPAA, 2008). Optimum settings for maximum tensile strength shown in Table 19 and main effects plot for tensile strength shown in Figure 18 were obtained.

Table 19: Prediction, optimization and optimum settings for banana bio-composite tensile strength

Goal: Maximized tensile strength (MPa)		Solution: Optimum settings	
Predicted tensile strength (MPa)	4.21	X_1	60
95% Confidence Interval	(3.50, 4.93)	X_2	140
95% Predicted Interval	(3.32, 5.12)		

X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams)

The regression model was used to determine alternative settings close to the optimum tensile strength settings in case the optimal settings were not practical during implementation. The alternative settings obtained were; fibre volume fraction (X_1) of 60% and bio-resin weight (X_2) of 100grams hence a predicted tensile strength of 1.86MPa, which was still above that of the commercial medium density fibreboards.



X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams)

Figure 18: Main effects plot for tensile strength of banana bio-composites

From the tensile strength regression model, it was evident that doubling the fibre volume fraction (X_1^2) and the bio-resin mass (X_2^2) led to significant increase in banana bio-composite tensile strength. This was further confirmed by Figure 18 where (X_1^2) and (X_2^2) increased the tensile strength of the sisal bio-composite tremendously. This could be due to the presence of cellulosic fibres in the bio-composites that exhibit a plasticizing effect. Addition of fibres with higher strength and stiffness to a polymer matrix greatly improves tensile properties of composites (Ku, 2011). Significant increase in tensile strength could also be explained by the appropriate length of fibres (15mm) used in the bio-composites. This was supported by Ajith et al (2015), who stated that tensile strength increases with increase in fibre length, up to a maximum value of 30mm and thereafter decreases. A stable network structure can occur for higher fibre lengths throughout the composite, hindering easy deformation upon application of an external stress.

Multiple regression analysis of percentage elongation (Y_E) exhibited a model with an R^2 value of 0.962 and a significant P-value of 0.0001.

$$Y_E(Banana) = -1.21 + 0.057797\,X_1 + 0.00799\,X_2 + 0.1889\,X_3 - 0.00402\,X_1X_3 .. Eqn.6$$

Table 20 was a summary of analysis of variance and variation inflation factors generated by the elongation regression model. There was no multi-colinearity as evidenced by a variance inflation factor of 1 which was less than the required value of 5. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Variance inflation factors proved that there was no multi-colinearity among the variables and interaction effects.

Table 20: ANOVA and VIF for elongation of the banana bio-composites

Source	ANOVA (P-Value)	VIF
Regression	0.000	
X_1	0.000	1.23
X_2	0.000	1.21
X_3	0.002	1.08
X_1*X_3	0.002	1.17

X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams) X_3 – Glycerine (Grams)

Table 21 determined the optimum settings at which minimum elongation was achieved. The percentage elongation regression model for banana bio-composites predicted the percentage elongation as 1.53% in a confidence interval range of 1.47% to 2.1%. This value was in close range to the percentage elongation of banana reinforced phenol formaldehyde composite ranging between 1.72% to 2.65% (Ajith et al, 2015).

Table 21: Prediction and optimization for elongation of banana bio-composite

Goal: Minimized Elongation (%)		Solution: Optimal settings	
Predicted Elongation	1.53	X_1	20
95% Confidence Interval	(1.27, 1.83)	X_2	60
95% Predicted Interval	(1.1, 2.1)	X_3	0

X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams) X_3 – Glycerine (Grams)

From Table 22, the top five predicted alternatives are considered in case optimal settings were not feasible.

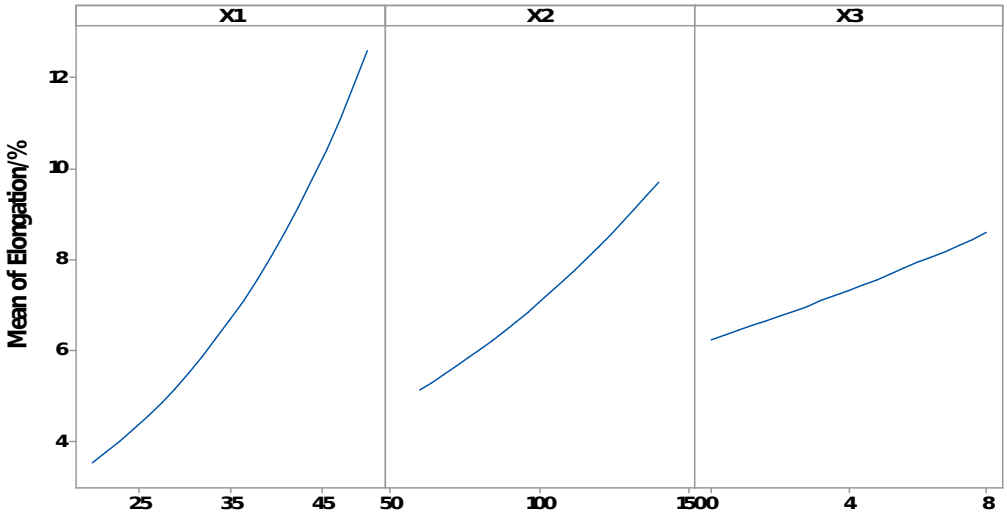
Table 22: Alternative solutions close to optimal elongation settings

X1	X2	X3	Predicted elongation (%)
20	100	4.3	3.35
30	76	6	4.67
30	124	2	5.21
30	124	6	6.84
40	100	0	6.68

X_1 – Fibre Volume Fraction (%) X_2 – Bio-resin Weight (Grams) X_3 – Glycerine (Grams)

The percentage elongation model showed that increase in fibre volume fraction (X_1), bio-resin mass (X_2) and glycerine mass (X_3) contributed positively to the percentage elongation yield whereas the interaction of fibre volume fraction and glycerine mass (X_1*X_3) reduced the percentage elongation. Figure 19 was in agreement with the banana bio-composite elongation model that increase in fibre volume fraction (X_1) resulted into increase in percentage elongation (Y_E). The goal of the regression model was to minimize elongation since reduction in elongation implies higher tensile strength and Young's modulus. According to Maria etal (2011), percentage elongation decreased with increasing fiber content for both types of composites (treated and untreated). The differences in performance of the matrix and composites suggest that the plasticizer used causes starch chains to have better packing, resulting in better organization due to more intense interactions of macromolecules (amylase and amylopectin). This could result in the positive effect on the mechanical properties, increasing the tensile strength, Young's modulus while reducing the percentage elongation compared with the composites without plasticizers. Table 23 is a summary of analysis of variance (ANOVA) and variation inflation factors (VIF) statistics generated by the model. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05

hence significant in the model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects.



