DEVELOPMENT AND CHARACTERIZATION OF ETHIOPIAN BAMBOO FIBRE REINFORCED POLYMER COMPOSITE FOR AUTOMOBILE INDUSTRY

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A Dissertation Submitted to:

The Department of Mechanical Engineering

School of Mechanical, Chemical, and Materials Engineering

Presented in Fulfillment of the Requirement for the Degree of Doctor of Philosophy in Manufacturing Engineering

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this Dissertation entitled "**Development and characterization of Ethiopian bamboo fibre reinforced polymer composite for automobile industry** " is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials used for this thesis have been duly acknowledged through appropriate citations.

Yalew Dessalegn Asfaw	________________	March 2023
Name of student	Signature	Date

RECOMMENDATION

We, the supervisors of this dissertation, hereby certify that we have read and revised the dissertation entitled "**Development and characterization of Ethiopian bamboo fibres reinforced polymer composite for automobile industry**" prepared under our guidance by **Yalew Dessalegn** submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in **Manufacturing Engineering**. Therefore, we recommend the submission of the dissertation to the department for further review and defense.

AART W. VAN VUURE ________________ **28 March 2023**

Main Supervisor Signature Date

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Co-supervisor Signature Date

APPROVAL PAGE OF Ph.D. DISSERTATION

Hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled "**Development and characterization of Ethiopian bamboo fibre reinforced polymer composite for automobile industry**" by **Yalew Dessalegn**.

AART W. VAN VUURE ________ **28 March 2023**

Major Supervisor Signature Date

________________ ________________ ________________

Co-supervisor Signature Date

We, the undersigned, members of the Board of Examiners of the dissertation open defense by **Yalew Dessalegn** have read and evaluated the dissertation entitled "**Development and characterization of Ethiopian bamboo fibre reinforced polymer composite for automobile industry**" and examined the candidate during open defense. This is, therefore, to certify that the dissertation is accepted for partial fulfillment of the requirement of the degree of Doctor of Philosophy **in Manufacturing Engineering**.

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Finally, approval and acceptance of the dissertation is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the candidate's Department Graduate Council (DGC) and School Graduate Committee (SGC).

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LIST OF ACRONYMS

ASTM	American society for Testing and Materials
ANOVA	Analysis of variance
BFRPPCs	Bamboo fibre reinforced polypropylene composites
BFREPCs	Bamboo fibre reinforced epoxy composites
BF	Bamboo Fibres
CFD	Coefficient of variation of the fibre diameter
DSC	Differential Scanning Calorimetry
DTG	First derivative of the TGA curve
EP	Epoxy
FTIR	Fourier Transform Infrared spectroscopy
GPa	Giga Pascal
ISO	International Standard Organization
MPa	Mega Pascal
NaOH	Sodium hydroxide
PP	Polypropylene
s	Second
TGA	Thermo-gravimetric analysis
Wt%	Weight Percentage
W/v	Weight/volume ration
ºC	Degree Celsius
EF	Efficiency factor
IBFT	Impregnated bundle fibre test
RH	Relative humidity
ROM	Rule of mixtures
RT	Room temperature
SF	Single technical bamboo fibre
TP	Thermoplastic
TS	Thermoset
UD	Unidirectional
3PBT	Three-point bending test

DBH	Diameter at Breast Height
DMM	*Dendrocalamus membranaceus* Munro
PAS	phyllostachys aureosulcata Spectabilis
PNB	*phyllostachys nigra* Boryana
PVMJ	*Phyllostachys vivax* McClure Jiantonging
INJ	Injibara
KOCH	Kombolcha
MEKS	Mekaneselam
ms	Mean square
ss	Sum square
df	Degree of freedom
HT	Height
CVFD	Coefficient variance of fibres diameter
Eqn.	Equation
std	Standard
TS	Tensile strength
FS	Flexural strength
MOE	Modulus of elasticity
PU	Polyurethane
CFPU	Carbon fibres polyurethane
GF	Glass fibres
GFPU	Glass fibres polyurethane
TPU	Thermoplastic polyurethane
PE	Polyester
Feb.	February
Nov.	November
UDMA	Urethane dimethacrylate
GFMPU	Glass fibres mat polyurethane

LIST OF ABBREVIATIONS

A	Cross sectional area
A_w	Cross sectional area of individual technical fibre measured by mass, length and apparent density
α	Level of confidence in a statistical analysis
ρ	Density
$\rho_{\mathbf{f}}$	Fibres density
σ	Tensile strength
σ_f	Fibres tensile strength
d	Fibre diameter
E	Young's modulus
m	Mass of the fibres
m_d	Dry mass
ΔL	Cross displacement
m_w	Wet mass
E_f	Fibres Young's modulus
E_c	Stiffness of the composite
E_f	Stiffness of the fibre
E_m	Stiffness of the matrix
β	Shape parameter in the Weibull distribution
V_f	Fibre volume fraction
V_m	Matrix volume fraction
ε	Strain
λ	Within-fibre diameter variation parameter in the Weibull distribution
ε_{max}	Strain at maximum load in the dry fibre bundle tensile test
σ_f	Strength of the fibre
σ_c	Strength of the composite
σ_o	Scale parameter in the Weibull distribution
σ_m	Tensile strength of the matrix at fibre failure
γ	Sensitive parameter
β	Shape parameter

ABSTRACT

More than 1 million hectares of bamboo were found in the different regions of Ethiopia which were the largest coverage of bamboo plants in Africa. However, the applications area of the bamboo culm was used for making furniture and utilized in structural purposes for low-level technology. Nowadays, synthetic fibres are substituted by natural fibres for the production of automobile parts, due to high weight, utilize high energy for production, expensive cost, ecologically unfriendly, and nonbiodegradable. Researchers have motivated and studied the properties of natural fibres for the application of the automobile and aerospace industry. Research has not been done on the properties of bamboo fibres and their polymer composites in Ethiopia so far. The current research studies develop and characterize Ethiopian bamboo fibres and their polymer composites for headliners which is the largest part of the automobile industry.

Three representatives of bamboo plants were harvested in three regions of Ethiopia, three group of age, and two harvesting months. Bamboo fibres are extracted using a roll milling machine which the authors developed in the workshop. The machine would be secreted for the authors' confidentiality and intellectual property protection. Bamboo powders and different type of chemicals were used to measure the chemical composition of bamboo fibres. Six-slot compression mold was used to produce bamboo fibers epoxy composite according to the testing procedures of ASTM standards. A hot press machine was used for the production of polypropylene prepregs and composites.

The Internodal length, outer diameter, and wall thickness of Injibara bamboo are 28–50 cm, 17–68 mm, and 6–15 mm, whereas Kombolcha bamboo is 27–45 cm, 59–128 mm and 8–21 mm and Mekaneselam bamboo are 46–62 cm, 27–56 mm and 5–17 mm, respectively. The fibres densities of Injibara, Kombolcha, and Mekaneselam are 1.35–1.38 g/cm3, 135–1.36 g/cm3, and 1.34–1.36 g/cm3, whereas the degree of crystallinities of them are 69–73%, 58–66%, and 66–68%, respectively. The cellulose, hemicelluloses, and lignin content of Injibara bamboo have 51–53%, 20–23%, and 19–21% whereas, Kombolcha bamboo has 46–49%, 17–19%, and 27–29% and Mekaneselam bamboo has 49–52%, 18–20% and 21–24%, respectively. The tensile strength and young's modulus of Injibara bamboo fibres have 431–548 MPa and 37–48 GPa, whereas Kombolcha bamboo fibres have 339–496 MPa and 25–36 GPa, and Mekaneselam bamboo fibres have 399–541 MPa and 38–45 GPa, respectively. The tensile, flexural, and impact strength of Injibara bamboo fibres epoxy composites has 171–227 MPa, 156–234 MPa, and 31–70 KJ/m^2, whereas Kombolcha has 129–205 MPa, 81–190 MPa, and 43–63 KJ/m^2, as well as, Mekaneselam has 151–216 MPa, 116–198 MPa, and 42–66 KJ/m^2, respectively. The tensile, flexural, and impact strength of Injibara bamboo fibres polypropylene composites has 91–125 MPa, 92–159 MPa, and 34–57 KJ/m^2 whereas Kombolcha has 60–111 MPa, 66–99 MPa, and 26–44 KJ/m^2, and Mekaneselam has 85–116 MPa, 89–152 MPa, and 34–46 KJ/m^2, respectively. 2–years old and in November bamboo fibres has a higher chemical composition, and degree of crystallinity. as well as, higher properties of bamboo fibres polymer composites. The highest to the lowest mechanical properties of bamboo fibres polymer composites are Injibara, Mekaneselam, and Kombolcha, respectively. Further research should be required to improve the mechanical properties of bamboo fibres epoxy and polypropylene composites. Researchers should optimize fibre matrix interaction using additives and treatment. Moreover, researchers should scale up the extraction process of fibres due to the difficult extraction of fibres from their culm.

Keywords: Ages, Bamboo species, Fibres properties, Fibres matrix, Harvesting months.

CHAPTER –1

BACKGROUND OF THE STUDY

Introduction

Natural fibers are replacing synthetic fibers in the various parts of automobiles due to their lightweight, low-cost, and environmental aspects. For centuries, natural fibers have been used for making baskets, clothing, and ropes. Now the trend is changing and natural fibers such as jute, hemp, flax, and sisal fibers are making their way, especially into the components of automobiles. Comparisons of material indices for beam and panel structures were made to investigate the possibility of using natural fiber composites instead of conventional and non-conventional. Natural fiber composites recently had a greatly renewed interest for a variety of reasons in the automobile industry for increased fuel efficiency, reduced cost, ease of production, lower density and weight, and increased awareness on the subject of recycling and the impact of materials on the environment have also played a major role in the adoption of natural fiber composites (Ahmad et al., 2015).

Bamboo fibres are very promising reinforcements for polymer composites production due to their high aspect ratio, renewability, eco-friendly, non-toxicity, cheap cost, non-abrasives, full biodegradability, CO_2 neutral, low density, and strong mechanical performances. Besides, bamboo has prospects and good potential to be used in biopolymer composites as an alternative to petroleum-based materials to be used in several advanced applications in the building and construction industry. The mechanical properties of BFRP are greatly influenced by many factors, such as the type of fibre and matrix used, fiber-matrix adhesion, fibre dispersion, fibre orientation, fibre extraction methods, fibre length, fibre size, resin application, temperature, composite preparation techniques, bamboo species, and bamboo age. The development of bamboo fiber-reinforced composites and interfacial adhesion fabrication techniques must consider the type of matrix, the microstructure of bamboo, and fibre extraction methods (Nurazzi et al., 2022).

The mechanical properties such as tensile strength, flexural strength, impact strength, and hardness of bamboo-epoxy composites are found to be superior as compared to neat epoxy composites. The bamboo fibres composites have also shown good water resistance making them suitable for outdoor applications. Bamboo epoxy composites form a new class of bio-fiber reinforced composites, which may find potential applications such as conveyor belt rollers, passenger seat frames (replacing wood/steel) in railway coaches/automobiles, pipes carrying pulverized coal in power plants, pump and impeller blades, household furniture and also as low-cost housing materials, helicopter fan blades, trim parts in dashboards, door panels and seat Cushions, parcel shelves, seat cushions, backrests and Cabin linings (Pramudi et al., 2021).

The tensile and flexural properties of all the BFRCs were found to be directly proportional to the fiber volume fractions. The BFREC plates with a 40 % fiber volume fraction exhibited the highest tensile strength (119.39 MPa) and flexural strength (161.58 MPa) compared to bamboo fiber reinforced by either polyester (BFRPC) or vinylester (BFRVC). The differences in tensile and flexural modulus between BFREC, BFRPC, and BFRVC were found to be insignificant at higher fiber loading (40 %) (Chin et al., 2020).

Many automotive components (interior and exterior) are now made from bio-fiber reinforced composite materials which are mainly based on polypropylene with reinforcing bio fibers jute, flax, hemp, kenaf, and wood. The primary importance to the automotive is possible up to 30 % with the using of bio-fiber. The opportunities for using bio-fibers as replacements for glass fibers in automotive applications are enormous. Headliners are based on three substrate types glass, foam, or cellulose (paper or cotton). The headliner's requirement of properties are stiffness for modular and structural configurations, structural rigidity and ductility over a wide range of temperatures, good dimensional tolerance, good chemical resistance, recyclability, easy molding of simple and complex shapes and contours, ability to incorporate fabric and other automotive coverings in a single step, good acoustical properties and light weight, good aesthetics and increased interior headroom (thin material), design flexibility and process reliability, reduced environmental, health, and safety (EHS) issues, and low cost (Haque et al., 2000)

There are 70 genera. and 1200 species of bamboo in the world which are widely distributed between 46^o N and 47^o S in the tropical, subtropical, and temperate regions of all continents except Europe (Yulin Wang et al., 2020). Africa possesses about 40 species and covered over 1.5 million hectares of land and two of the species are found in Ethiopia (Bahru et al., 2021). Though, there are different estimates of natural bamboo coverage in Ethiopia, (Kassahun Embaye, 2003) reported that it is over 1 million hectares, which is about 67% of the African bamboo and 7% of the world’s total covered.

The global temperature has raised by 0.85 ºC in the last 19 century. Global warming is increasing from year to year due to the emission of co_2 into the atmosphere. The greenhouse emission would be stopped by the year 2050 (Bush, E., and Lemmen, D.S., 2019).

Ethiopia's GHG (Greenhouse gas) emissions from the transport sector will increase from 4.9 Mt CO_2e (2010) to 40.7 Mt CO_2e (2030) which was an increase of more than 150%. In relative terms, the transport sector will increase its annual emissions by around 11% (Ethiopian Panel on Climate Change, 2015). According to the International Energy Agency (IEA), transport accounted for approximately 8 Gt CO_2 in 2016 (the equivalent of one-quarter of the total global GHG emissions), which marks a 71% increase from 1990 (Alzard et al., 2019). However, without aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from the other energy end-use sectors and reach around 12 Gt CO_2eq/yr by 2050 (Sims R., et al 2014).

The most common and acceptable synthetic fibres are glass and carbon fibres which have good mechanical properties. They are used as reinforcement of polymers in various fields, such as aerospace, automobiles, marine, sporting and leisure goods, and construction and civil engineering. However, they are non-renewable, environmentally unfriendly during fabrication, require high energy during processing, are non-biodegradable, and have a high production cost and higher weight. Several studies show that natural fibres are likely to be environmentally superior to synthetic fibres (Dinesh Bhonde et al., 2014).

The two native Ethiopian bamboo species were shown in Figures 1.1 and 1.2. Lowland bamboo has a completely solid culm as shown in Figures 1.1(b) and 1.2(b), with high bulk density and greater stability, while highland bamboo has a hollow culm that is easier to process as shown in Figures 1.1(a) and 1.2 (a).(Fayera et al., 2017).

FIGURE 1.1: (a) High-land bamboo (b) Low-land bamboo

FIGURE 1.2: Transversal section of bamboo (a) highland, (b) lowland (Fayera et al., 2017)

As shown in Figure 1.3, Ethiopian highland bamboo-based traditional handicraft outputs were produced in different sizes and shapes. The major ones include chairs, tables, benches, shelves, grain granaries, baskets, food utensils, mats, beehives, and umbrellas (Kebede, 2018).

FIGURE 1.3: Product of Ethiopian high land bamboo (Kebede, 2018)

The present research "Ethiopian bamboo fibres reinforced polymer composite for Automobile industry" development and characterization an environmentally friendly material as an alternative among synthetic fiber-reinforced composites. The products of headliners materials are made up of glass fibres and thermoplastics which are a higher weight of density, expensive in cost, higher energy required to process, environmentally unfriendly, nonbiodegradable, and nonrenewable. The current research study characterizes and measures the properties of Ethiopian bamboo fibres and their polymer composites. Research has not been done on the properties of bamboo fibres and their polymer composites in Ethiopia so far. Natural fibres have not been manufacturing standards for the fabrication of a product due to inconsistency variability of the properties. The current research results are compared with those across different regions of Ethiopian bamboo species and with other studies of bamboo fibres and their polymer composites. In the current research study, particular challenges must be overcome to extract the bamboo fibre and fabricate the composites.

1.1 Statement of the problem.

67% of Africa's bamboo and 7% of the world's bamboo has been covered in Ethiopia. Over 30%-40% of mature bamboo has been collected continuously every two years in Ethiopia. Bamboo species in Ethiopia are *Oxytenanthera abyssinica* and *Yushania alpina* which have been found in lowland and highland regions, respectively. The parts of *Y. alpina* bamboo have hollow culm, wall thickness, and culm Internodal length, but *O. abyssinica* bamboo does not have these parts. *Y. alpina* bamboo is soft and easy extraction of fibre from its culm which is used for fibres composite industry, but *O. abyssinica* bamboo is difficult to extract fibres from its culm. Nowadays, *Y. alpina* bamboo in Ethiopia is used for making furniture like chairs, beds, tables, shelves, lampshades, and fruit trays which is used for low-level technology.

Headliners have evolved as the most dynamic, multifunctional interior component in a car. Several design factors have evolved for the headliner material to meet the appearance, performance, and cost requirements in today's competitive market. The materials of headliners are stampable sheet made of GF and PP, GF laminated polyurethane foam, and thermoplastic foam. The features required for headliner materials include low release of harmful chemicals and foul odors in the process of molding headliner parts from material to improve the workplace environment, high handling stiffness during installation in the auto assembly process, light weight, and good recyclability when the automobile is scrapped.

Research and development into lightweight materials are essential for lowering their cost and maximizing their fuel economy benefits. Light weighting without loss of strength and speed properties is the present, and the future, of the automotive manufacturing industry. Nowadays, parts of the automobile industry are fabricated from natural fibres rather than glass fibres which have high density in weight, high energy utilization during production, are expensive in cost, ecologically unfriendly, and non-biodegradable. The weight of cars and their fuel efficiency has a strong negative correlation. The more fuel it will consume when the weight of the car increases. CO_2 emissions and fuel consumption are directly related to each other. The current research studies develop and characterize Ethiopian bamboo fibres polymer composites for headliners in the automobile industry. Therefore, significant efforts have been made to develop new alternative bamboo fibres for the performance of long-term growth in fibres composite production industry.

1.2 Objectives

1.2.1 General objective

The main goal of this research is to develop and characterize Ethiopian bamboo fibres and their reinforced polymer composite in the Automobile industry

1.2.2 Specific objectives

- To compare and discuss the structural, physical, chemical, and anatomical properties of bamboo species in Ethiopia across each other and other bamboo species
- To evaluate the suitability of bamboo fibres in Ethiopia for composite application based on fibres density, thermal properties, and degree of crystallinity
- To examine the effectiveness and quality of the developed extraction machines using single fibre tensile testing according to modified Weibull strength distributions.
- To investigate experimentally the tensile, flexural, and impact strengths of Ethiopian bamboo fibres reinforced epoxy, and polypropylene composites across each other and other bamboo species based on age and harvesting seasons.
- To assess and characterize the feasibility of Ethiopian bamboo fibres reinforced polymer composites for in the automobile industry.

1.3 Hypotheses, research questions

- Are Ethiopian bamboo species in different structural, chemical, physical, and anatomical properties?
- Do Ethiopian bamboo species measure the optimum fibres density, thermal, and degree of crystallinity?
- Are Ethiopian bamboo fibres and their polymer composites measured the highest mechanical properties?
- Which ages and harvesting seasons of the bamboo plants have reached their highest properties and are suitable for utilization in composite applications?
- Do Ethiopian bamboo species have the best properties compared with other bamboo species for fibres composite application?
- Are Ethiopian bamboo fibres and their polymer composites suitable for the application of headliners in the automobile industry?

1.4 Significance of the study

Bamboo culms in Ethiopia are used for home furniture and built the house in structural purposes which used for low-level technology applications. Nowadays, most bamboo fibres and their polymer composites in the world characterized their properties for different applications such as aerospace, automobile, construction, sports, and medical equipment. However, research has not been done on the properties of Ethiopian bamboo fibres and their polymer composites so far. The current research study aims to characterize and develop Ethiopian bamboo fibres polymer composites in the automobile industry for headliners. The traditional materials of headliners are produced from glass fibres and their expensive polymer composites, which have a higher weight in density, are uneco-friendly, have higher energy processing, and nonbiodegradable. The current research of bamboo fibres and their polymer composites in Ethiopia substituted the traditional materials for the headliners in the automobile industry.

The unemployment rate in Ethiopia is increasing year to year due to the limited number of vacant spaces in governmental offices for educated people. Bamboo fibres and their polymer composites provide livelihood services and bring new job opportunities and income through micro-enterprises run by rural communities and civil cooperatives, and small and medium-sized businesses. These are created by local entrepreneurs and larger companies producing high-value-added products of bamboo fibres polymer composites for export. Bamboo fibres have many attractive features, including high specific (weight-based) properties, attractive price-point, high acoustic damping properties, and minimum health risk during the processing and usage phase. The fuel consumptions and CO_2 emissions of the vehicles are important for the automotive industry to adopt bamboo fibre composites. Bamboo fibres have a strong green image due to their recyclability, light weight, and biodegradability. The automotive industry can use as a marketing tool in the current situation of environmental concerns which applied natural fibres and their polymer composites for the application of the automobile industry.

Therefore, the researcher investigated and characterized the structural, anatomy, physical and chemical properties of bamboo culm, degree of crystallinity, thermal, and density of fibres, and measured the mechanical properties of bamboo fibres and their polymer composites for the headliner in the Automobile industry. The measured properties of bamboo fibres and their polymer composites are compared across each other and other bamboo species.

1.5 Delimitations and limitations of the study

This Ph.D. program was carried out at Adama Science Technology University that has started the first time for us. This Ph.D. research work was delimitated into three regions, three groups of ages, and two harvesting seasons. The criteria for the selection of the region is the type of bamboo species that satisfied the research work. The selection of ages and harvesting months is based on the inherent properties of bamboo as described in the literature review. Two types of species of bamboo in Ethiopia are low-land bamboo (*O. abyssinica*) and highland bamboo (*Y. alpine*) species. The current research study selected *Y. alpine* which is easily fibres extraction from their culm for extraction of fibre from the culm. The region of the research work is found in the Amhara region at the West Gojam zone in Injibara town, the South Wollo zone in Kombolcha, and Mekanselam town.

Polypropylene (PP) film with a density of 900 kg/m^3 and 20 μm thickness and melting temperatures of 160.6˚C was used for composite fabrication. Epoxy resin Epikote 828 LVEL and a DYTEK® DCH-99 Amine (1,2-diaminocyclohexane) are used as matrix and hardener, respectively. The interior part of the automobile industry is the headliner which is the largest size of the automobile parts that improve durability, mechanical property, and esthetic value of the part.

The limitation of the current research studies are:

- Lack of associate professors and professors who graduate in the area of composite materials to advise and guide the research work of the dissertation.
- Limited access to the testing machines, tools, and types of equipment for proceeding experimental work which fulfilled the requirement of ASTM standards.
- Lack of clear way of the institutional guidance that leads the program in the right way since the institution has been a beginner to start the Ph.D. program.
- Constraints of time due to lack of free movement from place to place because of the spread of COVID-19 in the world and the security problem in the country.
- Constraints of research budget which allow for data collection and experimental work.

CHAPTER - 2

LITERATURE REVIEW

Introduction

The purpose of this chapter is to provide a broad understanding of the properties of bamboo fibers and their polymer composites, with a focus on critical factors influencing the mechanical properties of bamboo fiber and their polymer composites, as a result, their applicability in structural components is determined. This chapter essentially serves as a background and literature review for the work described in this thesis.

2.1 Bamboo species in Ethiopia

Ethiopia has a total coverage area of 1 million hectares of *Y. alpina* and *O. abyssinica* bamboo. When compared to many softwoods, bamboo plants have the shortest growth cycle, the fastest growth, and mature in 3-5 years (Mulatu et al., 2010).

As presented in Table 2.1, *Y. alpina* and *O.abyssinica* bamboo are found in the low and highland regions in Ethiopia. *O.abyssinica* are higher coverage of bamboo plant compared to *Y. alpina*.

Table 2.1: Characteristics of Ethiopian bamboo forests (Zhaohua, 2015).

	Natural bamboo forests	
	O. abyssinica	*Y. alpina*
Mean altitude	1000-1800 m	2200-3200 m
mean annual rainfall	1150 mm	1950 mm
Total area	850,000 ha	130,000 ha
Stand density(tree ha -1)	8,000	6,000
Percentage of dead trees	34	27
Above-ground biomass tonne ha-1	20	51
Culm	Semi-solid to solid	Hollow
The ratio of old to new shoots	-	5:01
seeds	Viable	Most empty, not viable

2.1.1 Highland bamboo (*Y. alpina*)

Y. alpina natural forests in Ethiopia are found in the central-southern, south-western, and north-western areas of the country like Hagere-Selam, Injibara, Gojjam, Shewa, Kefa, Gamo-Gofa, Sidamo, Bale, Jima (Agaro, Gera), Denkoro jungle (South Wollo), Debre Tabor (South Gonder), Qendach (East Gojjam), Wofwasha (North Shoa) and Bore/Gujji. *Y. alpina* is found in the states of southern Sudan, Ethiopia, Malawi, Kenya, Congo, Zaire, Rwanda, Uganda, Burundi, Tanzania, Cameroon, Malawi, and Zimbabwe (H. Wang et al., 2014).