X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams* *X_3 = Glycerine/Grams*

Figure 19: Settings and sensitivity for optimum elongation of banana bio-composite

Multiple regression analysis of Young's modulus (Y_Y) produced models with an R^2 value of 0.9311 and a significant P-value of 0.0001.

$$Y_Y(Banana) = 0.38 - 0.2091\,X_1 + 0.01801\,X_2 + 0.004706\,X_1X_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.7$$

Table 23: ANOVA, VIF for Young's modulus of banana bio-composites

Source	ANOVA (P-Value)	VIF
Regression	0.000	
X_1	0.000	1.06
X_2	0.003	1.06
X_1*X_1	0.000	1.01

X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams*

The regression model for banana bio-composites predicted Young's modulus as 7.24MPa in a confidence interval range of 6.29MPa to 8.19MPa. Optimum settings for Young's modulus were determined as shown in Table 24. The goal was to maximize Young's modulus of banana bio-composites.

Table 24: Prediction and optimization for banana bio-composite Young's modulus

Goal: Maximized Young's modulus (MPa)		Solution: settings	Optimal
Predicted Young's modulus (MPa)	11.99	X1	60
95% Confidence Interval	(10.72, 13.25)	X2	140
95% Predicted Interval	(10.22, 13.75)		

X_1 – Fibre Volume Fraction (%) *X_2 – Bio-resin Weight (Grams)*

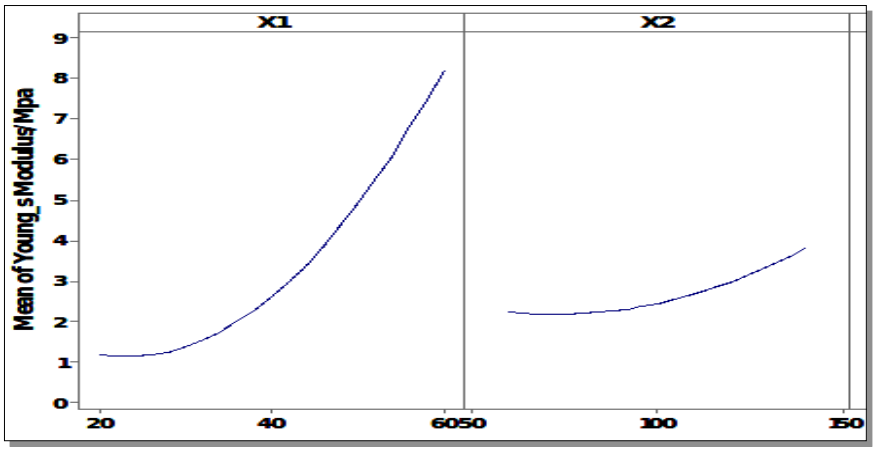
The determined optimum value for Young's modulus was less than values from previous studies. However, Young's modulus of 74.35MPa determined at 35% fibre volume fraction by Guimaraes et al (2010) was close to the value determined in this research. According to Lamis et al (2013), Young's modulus of 4.6GPa for banana fibre reinforced cornstarch bio-composites at 50% fibre volume fraction was obtained. Ajith et al (2015), determined a range of Young's modulus between 2GPa and 9.39GPa for banana phenol formaldehyde composite with fibre length between 1mm to 4mm. Different Young's modulus values could be explained by variations in reinforcement, type of matrix, fibre lengths, and fibre volume fractions used in previous studies. Top five alternative solutions closest to the optimum settings shown in Table 25 are used in case the optimum value was practically applicable.

Table 25: Alternatives close to optimum Young's modulus of banana bio-composites

X1	X2	X4 (Bio-composite)	Predicted Young's modulus (MPa)
50	124	Banana	3.61
60	140	Banana	7.23
50	76	Banana	3.07
60	100	Banana	6.22
40	140	Banana	2.01

X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams* *X_3 = Glycerine/Grams*

The main effects plot for tensile strength of banana bio-composites in Figure 20 was also determined.



X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams*

Figure 20: Main effects plot for Young's modulus of banana bio-composites

Figure 20 revealed that increase in fibre volume fraction (X_1) led to increase in Young's modulus whereas double increase in (X_1) resulted into increase in Young's modulus (Y_Y). Furthermore, increase in bio-resin mass (X_2) increased the tensile strength of the sisal bio-composite.

Multiple regression analysis of compressive strength (Y_C) exhibited a regression model with an R^2 value of 0.917 and a P-value of 0.0001 hence 0.917 significant.

$$Y_C(Banana) = 2.192 - 0.0961\,X_1 + 0.01764\,X_2 + 0.0009804\,X_1X_1 + 0.000549\,X_1X_2 .\ Eqn.8$$

Table 26 is a summary of analysis of variance (ANOVA) and variation inflation factors (VIF) statistics generated by the models. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects.

Table 26: ANOVA and VIF for compressive strength of banana bio-composites

Source	ANOVA (P-Value)	VIF
Regression	0.000	
X_1	0.000	1.08
X_2	0.015	1.05
X_1*X_1	0.008	1.44
X_1*X_2	0.003	1.41

X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams*

This was because all the VIF values presented in Table 25 were below 5. The developed regression model was used to design a prediction and optimization report for compressive strength of the developed bio-composites. The regression model for pseudo-stem banana fibre reinforced bio-composites predicted the compressive strength as 2.1MPa in a confidence interval range of 1.79MPa to 2.39MPa. However, the standard requirement for commercial medium density fibreboards was 10MPa that was higher than the obtained ranges. (EWPAA, 2008) Optimal settings for compressive strength optimization in Table 27 and top five alternative solutions closest to the optimum settings as shown in Table 28 were also determined.