Major areas of Ethiopian highland bamboo are presented in Table 2.2. The natural existence of Ethiopian high land bamboo is high coverage of bamboo in hectares compared to the plantation of the bamboo plant. The Oromiya region has high coverage of highland bamboo compared to Amhara and South. Bale mountain is the largest coverage of highland bamboo in the Oromiya region.

Table: 2.2 Major Highland Bamboo Areas in Ethiopia(Kelbessa et al., 2000).

No	Bamboo Area	Region	Natural stand(Ha)	Plantation (Ha)	Total area (Ha)
1	Injibara	Amhara	30	2350	2380
2	Agaro	Oromiya		1500	1500
3	Bale Mountains	Oromiya	56851	-	56851
4	Mekaneselam	Amhara	35	-	35
5	Kombolcha	Amhara	-	42	42
6	Shenen/jibat	Oromiya	1774	2561	4335
7	Gera	Oromiya	36000	1250	37250
8	Bore/Hagereselam	Oromiya		2460	2460
9	Chencha/Arbaminch	South	2460	3250	5710
10	Indibir/Jembero	South		1850	1850
11	Jima/Ameya	Oromiya/South		900	900
12	Mizan/Teferi/ Kulish	South		1850	1850
13	Debresina/Wofwasha	Amhara	35		35
14	Wushwush/Bonga	South		1120	1120
15	Bonga/Ameya	South	7997		7997
16	Masha	South	18652		18652
17	Munesa shashmene	Oromiya/South	4183		4183
18	Total		128,017	19133	143,150

2.1.2 Lowland bamboo (*Oxytenanthera abyssinica*)

As presented in Table 2.3, *O. abyssinica* forests are found in Gambella, Asossa, Dedessa, Pawe, West Wollega, north of Nekempte/Hinde, and the western part of the country along major river valleys. *O. abyssinica* has spread throughout tropical Africa outside the humid forest zone. Out of Ethiopia, it has been available in Senegal, Eritrea, Malawi, Angola, Mozambique, South Africa, Zimbabwe, and Zambia (Oumer et al., 2020). Previously and currently, the financial capacity of Ethiopian bamboo has not been explored, and the benefits of bamboo resources in national growth are insignificant. However, now a day, bamboo has been used in traditional ways in the countryside (H. Wang et al., 2014).

O. abyssinica grows in six regions in Ethiopia namely the Southern Nations, Nationalities, and Peoples Region in Gamo, Gaelebena, Hamer Baco, Bench-Maji, Majinal Goldiya; Gambela National Regional State; Amhara National Regional State in Chilga, Hinde, Wegera; Oromia National Regional State in Gimbi, Guten, Kelkon, Leka; Tigray National Regional State in the Shire; and Benishangul Gumuz National Regional State in Asosa, Bambesi, Begi, Demi, Guba, Dibate, Kamashi, Pawe. (Desalegn et al., 2014).

Table 2.3: Major Lowland Bamboo Areas in Ethiopia (Oumer et al., 2020).

Bamboo Area	Region	Natural stand(Ha)	Total area (Ha)
Hinde/North of Nekemte	Amhara	8,670	8,670
Asossa	Benshangul Gumuz	77,947	77,947
Bambasi	–	64,245	64,245
Begi	–	21,509	21,509
Nejo	Oromiya	27,612	27,612
Dibate	Benshangul Gumuz	14,200	14,200
Guba	–	7,757	7,757
Kemashi	–	33,723	33,723
Pawe	–	53,830	53,830
Gimbl	Oromiya	29,125	29,125
Guten	Oromiya	6,044	6,044
Metema/Dansha/Humera	Tigray/Amhara	425,000	425,000
Didessa Valley	Oromiya	135,000	135,000
Dangur	Benshangul Gumuz	27,350	27,350
Bulen	–	16,780	16,780
Galesa	–	10,870	10,870
Total	–	959,662	959,662

2.2 Bamboo plant

Bamboo culms are hollow cylinders with several diaphragms that appear to be ringing from the outside. The space between two rings is known as the Internode, and branches grow from it. The distance between each node varies depending on the species (Darwis et al., 2018). Bamboo's culm wall is made up of many vascular bundles that provide strength to the culm. The number of internodes can be defined by the height of the culm. As a result, the average size, density, and number of vascular bundles are important parameters for characterizing bamboo species. Bamboo culm anatomy determines physical properties, which reflect usability. The density of bamboo fibers increases as the upper diameter of the bamboo culm decreases. Therefore, the base section is weaker but more capable of withstanding force than the top section (Yap Thai Ming et al., 2017).

As shown in Figure 2.1, the commercial height of the bamboo culm is divided into 3 sections which are the bottom, middle and top segments. The highest and the lowest segment of culm diameter and wall thickness are found at the bottom and top segments, respectively. The bamboo culms consisted of the wall, diaphragm, Node, and Internode in one full length of the bamboo plant so that the internodes and the wall thickness depended on the age and the species of the bamboo which effected the properties of the bamboo fibres. At the node parts of the bamboo, discontinuous the fibres have formed so that they could not be used for fiber-reinforced composites due to poor mechanical properties where as the parts of internodes of the bamboo continuous fibres have formed so that it could be used for fibre reinforced composites moreover it has good mechanical properties (E. Trujillo, 2014)**.**

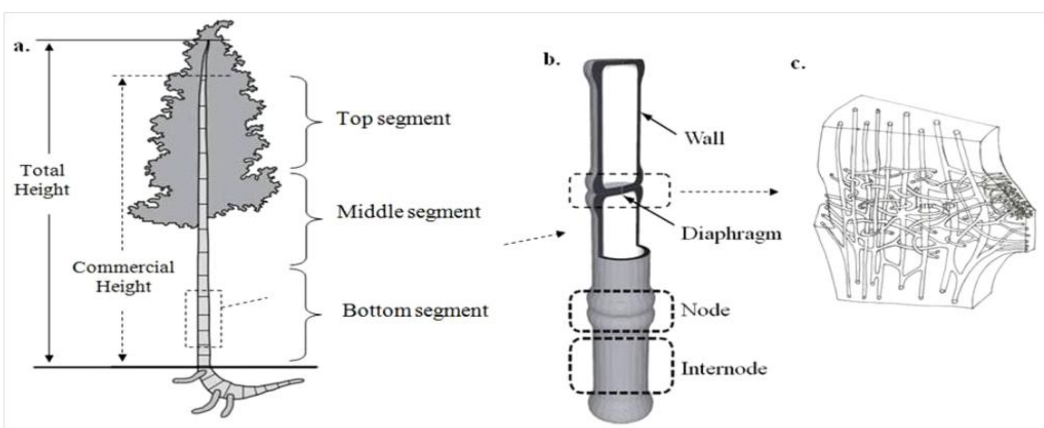


FIGURE 2.1: a) Different segments of the bamboo plant, b) parts in which are divided the bamboo culm and c) discontinuity of the bamboo fibre within the node (E. Trujillo, 2014)

2.3 Bamboo culm age

The aging of the bamboo culm is a phenomenon of considerable interest. Since aging influences certain properties and consequently the processing and utilization, numerous investigations have dealt with possible structural, chemical, and physical-mechanical modifications. Age-related changes have to be considered under different aspects, first during the differentiation and growth of an individual culm, second along the age of consecutive culms originating from a seedling, and third, and most importantly, during the life cycle of an individual culm from its immature stage towards maturation and death (Zhao X, 2017).

The different ages of bamboo are shown in Figure 2.2, bamboo harvesting takes place at different ages of the plants' growth according to the product requirements. Age of culm is an important consideration in fixing the felling cycle. Some structural characteristics such as the presence or absence of culm sheath, culm color and texture, bud break, and branching nature on the culm, and presence and absence of root ring on culm nodes are found useful in determining the culm age in a bamboo clump (Banik, 2015). The harvested bamboos are useful for making different products at different ages. For example, the recommended age to harvest for products to use in the construction industry is 3–5 years, yet for some craft uses, they may be harvested at a younger age depending on the species.

FIGURE 2.2: External characteristics of *Guadua angustifolia* based on age (Banik, 2015)

2.4 Structure of bamboo culm

Figure 2.3(a–d) shows a group of bamboo structures from the macroscopic to the microscopic level. The often-called technical fibers are extracted from the bamboo culms using an extraction process (A. U. M. Shah et al., 2016). The basic tissues comprising all herbaceous plants are epidermal, vascular, and hypodermis. Vascular bundles are commonly known as bamboo fibers (Li et al., 2011). As can be seen in Figure 2.3 (b), the content of vascular bundles tends to have a gradient variation from the outer to the inner layer of a piece of bamboo. At the outer periphery, vascular bundles are compacted and are more numerous than the bundles in the inner zone. On the other hand, the occupied volume of the sparsely distributed vascular bundles is larger in the inner layer. Such a gradient structure is commonly observed in biological plants. Recent research indicates that the graded surface can provide an appealing prospect for controlling surface damage and failure during repeated contact, leading to material performance improvement.

Figure 2.3 (d) shows SEM micrograph of the microstructure of a vascular bundle, indicating that a bamboo fiber consists of considerable elementary fibers (F. Wang et al., 2015).

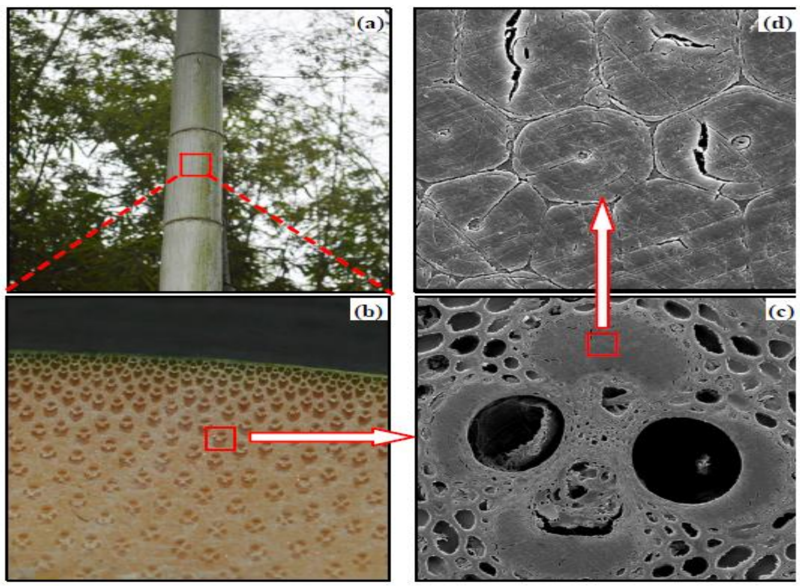


FIGURE 2.3: Structure of bamboo fiber across different length scales. (a) Bamboo culm;(b) Cross-section of the culm; (c) Vascular bundle; (d) Elementary fibers (Zhang et al., 2015)

As shown in Figure 2.4, the largest to the smallest size of the morphology hierarchy in bamboo fibres are bamboo culm, technical fibre (Bundle fibre), and elementary fibres respectively. The diameter and the length of bamboo culms are 6-11 cm and 23 cm respectively. The application area of bamboo culms is for structures such as household furniture, the construction of the house, and decoration application. The mechanical properties of tensile strength and young`s modulus of the bamboo culms are 237 MPa and 16 GPa respectively. The scan electron microscope of technical fibres (Bundle fibres) is the vascular bundle of elementary fibre. The size of the technical fibres is a diameter of 200-400 μm and a length of 20-34 cm and the tensile strength and young`s modulus of the technical fibres are 800MPa and 43GPa respectively. The smallest and the shortest size of the bamboo fibres are the elementary fibres. The diameter and the length of elementary fibres are 12-20 µm and 1.3 mm respectively and the tensile strength and young`s modulus of the elementary fibres are 1150 MPa and 50 GPa, respectively. The mechanical properties of the elementary fibres are comparable with glass fibres. Regarding the better mechanical properties of elementary fibres are used for the construction of airplanes and automobile parts.

The length and diameter of the technical fibres guarantee a suitable aspect ratio which is an important factor for reinforcing material. Also, the high elementary fibre content within the technical fibre bundle assures that more than 80% of the modulus of the elementary fibres is transferred to the technical fibre after the extraction process (Osorio et al., 2018).