Table 27: Prediction and optimization for banana bio-composites compressive strength

Goal: Maximized compressive strength (MPa)		Solution: Optimal settings	
Predicted compressive strength	2.94	X1	60
95% Confidence Interval	(2.64, 3.24)	X2	140
95% Predicted Interval	(2.38, 3.5)		

X_1 = Fibre Volume Fraction/% X_2 = Bioresin/Grams

Table 28: Solutions close to optimal compressive strength of banana bio-composites

X_1	**X_2 (MPa)**	**Predicted compressive strength**
60	100	2.09
60	140	2.09
50	124	1.07
60	100	1.48
50	76	0.67

X_1 = Fibre Volume Fraction/% X_2 = Bioresin/Grams X_3 = Glycerine/Grams

From Table 28, the top five predicted alternatives are considered in case optimal settings were not feasible. From the predictive regression model generated, fibre volume fraction (X_1) contributed the highest percentage towards the model.

4.3.3 Characterization of sisal bio-composites

Multiple regression analysis of tensile strength (Y_T) exhibited models with an R^2 value of 0.929 and a P-value of 0.0001 hence the model was significant.

$$Y_T(Sisal) = 8.38 - 0.2107\,X_1 + 0.091\,X_2 + 0.001604\,X_1X_1 + 0.000231\,X_2X_2 \ldots\ldots Eqn.9$$

Table 29 is a summary of analysis of variance (ANOVA) significance, percentage factor contributions and variation inflation factors (VIF) statistics generated by the model. The sisal bio-composite regression model was optimal and significant (P-value <0.05) with a percentage contribution of 34.1% and did not exhibit multi-colinearity as evidenced by a variance inflation factor of 1. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Percentage contributions of various factors were presented, with fibre volume fraction contributing the highest percentage of 38.1% to the model and bio-resin mass at 8.1%.

Table 29: ANOVA, factor contributions and VIF for tensile strength of sisal bio-composites

Source	ANOVA (P-Value)	Factor Contributions (%)	VIF
Regression	0.000	95.03	
X_1	0.000	38.11	1.00
X_2	0.000	8.11	1.01
X_1*X_1	0.000	3.48	1.05
X_2*X_2	0.020	1.59	1.05
X_1*X_2	0.000	7.49	1.00
Bio-composite type (Sisal)	0.000	34.10	1.00
Error		7.12	
Lack-of-Fit	0.000	6.91	
Pure Error		0.21	
Total		**100.00**	

Curvilinear and interaction effects revealed that interacting fibre volume fraction with bio-resin mass (X_1*X_2) contributed a higher percentage of 7.5% to the regression model compared to other effects. Curvilinear effects of squaring fibre volume fraction (X_1) and bio-resin mass (X_2) contributed 3.5% and 1.6% to the model respectively. Variance

inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects.

The developed regression model was used to design a prediction and optimization report for tensile strength of the developed bio-composites. Optimal settings yielded maximum tensile strength of 5.23MPa for sisal-reinforced bio-composites. Furthermore, at 95% confidence interval (CI) a tensile strength range was determined between 4.59MPa to 5.99MPa, and a predicted interval (PI) of 4.39MPa to 6.18MPa. This tensile strength was close to the one obtained by Olusegun et al (2012) of 5.4MPa. However, this tensile strength values were above the required standard values for medium density fibreboards of 1.15MPa (EWPAA, 2008). Optimal settings for tensile strength optimization Table 30 and alternative solutions closest to the optimum settings Table 31 were obtained.

Table 30: Optimum settings for sisal bio-composite tensile strength

Goal: Maximized tensile strength (MPa)		Solution: Optimal settings	
Predicted viscosity	5.23	X1	60
95% Confidence Interval	(4.59, 5.99)	X2	140
95% Predicted Interval	(4.39, 6.18)		

X_1 – Fibre Volume Fraction (%) *X_2 – Bio-resin Weight (Grams)*

Table 31: Alternative solutions close to optimum tensile strength settings of sisal bio-composites.

X_1	**X_2**	Predicted tensile strength (MPa)
60	100	3.59
50	124	3.1
40	140	2.28
50	76	1.87

X_1 – Fibre Volume Fraction (%) *X_2 – Bio-resin Weight (Grams)*

From Table 31, the top five predicted alternatives are considered in case optimal settings were not practical. From the predictive regression model generated, it was evident that fibre volume fraction (X_1) contributed the highest percentage towards the model.

For percentage elongation (Y_E), multiple regression analysis exhibited models with an R^2 value of 0.962 and a P-value of 0.0001 hence was significant model.

$$Y_E(Sisal) = -1.063 + 0.057797\,X_1 + 0.00799\,X_2 + 0.1889\,X_3 - 0.00402\,X_1X_3 .. Eqn.10$$

Table 32 is a summary of analysis of variance (ANOVA) significance, percentage factor contributions and variation inflation factors (VIF) statistics generated by percentage elongation of the sisal bio-composite model. The elongation model generated showed that increase in fibre volume fraction (X_1), bio-resin mass (X_2) and Glycerine mass (X_3) contributed positively to the percentage elongation yield whereas the interaction of (X_1*X_3) reduced elongation. However, the goal of this study was elongation minimization.

Table 32: ANOVA, % contributions and VIF for elongation of sisal bio-composites

Source	ANOVA (P-Value)	Factor Contributions (%)	VIF
Regression	0.000	95.03	
X_1	0.000	77.08	1.23
X_2	0.000	11.09	1.21
X_3	0.002	2.77	1.08
X_1*X_3	0.002	2.13	1.17
Bio-composite type (Sisal)	0.007	1.06	1.00
Error		3.77	
Lack-of-Fit	0.273	3.52	
Pure Error		0.26	
Total		**100.00**	

There was no multi-colinearity as evidenced by a variance inflation factor of 1 which was less than the required value of 5. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Percentage contributions of various factors were presented, with fibre volume fraction (X_1) contributing the highest percentage of 77.8% to the model. The bio-resin mass (X_2) and Glycerine mass (X_3) contributed 11.9% and 2.8% to the model respectively. Interaction effects revealed that interacting fibre volume fraction with bio-resin mass (X_1*X_3) contributed a percentage of 2.13% to the regression model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables and interaction effects. This was because the VIF values presented in Table 32 were below 5. The developed regression model was used to design a prediction and optimization report for percentage elongation of the developed bio-composites. Optimal settings yielded minimum elongation of 1.77% for sisal-reinforced bio-composites. Furthermore, at 95% confidence interval (CI), a percentage elongation range was determined between 1.47% to 2.12%, and a predicted interval (PI) of 1.28% to 2.45%. The percentage elongation was close to values of sisal fibre reinforced composites obtained by (Kuruvilla etal, 1999), ranging between 4% to 10%. Optimal settings for elongation optimization shown in Table 33 and top five alternative solutions closest to the optimum settings Table 34.