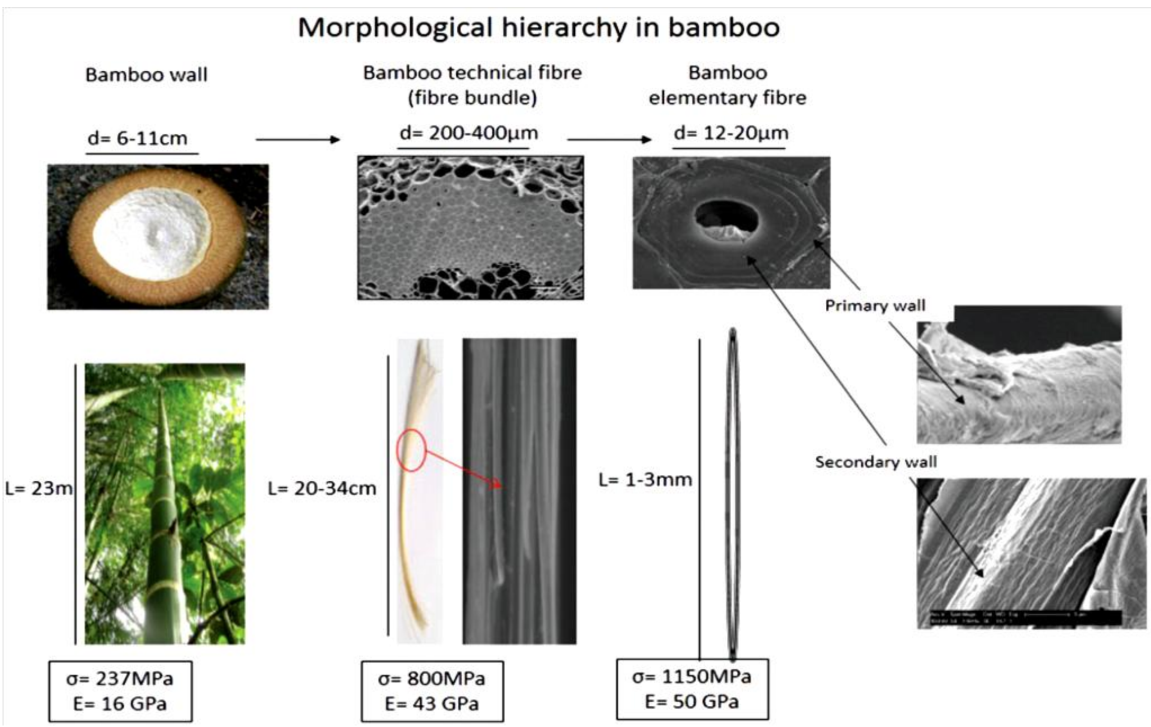


FIGURE 2.4: Morphological hierarchy in bamboo(Osorio et al., 2018)

2.4.1 Characteristics of structural properties of the bamboo

As shown in Figure 2.5 (a), the Internodal length along the culm is a function of the serial number of the Internode for each species. Species *Dendrocalamus asper* is the highest Internodal length, and *Gigantochlos bambos*, *Phyllostachys edulis,* and *Gigantochloa hasskarliana* are similar internodal length each other. The outer diameters along the culm length shown in Fig. 2.5 (b), *Dendrocalamus asper*, and *Phyllostachys edulis* have similar and the highest outer diameter, but *Gigantochlos bambosand,* and *Gigantochloa hasskarliana* have a similar and the lowest outer diameter of bamboo species. As shown in figure 2.5 (c), the culm wall thickness significantly decreases with height. From the highest to the lowest wall thickness of the bamboos are *Dendrocalamus asper*, *Gigantochlos bambos*, *Phyllostachys edulis*, and *Gigantochloa hasskarliana*, respectively (Chaowana, 2013).

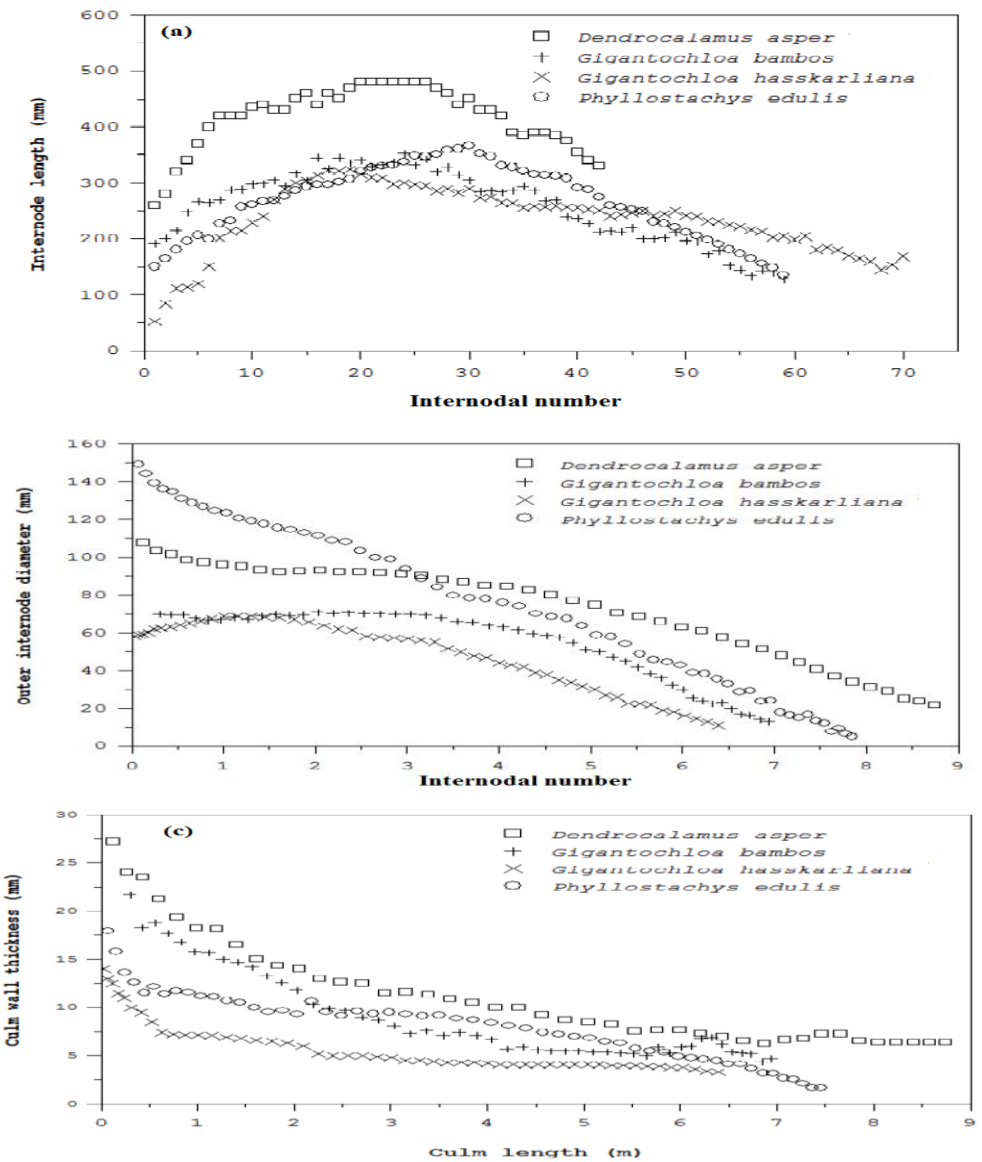


FIGURE 2.5: a) intermodal number & intermodal length, (b) Internodal number & Culm outer diameter (c) internode number & wall thickness (Chaowana, 2013)

2.4.2 Characteristics of anatomical structure

Figure 2.6 gives an overview of the four most common types of vascular bundles of bamboo. The presence of extra isolated fiber strands causes differences. Once extracted from the plant, both the fibre sheaths and the strands are referred to as technical fibers. Because the longitudinal orientation of the fibres is lost in the node as they become entangled, their length equals the internodal length. Technical fibers typically have lengths of 20–35 cm and diameters of 90–280 mm (Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

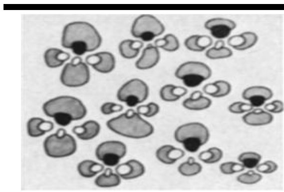
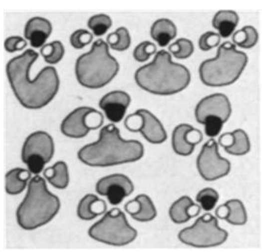
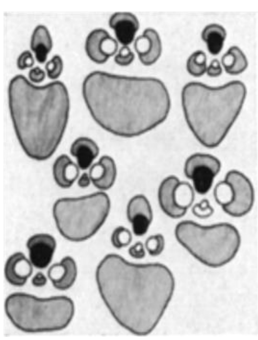
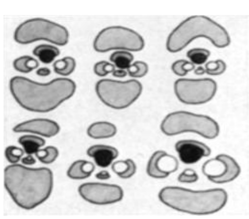
Vascular bundles types	Characteristics	Occurrence
 I	Consists of one part (the central vascular strand); supporting tissue only in the form of a sclerenchyma sheath, and an intercellular space with tyloses.	In all species, leptomorphrhizomes are the only type found throughout the culm (Arundinaria, Phyllostachys)
 II	Consists of one part (central vascular strand); supporting tissue only in the form of a sclerenchyma sheath; and a sheath at the intercellular space (protoxlem) that is noticeably larger than the others. tylose-free intercellular space	In species with pachymorphrhizomes that grow as single culms (Melocanna) or in clumps (Cephalostachyum, Schizostachyum, Teinostchyum). Cephalostachyum is the only type found throughout the culm; in Melocanna, Schizostachyum and Teinostachyum are found in the base internodes, frequently together with type III.
 III	Consisting of two parts (a central vascular strand and a fiber strand); a fiber strand inside the central strand; and a sheath at the intercellular space (Protoxylem) that is generally smaller than the others.	In clump-forming species with pachymorph rhizomes (Gigantochla, Thyrsostachys); the base, internodes are mostly combined with type IV, in the middle and upper parts as the only type. Schizostachyum and Teinostchyum combined with type II at the base internodes in Melocanna. Some Oxytenanthera spp. are the only type found throughout the culm.
 IV	Composed of two parts (a central vascular strand and two fiber strands); the fibers strands are located outside and inside the central strand.	In clump-forming species with pachymorph rhizomes (Bambusa Dendrocalamus, Gigantochloa, Thyrsotsachys); mostly at the base internodes, rarely in the middle; always in combination with type III.

FIGURE 2.6: Overview of the basic vascular bundle of bamboo (Siam et al., 2019)

2.4.3 Characteristics of vascular bundle bamboo fibres

The primary structural component of the bamboo culm is the elementary fibers, which have a hexagonal or pentagonal shape. The lumen is the small hole in the center of each elementary fibre (Figure 2.7(d)).

Each elementary bamboo fibre wall has a distinct multilayer configuration known as the polylamellate structure, which contributes to the strength and modulus of the bamboo culm. As shown in Figures 2.7(b) and (d), the proportion of lumen tends to be higher near the periphery of the fibre bundle, close to the parenchyma tissue, implying that during the extraction process and subsequent refining of the fibre. It is preferable to remove some of these peripheral elementary fibres to reduce both the technical fibre diameter and the presence of large lumens, which may result in high void content in the final composite. The wall accounts for 96 % of the total area in elementary fibers on average. The thickness of the middle lamella is roughly 0.5 mm (Zhang et al., 2017).

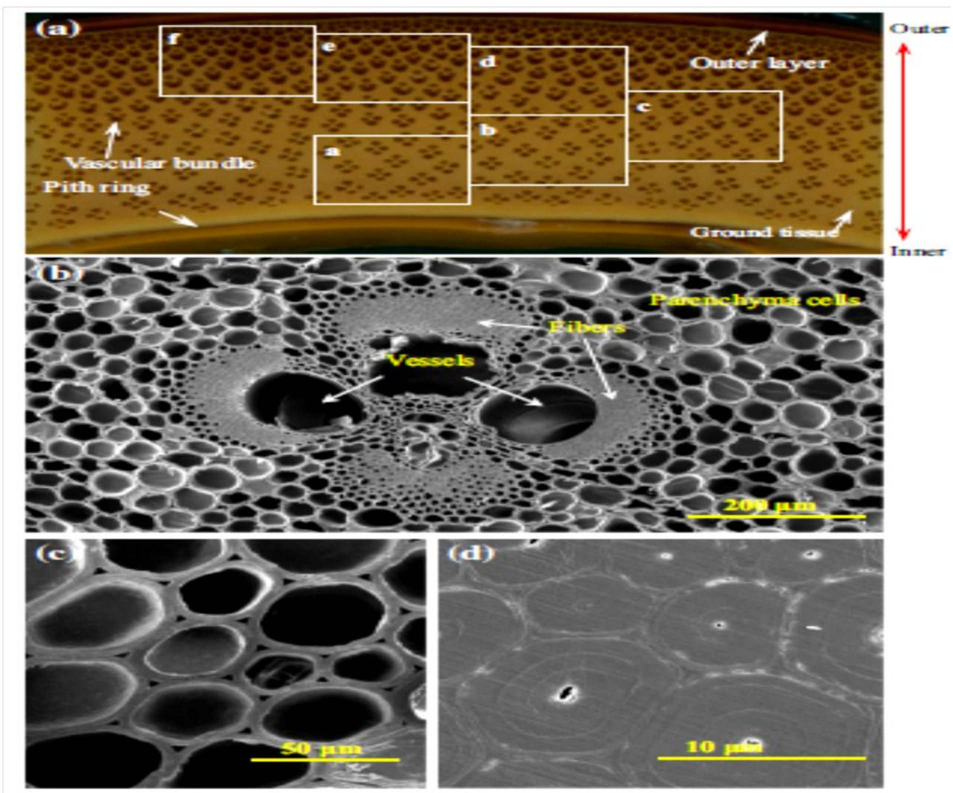


FIGURE 2.7: (a) Optical micrographs of bamboo, (b) SEM images of bamboo, (c) parenchyma cells and (d) fiber within Vascular bundles (Zhang et al., 2017)

2.4.4 Effect of age on the vascular bundles of bamboo

Mature bamboo fibers have more cell wall layers than younger bamboo fibers (Wang et al., 2012), and this is presented also by the micrographs in Figure 2.8. When compared to younger bamboo fibers, matured bamboo fibers have larger diameters and lumen bundles.

In general, elementary fibers in the outer zone have 2–4 layers, and in some cases, five layers were visible under LM in Figure 2.8 (c), and (d). Figures 2.8(a), and (b) depict an elementary fibre with no obvious layering of the wall, which was found in the majority of the observed elementary fibres.

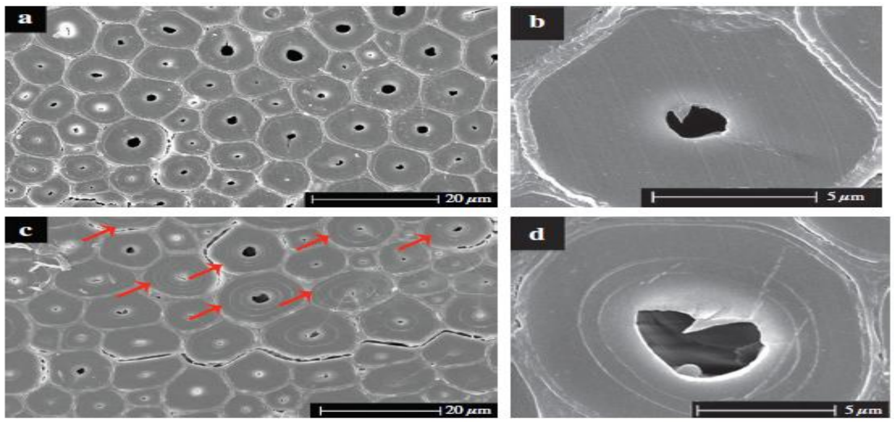


FIGURE 2.8: SEM images of Ma bamboo fibers for 1-year-old (a and b), and 4-year-old (c and d) samples (H. Wang et al., 2014)

2.5 Polymer matrix materials

Polymers are divided into three types: thermoplastics, thermosets, and elastomers. Elastomers are rubbery materials that are both viscous and elastic. Natural polyisoprene, polybutadiene, chloroprene, and other important elastomers include: Thermoset polymers are polymers with a three-dimensional network structure that are interconnected by covalent bonds. Thermoset polymer composites are not remolded or recyclable. Thermoplastic polymers, on the other hand, have linear and branched molecular chains with weak intermolecular bonding such as van der Waals force or hydrogen bonding. It is possible to recycle thermoplastic polymer composites. In this study, a thermoset (epoxy) and thermoplastic (polypropylene) matrix are used to develop bamboo fiber-reinforced polymer composites (Madalina Elena Grigore, 2017). Polymer composite materials have been widely used in a variety of industries, including aircraft, automobiles, and submarines, due to their superior mechanical and thermal properties. However, the end-of-life disposal of polymer and synthetic materials is unknown and non-biodegradable (Zakikhani et al., 2014).

2.5.1 Epoxy resin

Epoxy resin (EP) is a type of polymer oligomer with a high degree of cohesion and a dense molecular structure. EP's curing system contains a variety of reactive groups, including epoxy groups, hydroxyl groups, ether bonds, and amine bonds, resulting in high reactivity and superior bonding strength. Furthermore, EP is widely used as a matrix resin for a variety of high-end structural materials via a variety of fabrication techniques, including casting and injection molding (Vu et al., 2017; Zabihi et al., 2018; Zhou et al., 2019). Cure EP, on the other hand, has high internal stress, poor fatigue resistance, high brittleness, poor toughness, inferior impact resistance, and poor weather resistance. Furthermore, the high surface energy limits the use of EP in high-performance structural components (Kang et al., 2012). As a result, it is critical to carry out structural modifications to improve the toughness and reduce the brittleness of EP for a wide range of applications (Wu et al., 2021).

2.5.2 Polypropylene (PP)

PP is one of the most widely used thermoplastic polymers in the applications such as automotive, home appliances, packaging, construction, etc. owing to its ease of processing, low cost, and high recyclability (Pérez et al., 2013). However, due to the widespread use of petroleum-based synthetic polymers in recent years, plastic waste management has become a major issue (Azwa et al., 2013).

2.6 Chemical composition of bamboo species

The chemical composition of differnt bamboo species are presented in Table 4.2. The main constituents of bamboo culms are cellulose, hemicellulose, and lignin; minor constituents consist of resins, tannins, waxes, and inorganic salts. The composition varies depending on the species, the growth conditions, the age of the bamboo, and the part of the culm. The proportion of lignin and carbohydrates changes during this period because the bamboo culm tissue matures within a year when the soft and fragile sprout becomes hard and strong. However, after the culm has fully matured, the chemical composition tends to remain relatively constant. The chemical composition and structure of natural fibers are primarily determined by several factors, including the nature of the plant source, the plant's growing conditions, climate, the plant's age, and the fiber extraction process (Faruk et al., 2012).

Natural fibers made up of cellulose, hemicellulose, lignin, and pectin account for 80 to 90 % of the total. Natural fibers also contain minerals, waxes, and other water-soluble components (Majeed et al., 2013).

The secondary cell wall of the fibre materials contains a rigid cellulose component embedded in a soft lignin and hemicellulose matrix (Dittenber et al., 2012). Bamboo has a cellulose content of 40-50%, which is comparable to the cellulose contents of softwoods (40-52%) and hardwoods (38-56%) reported (Fagerstedt et al., 2015). Bamboo is a suitable raw material for the pulp and paper industry due to its cellulose content in this range.

Bamboo's lignin content (20-26%) places it at the high end of the normal range (11-27%) reported for nonwoody biomass (Bagby et al., 1971) and close to the ranges reported for North American softwoods (24-37%) and hardwoods (17-30%). Bamboo's lignin content contributes to its high heating value and structural rigidity, the latter of which makes it a valuable building material (Scurlock et al., 2000).

(Kalidhar et al., 2013) reported that the Holocellulose content in bamboo normally consists of about 50-70%. The chemical composition of different bamboo species is indicated in Table 2.4. Holocellulose exists significant differences between species. *G.levis*, *G.scortechin*, *G.wrayi*, and *Y. alpina* have the lowest cellulose content compared to other bamboo species. PV, PVMJ, and GAK are the highest cellulose content on the list of bamboo species. The lignin content of PV, PVMJ, and GAK have a similar value recorded, as well as, *Bambosa vulgaris*, and *Y. alpina* have a similar value recorded in the list of Table 2. 4

Table 2.4: Chemical composition of different bamboo species (Kalidhar et al., 2013; Nahar et al., 2013; Cao et al., 2014; Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

Bamboo species	Holocellulose (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Ash (%)
G. brang	78.33	51.75	26.57	30.02	7.3	1.01
G. levis	85.9	31.79	54.11	29.88	9.53	1.29
G. scortechin	72.48	47.35	25.12	34.64	8.16	2.29
G.wrayi	83.54	38.97	44.57	33.56	8.8	1.12
PNB	–	51.3±0.3	16.2±0.2	32.6±0.8	5.4±0.4	1±1.1
PAS	–	52.3±0.5	12±0.8	35.7±1.2	14.7±0.4	1.2±0
PV	–	56.8±0.5	12.1±1	31.1±0.7	9.6±0.8	1.8±0
PVMJ	–	54.7±0.3	14.4±0.7	31±0.7	8.3±0.3	0.3±0.1
GAK	–	54.6±1.2	14±0.3	31.4±1	0.7±0.5	0.6±0.1
Bambosa vulgaris	67.08	50.23±0.18	16.85±0.09	23.9±0.58	5.07±0.06	1.38±0.05
G. aspera	61.3	–	–	25.5	3.8	4.1
Bambosa vulgaris	66.5	–	–	26.9	5.1	2.4
Y.alpina	–	46.76	12.18	25.27	12.23	3.77
O.abyssinica	–	52.06	16.9	22.47	6.8	–

2.6.1 Effect of age on the chemical composition

Chemical composition changes with age are less well understood. It was assumed that lignification was completed during the first growing season (Tsuyama et al., 2017), on the other hand, demonstrated that lignification continues after the first year of growth, particularly in the parenchyma cell walls; fibre and most parenchyma cell walls thicken during stem growth to form a polylamellate structure, and the lignifications process of these cells may last up to seven years (Marinho et al., 2013). Investigated the chemical constituents of one, two, and three-year-old *Gigantochloa scortechinii* and discovered that holocellulose, cellulose, and lignin content increased slightly from one to three years of age. As presented in Table 2.5, the chemical composition of bamboo fibres demonstrated the effect of age on different bamboo species. Lignin and Hemicelluloses of *Phyllostachks Pubescens* are increased from 1 to 3 years, but cellulose is insignificant changes after 1 year old. Extractive contents of *Phyllostachks Pubescens* increase with the age, but ash content decreased when the age matured (Guo et al., 2020). As observed in Table 2.5, the cellulose content of GAK, DMM, PNB, and *bamboos Vulgaris* decreased when the age increased, but Hemicelluloses increased when the age matured. The lignin content of GAK is insignificant change when the age matures, but DMM, PNB, and *Bambosa Vulgaris* are increased when the age matured.

Table 2.5: Chemical composition of bamboo species based on age (Technology et al., 2016; Delphine E.C. Depuydt, Sweygers, et al., 2019; Guo et al., 2020)

B. species	Age (yrs)	Holocellulose (%)	Cellulose (%)	H.cellulose (%)	Lignin (%)	Extractives (%)	Ash (%)
Phyllostachks Pubescens	1	68.92–71.95	46.52–47.51	22.4–24.44	21.26–22.11	2.86–3.48	1.82–1.95
	3	68.58–73.82	46.21–46.99	22.37–26.83	23.21–23.91	4.17–5.21	1.30–1.41
	5	69.94–73.65	46.68–47.91	23.26–25.74	22.93–23.02	6.61–7.34	1.26–1.35
GAK	1–3	–	54.6±1.2	14±0.3	31.4±1	0.7±0.5	0.6±0.1
GAK	3–5	–	53.7±0.2	15.2±0.5	31±0.1	0.5±0.4	5.0±0.4
DMM	1	–	58.5±0.4	15.3±0.3	26.7±0.4	0.0±0.3	0.3±0.2
DMM	3	–	50.4±0.3	16.8±0.1	32.8±0.7	9.7±0.6	0.1±0
PNB	0.75	–	52.8±1	17.9±1	29.3±0.5	7.9±0.6	0.2±0
PNB	2–4	–	49.2±0.2	16.5±0.1	34.2±0.4	4.7±0.4	0.5±0.1
Bambosa vulgaris	0.5	78.6	64.6	14	23.4	5.8	1.9
	1.5	80.1	64.1	16	26.8	3.4	2.5
	3.5	80.6	64.6	16	27.8	5.3	2.8
	5.5	81.5	63.3	18.2	28.7	3.5	3.0
	6.5	82.3	64.4	17.9	29.01	5.6	3.5

2.6.2 Cellulose contents

Cellulose is one of the most abundant polymers on the planet, and it is commercially exploited as wood. The main structural component of natural fibers is cellulose, and the mechanical properties of these fibers are primarily determined by the percentage of cellulose content. The plant stem's strength is attributed to the growth conditions of the plant such as botanical origin, soil characteristics, and weather conditions, and the variation in strength is attributed to the plant's growth conditions such as botanical origin, soil characteristics, and weather conditions (Majeed et al., 2013). Cellulose is a semi-crystalline linear polysaccharide composed of polymer chains made up of repeating units of anhydrous-glucose linked by 1,4--D-glucosidic linkages, as shown in Figure 2.9. Cellulose refers to the repeating units of these monomers (Zhu et al., 2016). The molecular weight of these 1,4--D-glucosidic linkages varies depending on the cellulose source. Polymerization (number of glucose units) in general lignocellulosic fibres can reach 10000 (Abdul Khalil et al., 2012). The cellulose chain's glucose monomers form hydrogen bonds within the chain, forming fibrils as well as neighboring chains. These intra and intermolecular hydrogen bonds result in the formation of a linear crystalline structure (Eichhorn et al., 2010).