Table 33: Optimum settings for the sisal bio-composite elongation

Goal: Minimized elongation (%)		Solution: Optimal settings	
Predicted viscosity	1.77	X1	20
95% Confidence Interval	(1.47, 2.12)	X2	60
95% Predicted Interval	(1.28, 2.44)	X3	0

X_1 = *Fibre Volume Fraction/%* X_2 = *Bioresin/Grams* X_3 = *Glycerine/Grams*

Table 34: Solutions close to optimum sisal bio-composite elongation settings

X1	X2	X3	Predicted elongation (%)
20	100	4.3	3.41
30	76	6	5.01
30	124	2	6.24
30	124	6	6.98
40	100	0	7.82

From Table 34, the top five predicted alternatives are considered in case optimal settings were not feasible. From the predictive regression model generated, it was evident that fibre volume fraction (X_1) contributed the highest percentage towards the model. Increase in fibre volume fraction (X_1) resulted into increase in percentage elongation (Y_E). Furthermore, increase in bio-resin mass (X_2) and Glycerine mass also increased the elongation of the sisal bio-composite.

Multiple regression analysis of Young's modulus (Y_Y) produced models with an R^2 value of 0.9311 and a P-value of 0.0001 hence 0.9311 the model was significant model.

$$Y_Y(Sisal) = 3.5 - 0.2091\,X_1 + 0.01801\,X_2 + 0.004706\,X_1 X_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.11$$

Table 35 is a summary of analysis of variance (ANOVA) significance, percentage factor contributions and variation inflation factors (VIF) statistics generated by the models.

Table 35: ANOVA, factor contributions and VIF for Young's modulus of sisal bio-composites

Source	ANOVA (P-Value)	Factor Contributions (%)	VIF
Regression	0.000	93.11	
X_1	0.000	45.13	1.06
X_2	0.003	4.37	1.06
X_1*X_1	0.000	4.41	1.01
Bio-composite type (Sisal)	0.000	39.02	1.02
Error		6.89	
Lack-of-Fit	0.611	5.80	
Pure Error		1.09	
Total		**100.00**	

The sisal bio-composite regression model was optimal and significant (P-value <0.05) with a percentage contribution of 39.02% and did not exhibit multi-colinearity as evidenced by a variance inflation factor of 1.02. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Percentage contributions of various factors were presented, with fibre volume fraction contributing the highest percentage of 45.13% to the model and bio-resin mass at 4.37%. Curvilinear effect of squaring fibre volume fraction (X_1*X_1) contributed a percentage of 4.41% to the regression model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects. This was because all the VIF values presented in Table 35 were below 5.

The developed regression model was used to design a prediction and optimization report for Young's modulus of the developed bio-composites. Optimal settings yielded maximum Young's modulus of 11.99MPa for sisal-reinforced bio-composites. Furthermore, at 95% confidence interval (CI) Young's modulus range was determined between 10.72MPa to

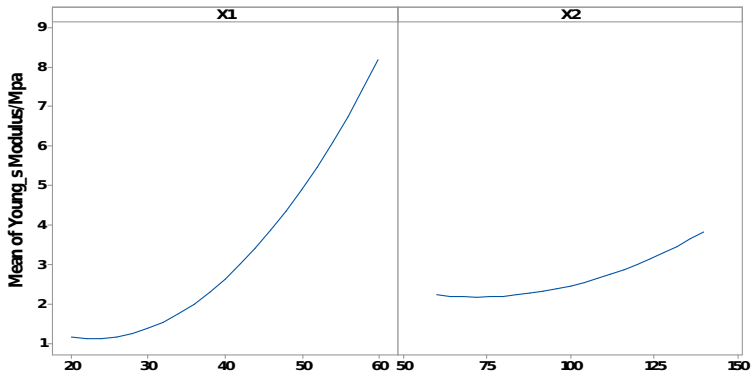
13.25MPa, and a predicted interval (PI) of 10.22MPa to 13.75MPa. Young's modulus was much lower than values for low density polyethylene sisal composites obtained by (Kuruvilla etal, 1999) at 140MPa. This may be due to variations in the origin and gauge length of the fibres used in the composite. Optimal settings for Young's modulus optimization as shown in Table 36 and top five alternative solutions closest to the optimum settings in Table 37 were obtained.

Table 36: Prediction and optimization for sisal bio-composite Young's modulus

Goal: Maximized Young's modulus (MPa)		Solution: Optimal settings	
Predicted viscosity	11.99	X1	60
95% Confidence Interval	(10.72, 13.25)	X2	140
95% Predicted Interval	(410.22.39, 13.75)		

Table 37: Solutions close to optimum sisal bio-composite Young's modulus settings

X1	X2	Predicted Young's modulus (MPa)
50	124	7.64
60	140	11.98
50	76	6.26
60	100	10.26
40	140	5.99



X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams*

Figure 21: Main effects plot for Young's modulus of sisal bio-composites

From Table 37, the top five predicted alternatives were considered in case optimal settings were not feasible. From the predictive regression model generated, it was evident that fibre volume fraction (X_1) contributed the highest percentage towards the model. This was further, evidenced by Figure 21 where increase in fibre volume fraction (X_1) led to increase in Young's modulus whereas double increase in (X_1) resulted into increase in Young's modulus (Y_Y). Furthermore, increase in bio-resin mass (X_2) increased the tensile strength of the sisal bio-composite.

The sample data of 40 points was a precise estimate of the strength of the model. There were no unusual data points to have a strong influence on the results. Furthermore, the normality test was passed since more than 15 data points were used.