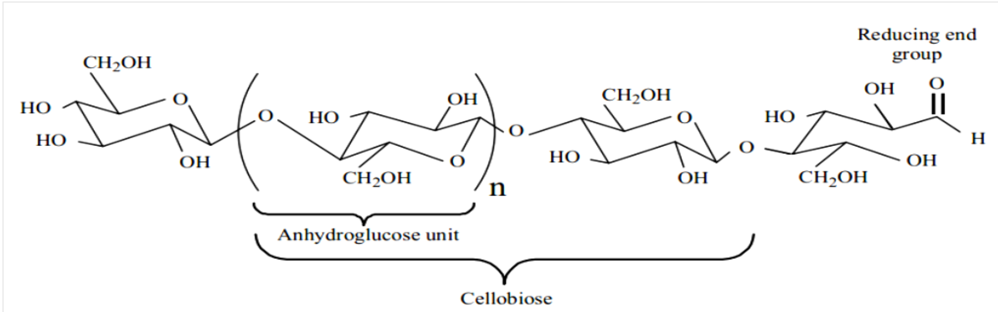


FIGURE 2.9: Haworth projection formula of cellulose (Zhu et al., 2016)

2.6.3 Hemicelluloses content

Hemicelluloses is a heterogeneously branched polysaccharide made up of many different glucose monomers, whereas cellulose only has 1,4--D-glucopyranose repeating units. The chemical structure of hemicellulose is depicted in Figure 2.10. Unlike cellulose, the constituents of hemicellulose vary from plant to plant. Hemicellulose has a high degree of chain branching, which confirms its amorphous nature. Hemicellulose has a degree of polymerization of only 200, whereas cellulose has a degree of polymerization of more than 10000 (Hu et al., 2020).

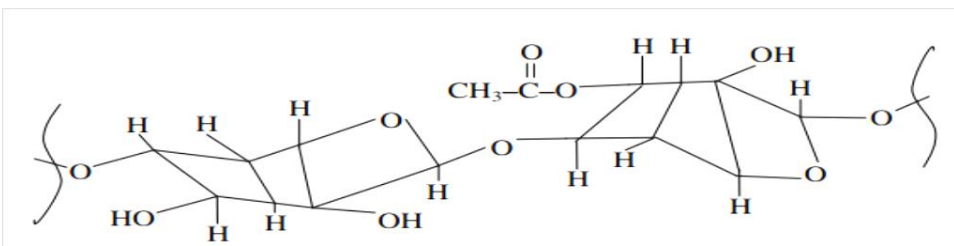


FIGURE 2.10: Chemical structure of hemicellulose (Hu et al., 2020)

2.6.4 Lignin contents

Lignin gives the plant compression strength by binding the fibers together to form a stiff structure on the fiber surface (Laurichesse & Avérous, 2014). Figure 2.11 depicts the chemical structure of lignin, which is a complex hydrocarbon polymer that contains both aliphatic and aromatic constituents. Along with cellulose, lignin is the most abundant organic polymer on the earth (Hu et al., 2020).

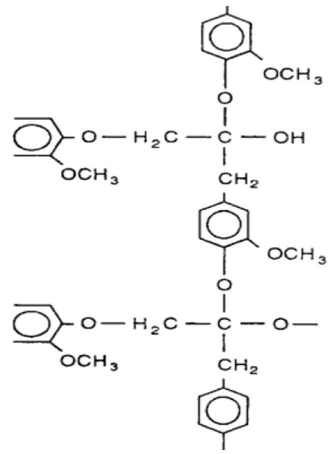


FIGURE 2.11: Chemical structure of lignin(Hu et al., 2020)

2.7 Bamboo fibres extraction methods

As shown in Table 2.6, bamboo fibres extraction methods are three groups such as mechanical, chemical, and combined chemical and mechanical extraction methods. Mechanical extraction methods contain steam explosion, crushing, grinding, roll mill, and retting. Chemical extraction methods are listed as chemical and alkaline extraction methods. Combined with chemical and mechanical extraction methods exists chemical + compression and chemical + roll mill.

2.7.1 Mechanical extraction

Mechanical extractions have impacted the properties of the bamboo fibres whether on the mechanical and physical properties or the structure of the fibres. Mechanical extraction methods are relatively low energy required, acceptable fibre properties, and no environmental impact whereas alkali-treated and steam-exploded methods have high aspect ratios and good control of fibre properties. On the other hand, they reduced the percentage of lignin and hemicelluloses in the constituent of the bamboo. Grinding in the mechanical extraction methods has the highest tensile strength and the lowest young`s modulus (Subash et al., 2017).

2.7.2 Chemical extraction

Chemical extraction methods have influenced the chemical properties of the fibres so that they affect and damage the structure of the fibres. Hence it reduced the mechanical properties of the fibres such as tensile strength and young `s modulus. Chemical extraction methods depend on the concentration of the solution, temperature, and waiting time. Chemical methods are higher tensile strength than alkali-treated methods in the chemical extraction methods. However, it has a lower young`s modulus (GPa) than alkali-treated methods (Rocky et al., 2020).

2.7.3 Combined mechanical and chemical extraction

As presented in Table 2.6, the combination use of extraction methods has good tensile properties compared to other extraction processes. Mechanical extraction methods (in some cases chemical process is required) are the highest tensile strength (MPa) of the extraction methods. However, mechanical extraction methods (roll mill machine) is the lowest tensile strength (MPa) in the extraction methods. Chemical + compression is higher tensile strength than chemical + roll mill in the combined mechanical with chemical methods. Bamboo fibres have higher specific young`s modulus (GPa) and lower fibre density than E-Glass fibre in synthetic fibres (Rocky et al., 2018).

Table 2.6 Comparison of mechanical and physical properties of bamboo fibre based on the extraction method with glass fibre (Subash et al., 2017)

Fibre	Extraction procedure	Tensile strength (MPa)	Young's modulus (GPa)	Fibre diameter (μm)	Fibre length (mm)	Density (g/cm3)
Bamboo	**Mechanical methods**					
	Steam explosion	441 ± 220	36 ± 13	15–210	–	–
	Crushing	420 ± 170	38.2 ± 16	262 ± 160	–	–
	Grinding	450–800	18–30	–	–	1.4
	Rolling mill	270	–	100–600	220–270	–
	Retting	503	35.91	–	–	0.91
	Chemical methods					
	Chemical	450	18	270	10	1.3
	Alkaline	395 ± 155	26.1 ± 14.5	230 ± 180	–	–
	Combined chemical and mechanical methods:					
	• Chemical + Compression	645 Max: 1000	–	50–400 HC:150–250	>10	0.8–0.9
	• Chemical + Roller mill	370 Max: 480	–	HC: 50–100	120–170	–
E-Glass	–	1200–1500	70	9–15	–	2.5

2.8 Composite manufacturing method

The composite manufacturing technique influences the typical achievable fibre volume fraction and porosity. High fibre volume fraction and low porosity are desired for high composite mechanical properties. With increasing consolidation pressure, the achievable and typical fibre volume fractions tend to increase. As shown in Table 2.7, consolidation pressures and thus typically achievable fibre volume fractions increase in the following order: vacuum infusion/RTM, prepreg (with autoclave consolidation), and compression molding. Natural fiber-reinforced polymer composites are typically manufactured in the automotive industry using press-molding techniques with thermoplastics (primarily polypropylene, but polylactic acid may be used), hand lay-up, and resin transfer molding techniques with thermosetting plastics (primarily unsaturated polyester) (Martin et al., 2020).

2.8.1 Compression moulding

The current research study used compression molding, also known as hot pressing, which is a commonly used method for the processing of polymer composites, as shown in Table 2.7. When compared to other processing techniques, compression-molded composite materials have relatively good mechanical properties.

Compression molding allows for the production of larger and simpler composite materials. Compression molding is used to create composite materials by sandwiching a weighed amount of mixed fiber-matrix stack between two pre-heated mold cavities. The temperature and applied pressure of the mold cavities are set based on the matrix and filler materials used, as well as the thickness of the composite samples. The top of the mold cavity moves at a constant speed and comes into contact with the bottom of the mold cavity. After reaching the predetermined compression time, the composite samples are cooled by placing them under the same pressure cooling plates, and then the composite samples are removed from the mold (Ho et al., 2012; Madiwale, 2019).

Table 2.7 Manufacturing technique is interrelated with other composite parameters (Phong et al., 2011).

Manufacturing technique	Consolidation pressure[bar]	Fibre volume fraction [%]	Porosity Volume fraction [%]	Matrix type useable
Injection moulding (IM)	>1000bar	Up to 45% (typically 15-30%)	-	Thermoplastics
Compression molding	Up to 40 bar (typically 20-30 bar)	Up to 85% (typically 25-50%)	Up to 25% (typically 2-8%)	Thermoplastics or Thermoset
Prepregging (with autoclave)	0-10 bar (typically 4-6 bar)	Up to 60% (typically 35-50%)	Up to 10% (typically 0-4%)	Thermoset
Vacuum infusion/ RTM	0-4 bar (typically 0-4 bar)	Up to 60% (typically 25-50%)	Up to 10% (typically 1-4%)	Thermoset

2.9 Bamboo fibres

Bamboo fiber has several advantages over other plant natural fibers, including high growth rate, strength, and carbon dioxide fixation. The benefits of bamboo over glass fibres are presented in Table 2.8. It is also comparable to glass fiber due to its light weight, biodegradability, and low cost. There is a lot of excitement about using bamboo fiber as a reinforced composite material in a variety of applications (Zakikhani et al., 2014). Controlling fiber properties is critical in the automotive industry, and the parameters are heavily influenced by the relationship between bamboo age and processing conditions such as alkali concentration, temperature, and immersing time (Phong et al., 2011).

Bamboo has piqued the interest of researchers all over the world as a potential reinforcement for polymer composites because it is one of the fastest-growing renewable plants, with a maturity cycle of 3–4 years (Rawi et al., 2013).

The reinforcing phase of a composite can be either fibrous or particulate, with the difference being that a particle has nearly equal dimensions in all directions, whereas a fibre has a greater length than its cross-sectional area, and both of these reinforcements have been used to produce composites. Fibre materials have received a lot of attention in recent years because of their high tensile strength and young's modulus, low density, and ability to provide better mechanical and thermal properties to end-use applications. Fibres are used to carry loads in fiber-reinforced composite materials, while matrices are used to bind the fibres together.

Many fiber-reinforced polymer matrix composites have strength and stiffness characteristics that are comparable to, if not superior to, those of traditional metallic composite materials (matrix). All of the studies mentioned above have demonstrated the potential of bamboo as reinforcement. However, when compared to other natural fibers, the use of bamboo fibers or fiber bundles in composites has been very limited (Manickavasagam et al., 2015). Long bamboo fibers' specific properties, such as low density, specific strength, and stiffness, can be compared to glass fiber (Yu et al., 2014). However, some issues prevent bamboo fibers from being widely used. These are the following:

• Bamboo's moisture resistance is low, and its mechanical and chemical properties are insufficient at the fundamental stage.

• The current method of extracting fibers from bamboo culm is unsuitable for industrial and commercial production. Bamboo-based products have been used in a variety of applications, including transportation, furniture, packing, and other fields (Abdul Khalil et al., 2012). Currently, advanced processing technology has increased the use of bamboo fibers as reinforced polymer composite materials.

Table: 2.8 Comparison of bamboo and glass fibres (Kushwaha et al., 2010).

Properties	Bamboo	Glass
Density	Low	Higher than bamboo fibres
Cost	Low	Higher than bamboo fibres
Disposal	Biodegradable	Non-biodegradable
CO2 Absorption	Yes	No
Recyclability	Yes	No
Renewability	Yes	No
Energy for extraction	Low	High

2.9.1 Tensile strength of single bamboo fibres test

The calculated theoretical strength of cellulosic fibrils is 810 MPa based on the rule of mixtures. The maximum and average strengths for bamboo fibers from the compression molding technique (CMT) were found to be 1000 MPa and 645 MPa, respectively. However, the tensile strength of fibers obtained from the roller mill technique (RMT) was considerable with maximum and average tensile strengths of 480 MPa and 370 MPa, respectively. The fibers from RMT have lower tensile strength and lower variation in tensile strength when compared to the fibers obtained from CMT. It should be noted that fibers from RMT also had lower average diameters as well as lower variations in diameters(A. U. M. Shah et al., 2016).