Multiple regression analysis of compressive strength (Y_C) exhibited models with an R^2 value of 0.917 and a significant P-value of 0.0001.

$$Y_C(Sisal) = 3.041 - 0.0961\,X_1 + 0.01764\,X_2 + 0.0009804\,X_1X_1 + 0.000549\,X_1X_2 \ldots Eqn.12$$

Table 38 is a summary of analysis of variance (ANOVA) significance, percentage factor contributions and variation inflation factors (VIF) statistics generated by the models. The sisal bio-composite regression model was the most optimal and significant (P-value <0.05) with a percentage contribution of 34.1% and did not exhibit multi-colinearity as evidenced by a variance inflation factor of 1. The P-values for individual factors, curvilinear and interaction effects revealed that all the values were less than 0.05 hence significant in the model. Variance inflation factors (VIF) proved that there was no multi-colinearity among the variables, curvilinear and interaction effects. This was because all the VIF values

presented in Table 38 were below 5. The developed regression model was used to design optimum settings for compressive strength of the developed bio-composites.

Table 38: ANOVA, % contributions and VIF for sisal bio-composites compressive strength

Source	ANOVA (P-Value)	Factor Contributions (%)	VIF
Regression	0.000	95.03	
$\mathbf{X_1}$	0.000	42.88	1.08
$\mathbf{X_2}$	0.015	4.43	1.05
$\mathbf{X_1*X_1}$	0.008	8.45	1.44
$\mathbf{X_1*X_2}$	0.003	1.81	1.41
Bio-composite type (Sisal)	0.000	34.10	1.01
Error		8.32	
Lack-of-Fit	0.003	8.26	
Pure Error		0.06	
Total		**100.00**	

Optimal settings yielded maximum compressive strength of 2.94MPa for sisal-reinforced bio-composites. Furthermore, at 95% confidence interval (CI) a compressive strength range was determined between 2.64MPa to 3.24MPa, and a predicted interval (PI) of 2.38MPa to 3.5MPa. The regression model for pseudo-stem banana fibre reinforced bio-composites predicted the compressive strength as 2.1MPa in a confidence interval range of 1.79MPa to 2.39MPa. According to Olusegun et al (2012), sisal and pseudo-stem banana fibre reinforced bio-composite laminates yielded compressive strength of 42MPa and 16.5MPa respectively, which was higher than obtained values in this research. However, the standard requirement for commercial medium density fibreboards was 10MPa that was in proximity to the obtained ranges (EWPAA, 2008).

Table 39: Optimum settings for sisal bio-composites compressive strength

Goal: Maximized compressive strength (MPa)		Solution: Optimal settings	
Predicted compressive strength	2.94	X1	60
95% Confidence Interval	(2.64, 3.24)	X2	140
95% Predicted Interval	(2.38, 3.5)		

X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams* *X_3 = Glycerine/Grams*

From Table 40, the top five predicted alternatives are considered in case optimal settings were not feasible. From the predictive regression model generated, fibre volume fraction (X_1) contributed the highest percentage towards the model.

Table 40: Solutions close to optimum sisal bio-composite compressive strength settings

X1	X2	Predicted compressive strength (MPa)
60	100	2.33
60	140	2.90
50	124	1.90
60	100	3.19
50	76	1.43

X_1 = Fibre Volume Fraction/% *X_2 = Bioresin/Grams* *X_3 = Glycerine/Grams*

Chapter 5 : CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

This chapter focused on the results from this research, conclusions and recommendations pertaining to the natural fibre reinforced bio-composites as an alternative to petroleum-based composites. This research work concentrated on a bio-resin from raw banana peels and bio-composite boards made from pseudo-stem banana and sisal fibres.

5.1 Conclusion

The banana peels bio-resin produced in this research work was characterized for viscosity and density. The multiple regression model for the viscosity exhibited an acceptable R^2 value of 0.95 and an optimized viscosity value of 242.01MPa.s. For bio-resin density, the R^2 was 0.834 and the optimum density was 0.95g/cm^3. Percentage contributions of various factors that affected the viscosity of the bio-resin were amount of water (20%), Glycerine amount (18.6%), temperature (4%) and time (1.2%). This bio-resin's properties were in close proximity to existing commercial resins including urea formaldehyde, polypropylene maize cornstarch and cassava starch that have been used in bio-composites development. Similarly, the developed raw banana peels bio-resin has adhesive properties and have been used for development of banana and sisal bio-composites in this research.

The fibres used in this research work were characterized (treated and untreated). Linear density of the untreated pseudo-stem banana fibres was higher at 24.85tex as compared to 12.52tex for the treated fibres. Untreated pseudo-stem fibres exhibited a lower percentage elongation at break of 0.22% against 0.49% of the treated fibres. Tenacity of treated pseudo-stem banana fibres was higher at 189.5MPa than values for the untreated fibres at 9.3MPa. Young's modulus obtained at 608.62MPa represented untreated fibres while

3,074.45MPa was for treated fibres. There was great improvement in the modulus for the treated banana fibres in comparison to the range of the untreated fibres. Untreated sisal fibres had a linear density of 46tex as compared to 23.8tex of treated sisal fibres. Untreated sisal fibre tenacity was 88MPa as opposed to 217.13MPa of the treated fibres. Young's modulus of untreated fibres was 4GPa against 5.76GPa for treated fibres. The obtained elongation of 1.85% represented untreated sisal fibres as compared to 1.03% representing the treated sisal fibres. The Paired T-test used in fibre properties analysis indicated a significant improvement in the linear density and mechanical properties of treated fibres rather as compared to untreated. The values obtained were in a close range to existing commercial sisal fibres hence good for bio-composites development. Both banana and sisal fibres used in this research were used for developing bio-composites with exceptional properties comparable to commercial bio-composites.

Sisal and pseudo-stem banana fibre reinforced bio-composites were characterized in terms of tensile strength, elongation, Young's modulus and compressive strength. Sisal reinforced bio-composites exhibited a model with an R^2 value of 0.929 and tensile strength of 5.23MPa in a confidence interval of 4.59MPa to 5.99MPa. Percentage elongation model yielded an R^2 value of 0.962 and elongation of 1.53% with a confidence interval range between 1.27% to 1.84%. Multiple regression analysis of Young's modulus (Y_Y) produced a model with an R^2 value of 0.931 between 10.72MPa to 13.25MPa. Compressive strength (Y_C) exhibited a regression model with an R^2 value of 0.917 and 2.94MPa between 2.64MPa to 3.24MPa. Pseudo-stem banana fibre reinforced bio-composites yielded the same R^2 values as above but with different predicted values. The regression model exhibited tensile strength as 4.2MPa in a confidence interval range of 3.5MPa to 4.9MPa;

elongation as 1.77% in a confidence interval range of 1.47% to 2.1%; Young's modulus of 7.24MPa in a confidence interval range of 6.29MPa to 8.19MPa and compressive strength of 2.1MPa in a confidence interval range of 1.79MPa to 2.39MPa. The bio-composites tensile and compressive properties were in a close range to commercial bio-composites and solid boards hence could be commercialised and used in lighter applications like ceiling, partition and notice boards.