2.9.2 Effect of gauge length on the tensile strength

Table 2.9 shows the individual fibre strength values for each gauge length. These results show that as gauge length increases, fibre strength decreases. The fibres with a gauge length of 1 mm have a higher strength as well as a lower variance. Because the gauge length is less than the length of an elementary fibre (2.1 mm), entire elementary fibres are most likely clamped between the top and bottom (E. Trujillo et al., 2014).

The number of elementary fiber ends increases as gauge length increases. The interphase of lamellar pectin that connects the elementary fibers is weaker than the elementary fiber itself. The pectin interphase may become the critical site for fiber failure in tension (Fuentes et al., 2011). The greater the gauge length, the greater the number of critical sites, and thus the greater the likelihood of failure. Remember that critical flaws can also be caused by imperfections developed during growth or defects introduced during extraction (Islam et al., 2019).

All specimens exhibited a large linear elastic behavior up to fiber fracture under tensile load. Table 2.9 shows the tensile strength, Young's modulus, and strain-to-failure values for bamboo fibers at various span lengths after machine compliance correction (Osorio et al., 2011). The properties measured on technical fibers are typically lower than the properties calculated from the composite. As a result, (D. U. Shah et al., 2016) point out, it is debatable whether the reinforcing unit within a composite is a technical fiber or an elementary fiber. The difference between technical fiber tensile test and back-calculated properties is that when testing a technical fiber with a gauge length longer than the elementary fibre length, shear develops in the often pectin-rich middle lamellae and failure occurs at lower properties. The absence of this behavior in bamboo fibers can be attributed to the fiber's structure. Bamboo does not have pectin-rich middle lamellae, but rather lignin-rich zones where the three-dimensional polymer rigidly fixes the structure. When the difference in back-calculated Young's modulus between the different species and ages based on the IFBT is tested, a few significant differences emerge (Delphine E C Depuydt, Sweygers, Appels, et al., 2019).

Table 2.9: Tensile strength of bamboo bundle fibres based on gauge length (Defoirdt et al., 2010; Osorio et al., 2011; Shao et al., 2013; F. Wang et al., 2014; Trujillo et al., 2014; Depuydt et al., 2017).

B. species	Gauge length	Tensile Strength (MPa)	Young`s modulus (GPa)	Starin to failure (%)
Dendrocalamus membranaceus	5,10,15,20,25,30 mm	639±175–813±94	33.37	2.0±0.6–7.5±1.6
GAK	50 mm	658±135	52±7	1.33±0.2
Bamboo	5,15,25,35mm	775±103–860±119	43	1.7±0.2–1.9±0.3
Bamboo	1,2,5,10,20,30,40 mm	733±121–943±94	–	–
GAK	5,10,25,40 mm	775±103.3–860±119	42±1.1–46±1.2	1.7–1.9±0.3
Bamboo	20,30,40,50,60 mm	442–555	–	–
Bamboo	20,30,40,50,60 mm	352–518	–	–

GAK = *Guadua angustifolia Kunth*

2.9.3 Bamboo fibres tensile strength

Single fiber tensile (SFT) tests were performed on elementary fibers, and the results will be compared to the back-calculated properties obtained from the IFBT test. One potential disadvantage of the IFBT is that the back-calculated properties are dependent on the accuracy of the micromechanical equations used. This is not a problem for stiffness where the influence of matrix and interface is negligible, at least when using continuous fibers or discontinuous fibers with a very high aspect ratio. However, for strength, the matrix's influence, potential (local) fibre misorientations, fibre volume fraction, and fiber-matrix adhesion must all be considered (Bensadoun et al., 2017).

As of now, there are three distinct ways to characterize the properties of fibers. Single fiber tensile tests (SFT) or dry fiber bundle tests are used to test the fibers as they are. Alternatively, the impregnated fibre bundle test (IFBT) results are used to calculate the fibre properties.

In this method, a unidirectional composite is loaded in the fiber direction, and the fibre stiffness and strength are calculated backward from the measured composite properties using simple micromechanical equations like the rule of mixture (Bensadoun et al., 2017). There are two inherent benefits to using this method. The first is that a large number of fibres are tested at the same time, resulting in a relatively direct measure of the average "effective" back-calculated fibre stiffness and strength. Second, the test is less complicated than a single fiber test (SFT), which necessitates careful preparation of the fibers. Furthermore, a large number of individual fibers must be tested to provide statistically reliable results (Swolfs et al., 2015).

Table 2.10 shows the back-calculated tensile strength of bamboo fibers. When the back-calculated technical fiber properties obtained with the IFBT method (see Table 2.10) are compared to the elementary fibre properties measured by the SFT (see Table 2.9), some interesting observations can be made. First, the scatter in the IFBT back-calculated data is much smaller than in the elementary fibre test data.

Table 2.10: Back calculated tensile strength of bamboo fibres using the rule of mixture (Abdul Khalil et al., 2012; D. E. C. Depuydt, Sweygers, et al., 2019; Trujillo et al., 2014).

Fibre species	Extraction technique	Tensile Strength (MPa)	Young`s modulus (GPa)	Starin to failure (%)
Bamboo	CMT	645–1000	–	–
Bamboo	RMT	370–480	–	–
GAK (1-3 Yrs)	Mechanical rolling	481±93	44±2	1.06±0.06
GAK (3-5 Yrs)	Mechanical rolling	426±41	41±3	1.22±0.34
DMM (1 yrs)	Mechanical rolling	436±62	41±3	0.98±0.08
DMM (3 Yrs)	Mechanical rolling	380±28	41±1	0.93±0.06
PNB (0.75 Yrs)	Mechanical rolling	293±19	37±3	0.77±0.04
PNB (2-4 Yrs)	Mechanical rolling	329±31	35±3	0.9±0.1
Bamboo	Mechanical extraction	503	35.91	1.4
Bamboo	Chemical extraction	341	19.67	1.73
Bamboo	Steam explosion	441±220	35.9±13	1.3
Bamboo	Mechanical	860±119	46±2	1.9
Bamboo	Mechanical (beating)	391–713	18–55	–
Bamboo	Steam explosion	516	17	–
Bamboo	Chemical extraction	341	19	1.71
Bamboo	Manually	500–575	27–40	1.9–3.2

2.9.4 Effect of fibres diameter on the tensile strength

The tests were carried out with various diameters for the same gauge length, L = 20 mm, to investigate the effect of fibre diameter on fracture strength. Because the diameter varies from fiber to fiber, no testing fiber at constant gauge length has a completely uniform diameter. Table 2.11 depicts the relationship between the average diameter and fracture strength of bamboo fibers, demonstrating that as the between-fiber diameter increases from 196.6 to 584.3 μm, the fracture strength decreases from 568 to 483 MPa (Shao et al., 2013). According to (Yu et al., 2014), the average length and diameter of an elementary fibre range from 1.54 to 2.73 mm and 12.41 to 15.63 mm, respectively. Furthermore, these bundles exhibit high diameter variability, which is a critical tensile strength parameter. Moreover, the results are highly sensitive to variables such as the processing method, cultivation conditions, type of surface treatment, and percentage of humidity, all of which influence the final characteristics of this type of natural material (Faruk et al., 2012; Quintero-Giraldo et al., 2019).

Table 2.11: Tensile strength of bamboo fibres based on fibres diameter (F. Wang et al., 2015).

Test diameter (μm)	Number of elementary fibres, N	Measured strength (MPa)
196.6±16.9	235±28	568±143
317.3±20.1	402±+36	533±204
398.4±16	598±45	523±129
508.8±17.1	973±72	491±105
584.3±14.7	1192±93	483±98

2.10 Bamboo fiber polymer composites (BFPCs)

Among the various natural fibers, bamboo fiber is a good candidate for use as natural fibers in composite materials. (Kushwaha et al., 2010) discovered that the tensile strength of bamboo-fiber plastic composites is comparable to that of mild steel, even though their density is only 12% that of mild steel. As a result, BFPCs can be extremely useful in structural applications (Banga et al., 2015) investigated how multidirectional fiber orientation can achieve uniform strength in all directions of composites. Because of their high fracture toughness and thermal stability, thermoplastic composites have sparked a lot of interest in the manufacturing process (Akkerman et al., 2020; Martin et al., 2020).

Thermoplastic matrix composite materials provide a broad range of solutions in a variety of industries, including the automotive industry, construction, electrical appliances, and home/urban furniture. A reactive agent of Maleic anhydride was used to promote the interaction of Polypropylene (PP) and bamboo fiber (Banga et al., 2015). The development of composite materials entails four broad areas of investigation: (a) delignification, separation, and isolation of fibers; (b) characterization of these fibers; (c) studies on the interaction of the fibers with polymers; and (d) evaluation of composite properties. A significant portion of research has focused on the two areas of interaction with polymer matrix and composite properties (Rajak et al., 2019).

2.10.1 Mechanical strength of BFPCs

Table 2.12 shows the mechanical properties of some BFPCs. In other research, researchers thoroughly investigated the mechanical properties of bamboo reinforced with a modified polypropylene resin, and dramatic changes in these properties were observed (Abdul Khalil et al., 2012). The extent of adhesion and surface treatments revealed that adhesion improved significantly following this treatment. The Maleic anhydride grafted polypropylene was used to make composites with improved mechanical properties (Razak et al., 2018). Several studies on the effect of particle volume fraction on the mechanical properties of bamboo particle composite materials, both pure bamboo particles and a mixture of two different types of particles, have been conducted. Thermosetting and thermoplastic matrix types, fiber shape and size, and fiber orientation all aim to improve mechanical properties (Biswas et al., 2016; Verma et al., 2017; Djamil et al., 2019; Martijanti et al., 2021).

Fibers are typically stronger and stiffer than the matrix; composite strength and stiffness generally increase with increasing fiber content (Kumar et al., 2010). Several studies are currently being conducted to assess the effects of varying percentages and sizes of bamboo particles, as well as the additive factor between the fiber and the matrix, as well as the type of matrix and fiber (Martijanti et al., 2021). When the matrix is made of polymer, the composite is referred to as a polymer matrix composite. The properties of polymeric composite materials are primarily determined by three elements: the resin, the reinforcement in the form of particles or fibers, and the interface between them, which could be a filler. Reinforcements add strength and rigidity to structures, assisting in the support of structural loads (Aje et al., 2017; Mustapa et al., 2020).

The desirable physical and mechanical properties of bamboo fiber-reinforced composites, such as high specific modulus, strength, and thermal stability, have been well documented in the literature. (Bhowmik et al., 2021) compared bamboo fiber-reinforced epoxy composites (BFEPCs) to bamboo fiber-reinforced unsaturated polyester composites (BFUSP) (BFPE). These two composites' mechanical properties were comparable. BFEP composites demonstrated greater elongation and 10% high tensile strength. These composites have a wide range of commercial applications, including crash helmets, low-cost housing, and wind turbines (Banga et al., 2015).

The mechanical strength of bamboo fibers reinforced polymer composites was influenced by the type of bamboo species, polymer matrix, and fibre volume fraction, as shown in Table 2.12. Bamboo fiber-reinforced epoxy and polypropylene composites have maximum fibre volume fractions of 65 and 60 %, respectively. The maximum tensile and flexural strength of bamboo fiber-reinforced polypropylene composites are 62 and 78 MPa at 50% fiber volume fraction, respectively, whereas the maximum tensile and flexural strength of bamboo fiber-reinforced epoxy composites are 87-165 and 107-140 MPa at 50% fiber volume fraction, respectively. When compared to bamboo fiber-reinforced polypropylene composites, bamboo fiber-reinforced epoxy composites have higher tensile and flexural strength.

Table 2.12: Mechanical strength of bamboo fibre polymer composites (Cabrera De Lima et al., 2021; Nahar Keya et al., 2019;).