5.2 Recommendations

Apart from viscosity and density, other properties of this locally made bio-resin including, shear resistance, gelatinization, textures, solubility, tackiness, gel stability should be investigated. Since the obtained viscosity was in close proximity to some commercial resins including urea formaldehyde and maize cornstarch studying other properties could increase the bio-resin viability.

Apart from the optimized values of the factors affecting the bio-resin, other factors including combination of other natural products like cornstarch, tapioca and cross linking agents with the banana peels bio-resin can be undertaken. This could improve on the banana peels bio-resin properties especially including tensile and compressive properties.

The developed banana and sisal fibre reinforced bio-composites have good mechanical properties comparable to commercial fibreboards. Therefore, these bio-composites can be used for ceiling boards, partition boards, wall hangings and art boards. The bio-composites could be a good alternative to non- renewable and non- bio-degradable petroleum and solid wood products. The application of the banana peels bio-resin could be extended to other various natural fibres apart from pseudo-stem banana and sisal fibres for bio-composites

development. These would include the newly extracted cotton stalk bast fibres and pineapple fibres among others. Other tests including water absorption, flexural rigidity and impact tests have been recommended for further study.

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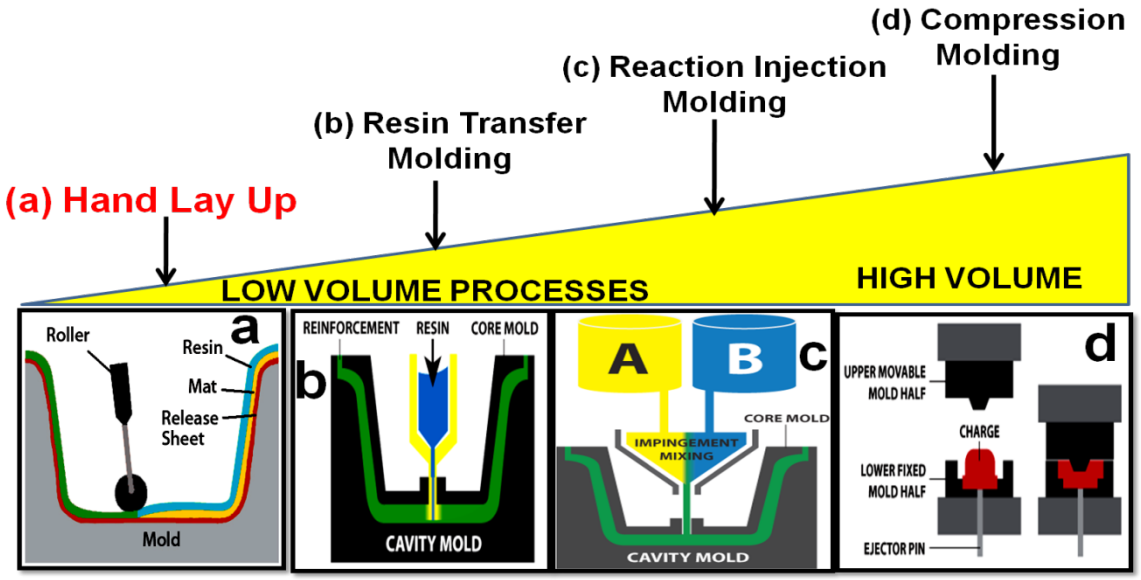
APPENDICES

Appendix A: Bio-composite fabrication techniques.



Appendix B: Published journal article: Viscosity of banana peels bio-resin

Abstract

Over 30 million tons of banana peels are thrown away annually worldwide, leading to disposal by burning which is environmentally unfriendly. Strong governments support for environmental conservation and increasing dangers of incineration emissions have directed research into eco-friendly materials. The aim of this research therefore, was to study the utilization of banana peels, a case study of factors affecting viscosity of locally made bio-resin from raw banana peels. The peels were washed, boiled and pureed. Effect of temperature, time, resin, glycerine, and water ratios on bio-resin viscosity were studied through use of the universal rotatable design and multiple regression analysis. Second order polynomial regression equation for viscosity was fitted and exhibited a co-efficient of determination (R^2) of 0.95. According to the results obtained in this research paper, resin quantity was the most influential factor towards the desired viscosity of the bio-resin contributing 41% to the regression model. Other factors included water ratio (20%), glycerin ratio (18.6%) among others. The developed bio-resin had an optimized viscosity response value of 242.01 mPa.s within confidence interval limits of 229.6 mPa.s to 254.5 mPa.s. This viscosity value was in a close range to existing commercial resins including maize cornstarch bio-resin and synthetic urea formaldehyde used in reinforced bio-composites development.

Keywords - Banana peels; Banana peels bio-resin; Viscosity; Universal rotatable design; Regression analysis

Mwesigwa, R., Mwasiagi, J. I., Githaiga, J. T., Nzila, C. and Oyondi. E. N.· (2016). The Study of the Factors Affecting Viscosity of Locally Made Bio-Resin from Raw Banana Peels. *Research and Reviews in Polymers* 7(2):101, 1 – 9. 2016 Trade Science Inc © (In Press). Online: www.tsijournals.com.

Appendix C: Conference proceedings: Density of locally made banana peels bioresin

Abstract

Density measurements are very useful for identification and characterization of different substances. It is a very important physical parameter in polymer engineering affecting production cost and profitability of the manufacturing process. A reduction in density reduces the raw material cost hence decreases the manufacturing costs. Therefore, the aim of this research was to study the factors affecting density of locally made bio-resin from raw banana peels. The raw banana peels were washed, boiled, pureed and treated with various ratios of glycerin to obtain a thermoplastic bio-resin. The effect of temperature, time, resin quantity, glycerin and water on bio-resin density were studied through use of the central composite rotatable experimental design and regression analysis. Second order polynomial regression equation for density was fitted and exhibited an R^2 value of 0.83. From the predictive model, it was evident that to obtain the objective of density minimization, temperature , time, resin and water ratios needed to be increased up to optimal values. However, glycerin ratio required to be eliminated from the model since increase led to increase in density. However, the top five density alternative solutions presented in this research paper permitted room for particular glycerin ratios to be maintained. The developed banana peels bio-resin had a density of 0.83g/cm^3. This density value was above that of tapioca bio-resin and close to that of polypropylene synthetic resin, both commercially used in bio-composites development.

Keywords — Banana peels, bio-resin, density, regression analysis.

Mwesigwa, R., Mwasiagi, J. I., Nzila. C., Oyondi. E.· and Githaiga, J. T. (2016). The Study of the Factors Affecting Density of Locally Made Bio-Resin From Raw Banana Peels. *Proceedings of the Annual Conference on Sustainable Research and Innovation.* Jkuat - Nairobi (Kenya), 61 – 64. Online: jkuat-sri.com.

Appendix D: Proceedings Book: Properties of treated pseudo-stem banana fibres

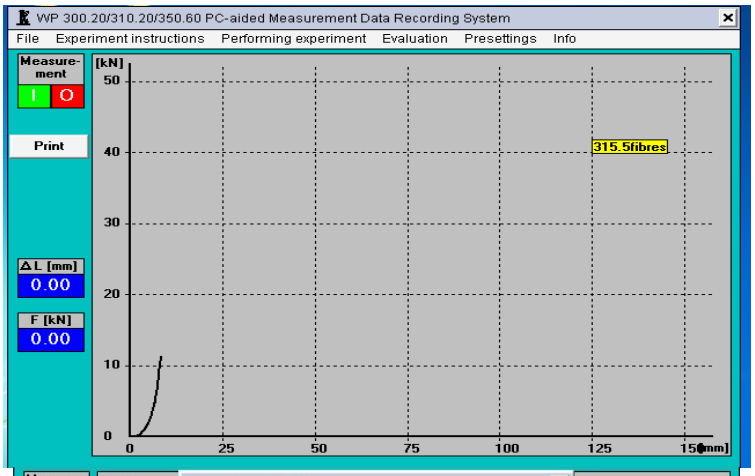
Abstract

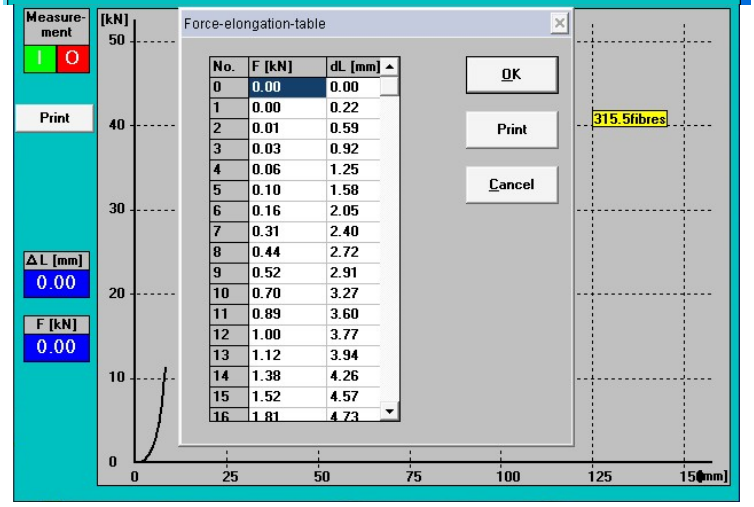
Banana pseudo-stems are used for paper pulp and fibres but some are thrown away in spite of their potential for further value addition. Agriculture is a major source of raw materials for the bio-composites market worldwide accounting for over 14% share and projected to rise to 28% by 2020. Banana plants are produced in over 135 countries and territories across the tropics and subtropics relating to continuous fibres supply. However, Uganda is one of the top banana producing countries in the world. The interest on agricultural fibres has grown rapidly due to their abundance, renewability, bio-degradability, low density and non-toxic nature hence an alternative to man-made fibres. The aim of this research therefore, was to characterize the physical and mechanical properties of pseudo-stem banana fibres, a case study of Uganda. The fibers were surface treated with 4% sodium hydroxide, boiled at 105^0C for four hours, washed in tap water, oven dried and characterized for linear density, elongation, and tenacity. Treated pseudo-stem banana fibres were characterized with a linear density of 2.683tex, percentage elongation at break of 2.12% and tenacity of 9.1 N/tex. These physical and mechanical properties are in the range of other pseudo-stem fibres that have been employed in bio-composites production.

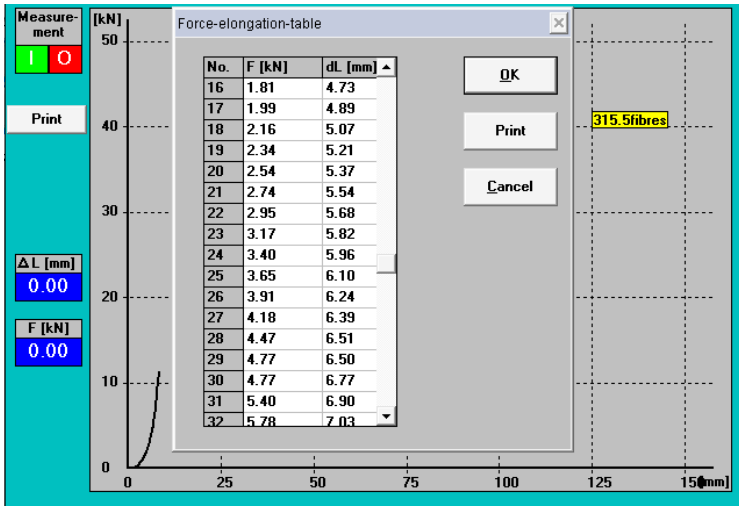
Keywords — Pseudo-stem banana fibres, surface treatment, physical properties, mechanical properties, bio-composites production.

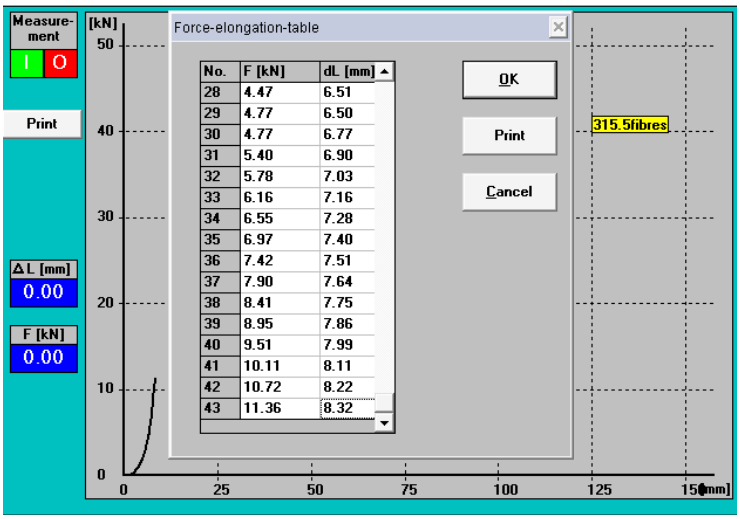
Mwesigwa, R., Mwasiagi, J. I., Nzila, C., Oyondi. E. N. and Githaiga, J. T. (2016). Characterization of the physical and mechanical properties of surface treated pseudo-stem banana fibres. Sino-Africa International Symposium on Textiles and Apparel & Sino-Africa Exchange Forum, Mombasa (Kenya). *Donghua University Press*, 333 – 335.

Appendix E: A representative extract of bio-composite characterization using the universal material tester (Tensile properties of banana bio-composite with 315.5grams of fibres)





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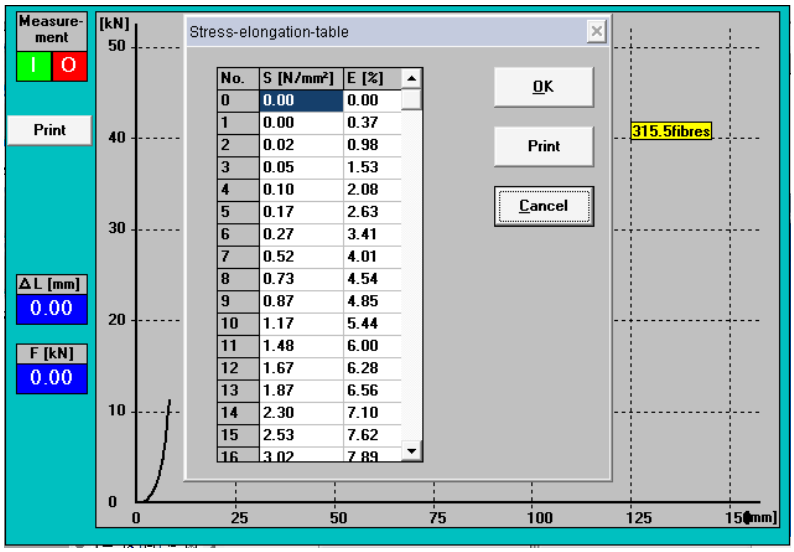
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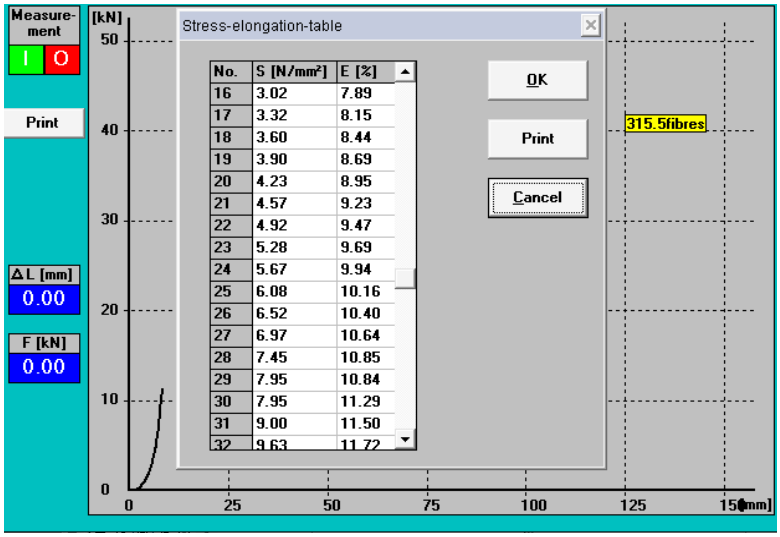
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Stress-elongation-table
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25 6.08 10.16
26 6.52 10.40
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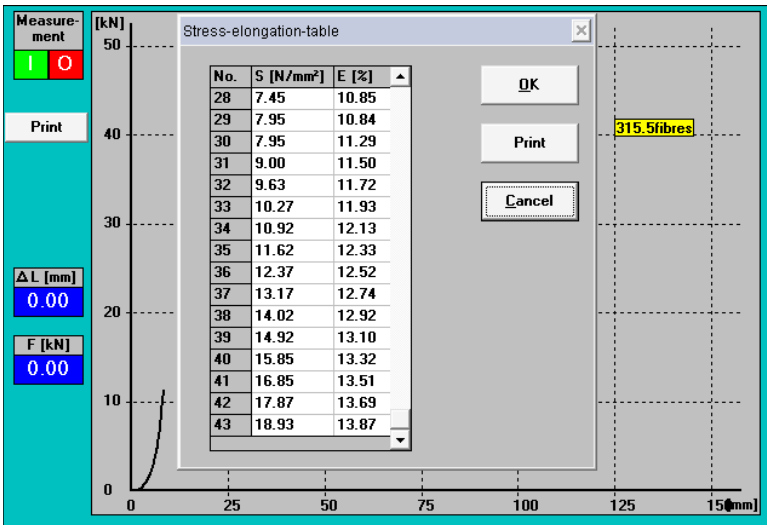
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Stress-elongation-table
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33 | 10.27 | 11.93
34 | 10.92 | 12.13
35 | 11.62 | 12.33
36 | 12.37 | 12.52
37 | 13.17 | 12.74
38 | 14.02 | 12.92
39 | 14.92 | 13.10
40 | 15.85 | 13.32
41 | 16.85 | 13.51
42 | 17.87 | 13.69
43 | 18.93 | 13.87
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315.5fibres