Bamboo Species	Composite	Volume raction	Tensile strength (MPa)	Young`s modulus (GPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)
Nigerian bamboo	BFEP	5–25%	40.7–65.8	–	9.00–14.57	0.429–1.736
Dentrocalamus strictus	BFPE	68%	101.8±2.8	–	108.6±6.4	8.5±1.8
Dentrocalamus strictus	BFEP	60%	112.8±1.4	–	118.5±1.5	7.8±3.8
Guadua angustifolia	BFPP	30%	5.43±0.36	1.3±0.13	26.1±0.46	1.43±0.01
Guadua angustifolia	BFMAPP	30%	15.83±0.43	1.63±0.10	29.4±0.31	1.8±0.02
Bambusa Balcoa	BFPP	30–60%	25.50–28.95	1.357–1.776	45.49-49.56	2.077–3.307
Bambusa Balcoa	BFMAPP	30-60%	37.37–50.26	1.37–1.633	56.73-68.85	2.929–4.127
Bamboo	BFPP	50%	62	4.96	78	5.76
Bamboo	BFEP	65%	87–165	3–15	107–140	10–12
Bamboo	BFEP	–	86.57	–	119.69	11.901
Bamboo	–	–	–	–	67.7	4.35

2.10.2 Effect of fibres cleanness on the tensile strength

To maximize benefits, it is sometimes necessary to use more than one treatment method at different stages of bamboo fiber extraction. Because bamboo's complex structure and high lignin content make fiber extraction difficult and time-consuming, it is difficult to extract fibers using only one technology (Fu et al., 2012; Rocky et al., 2018). It is critical to emphasize the significance of selecting a good extraction method because it is difficult to separate the fibrous bundles from the plants. When lignin and other components are removed, the cellulose microfibrils are also affected, potentially increasing bundle fragility and decreasing mechanical properties. Different extraction methods and chemical, physical, and biological surface treatments were used, resulting in significant differences in mechanical properties (George et al., 2016).

Non-cellulose components such as lignin and hemicellulose, which have an amorphous structure that significantly affects the mechanical strength of the fiber bundles, contribute a greater quantity of micro defects within them and counteract the crystalline structure of the cellulose component, are not removed by mechanical extraction (Johar et al., 2012; Quintero-Giraldo et al., 2019).

Table 2.13 shows three different 'grades of cleanliness.' To disentangle and align rough combed fibers, they were combed with a very rough comb. Only a very small amount of loose parenchyma is removed from between the fibres by using this procedure. To remove the parenchyma, the cleaned and ultra-cleaned fibres are manually brushed (Osorio et al., 2011). Bamboo fiber epoxy composites with the highest and lowest tensile strength are cleaned and rough combed, respectively. However, rough combed and cleaned fibers have the highest and lowest Young's modulus, respectively. The mechanical strength of bamboo fiber-reinforced polymer composites has been influenced by the quality of the extraction methods.

Table 2.13: tensile strength of bamboo fibre composites based on fibres cleanness (Delphine E.C. Depuydt, Soete, et al., 2019).

Types of fibres	Tensile strength (MPa)	Young's modulus (GPa)	Strain to failure (%)
Combed fibres	208±19	23±2	0.94±0.08
Cleaned fibres	232±20	20±3	0.95±0.07
Ultra-cleaned fibres	214±24	21±2	1.18±0.19

2.11 Application of bamboo fibres

Bamboo fibers can be used to create biodegradable and sustainable biocomposites for indoor and outdoor applications, replacing materials/products typically made from glass fiber-based composites and conventional composites. In comparison to conventional composites, bamboo fiber-based polymer composites have a high strength-to-weight ratio, dimensional stability, durability, and the ability to be engineered to any complex shape or size at a low cost of production. Recently, technology has been involved in the process of hybridization and reinforcement of bamboo fibers with glass, jute, oil palm, coir, and other fibers compounding or mixing with matrices, resulting in advanced composites with high mechanical and thermal properties(Jawaid et al., 2011; Abdul Khalil et al., 2012).

As shown in Table 2.14, natural plant fibers such as jute, bamboo, and kenaf are now widely used in automobiles as a replacement for glass fibers due to their sustainability and ease of waste, namely burnability, biodegradability, and cost. They are used to make interior parts such as rear partitions, ceilings, door panels, truck liners, parcel shelves, and so on. They are expected to be used more and more as automobile production increases (Alves et al., 2010).

Table 2.14: Automakers using green composites (Phong et al., 2011).

Manufacturer	Fiber	Resin	Parts
Toyota	Kenaf, sisal, ramie	Polypropylene, polylactic acid	Door trim, inner board, roof lining, cover board of the spare tire
Mercedes	Flax, hemp	Polypropylene	Inner board of instrumental panel, door, pillar inners, headliner, and trunk components.
Mitsubishi	Bamboo	Polybutylene succinate	Inner board of trunk door panel.
BMW	Flax	polypropylene	Inner board of door panel.

2.11.1 Value chain of bamboo fibres

As indicated in Figure 2.12, bamboo fibers are one of the most promising fiber plants due to their combination of suitable material properties and low price. Bamboo fiber costs the same as coir, sisal, or jute, but its tension and flexural strength are much higher than those of coir, sisal, or jute, approaching the physical properties of the more expensive flax fiber and glass fibers. As they are used in the automotive industry, bamboo fiber-reinforced polymer composites outperform other natural fiber/polypropylene composites.

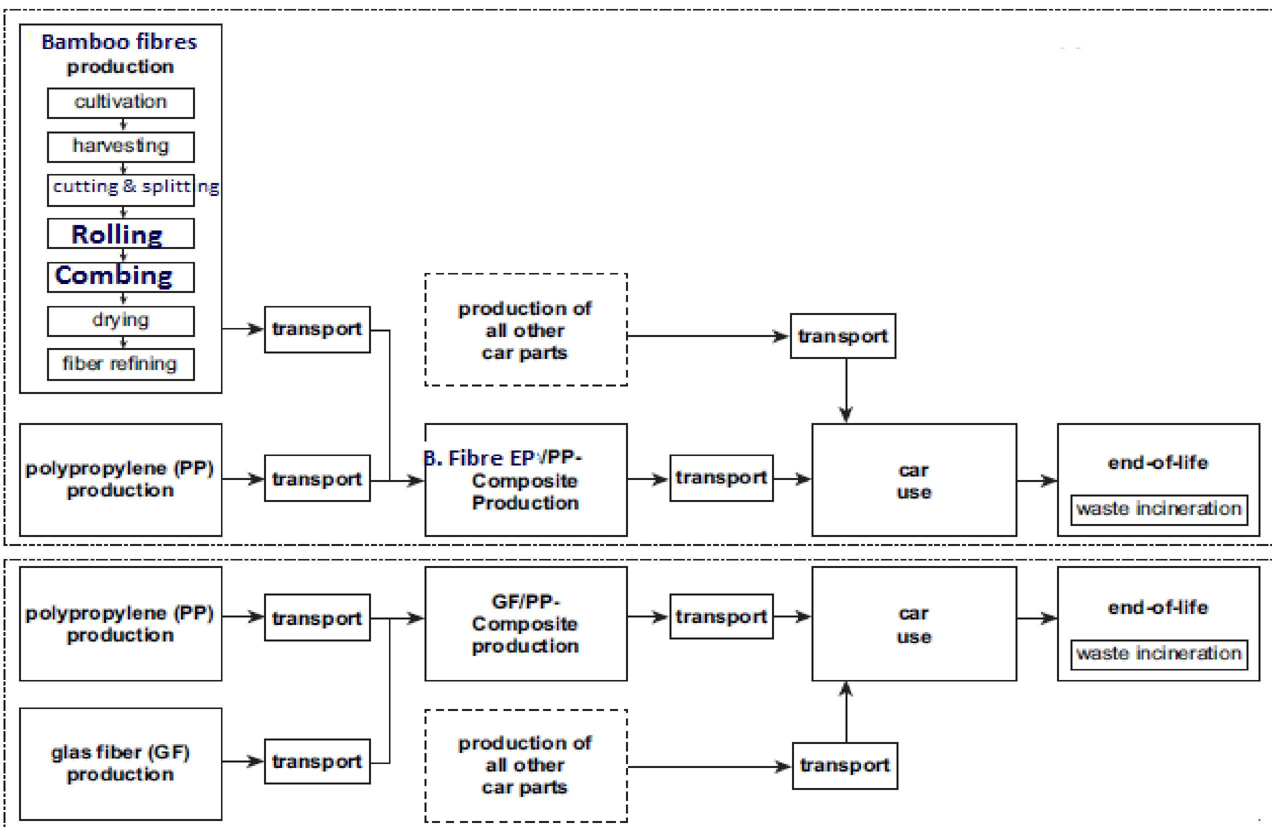


FIGURE 2.12: The production of bamboo fibres and glass fiber composites (Zah et al., 2007)

2.11.2 Benefits of bamboo fibres

As shown in Table 2.15, replacing glass fibers in the automobile industry with natural fibers can result in economic, environmental, and social benefits. The study discovered economic and social benefits to using bamboo fiber composites in car parts. Aside from being half the price of fibres glass, the use of bamboo fibers can promote regional development in Ethiopia. However, to achieve significant environmental benefits, the bamboo fiber-reinforced polymer composites must be lighter than their glass fiber-based counterparts.

BFEP and BFPP composites have the potential to replace glass fiber/polypropylene composites for sound insulation and structural parts, mainly in the vehicle's interior.

Table 2.15: Opportunities, risks, and potential risk avoidance strategies when replacing glass fiber composites with natural fibres based composites (Zah et al., 2007).

	Opportunities	Risk	Risk avoidance
Economical aspects	–Low raw material costs –More agricultural business –Eco-marketing	– Variable quality and availability – Lack of production	– Multiple suppliers; stock building –Building up production capacities
Environmental aspects	–impact compared to GF –Higher thermal recovery rate	–Higher weight than comparable GF parts –High environmental impacts by monocultures	–Natural fiber optimization (e.g. by alkali treatment) –Reduce fertilizers/pesticides; mixed cultivation
Social aspects	–Jobs for under-developed regions –Reduced health risks in production	–Unregistered workers' usage	/–Cooperation with social development programs (e.g. POEMA)

2.12 Summary of literature review

Over 1 million hectares of bamboo plants in Ethiopia are covered in the different regions of the country. However, the bamboo culms in Ethiopia were used for making home furniture, building the house, and constructing fences which were applied for low-level technology. Nowadays, bamboo fibres are used as polymer composites for advanced technology which is aerospace, automobile, sports, and medical types of equipment. Researchers have performed investigations on the properties of bamboo fibres and their polymer composites, but research has not been done an investigation on the properties of Ethiopian bamboo fibres and their polymer composites. The properties of natural fibres are influenced by methods of extraction, harvesting seasons, type of bamboo species, ages of the bamboo, and microstructure of the fibres. Due to the inherent properties of natural fibres, they have not been manufacturing catalogs that fabricated a product for specific applications. The advantage of natural fibres are light in weight, cheap in cost, biodegradable, eco-friendly, renewable, and have low energy utilization during processing compared to glass fibres. Moreover, natural fibres have benefits of an environmental, economical and social aspects for the country. The extraction of bamboo fibres is a challenging process to extract bamboo fibres from their culm that researchers have focused on the extraction process of the bamboo fibres.

The tensile, flexural, and impact strength of bamboo fibres reinforced polymer composites and the strength of single bamboo fibres were measured according to the testing procedure of ASTM standards based on the age, harvesting seasons, and bamboo species in Ethiopia. The structural, anatomical, and physical properties of the bamboo culm are examined, as well as, the chemical and thermal properties of the fibres are characterized in the current research work. The properties of bamboo fibres and their polymer composites are compared and contrasted with the traditional materials of the headliners in the automobile industry.

CHAPTER –3

MATERIALS AND METHODS

Introduction

The properties of natural fibres are influenced by many factors such as age, harvesting season, type of bamboo species, and methods of fibre extraction. The current research studies aim to develop and characterize Ethiopian bamboo fibres reinforced polymer composites. Two types of bamboo plants are available in Ethiopia such as *Y. alpina* and *O. abyssincia* which are found in high and lowland areas of the country respectively. Over one million bamboo plants are covered in Ethiopia in different regions of the country. Different types of materials were used for the current research work such as bamboo plants which are found in 3 regions of Amhara state (Injibara, Kombolcha, and Mekaneselam). Structural, physical, chemical, anatomical, mechanical, and thermal properties were investigated for the 3 regions of bamboo species in Ethiopia. This chapter described in brief the materials, research methods, composite processing, and characterization techniques.

The whole research activity was presented in Figure 3.1. The first research activities harvested the bamboo species in the 3 regions of Ethiopia. The bamboo culms were measured for structural, physical, and chemical properties to characterize their properties in comparison with other bamboo species. Bamboo fibres are extracted during the time of harvesting to prevent loss of water from their culm. The tensile strength of single bamboo fibres was measured using an UTS machine. The density, thermal properties, and degree of crystallinity are measured using standard equipment. The tensile strength, flexural, and impact strength of bamboo fiber-reinforced polymer composites were measured based on the ASTM standard using the required recommendation of the machine.

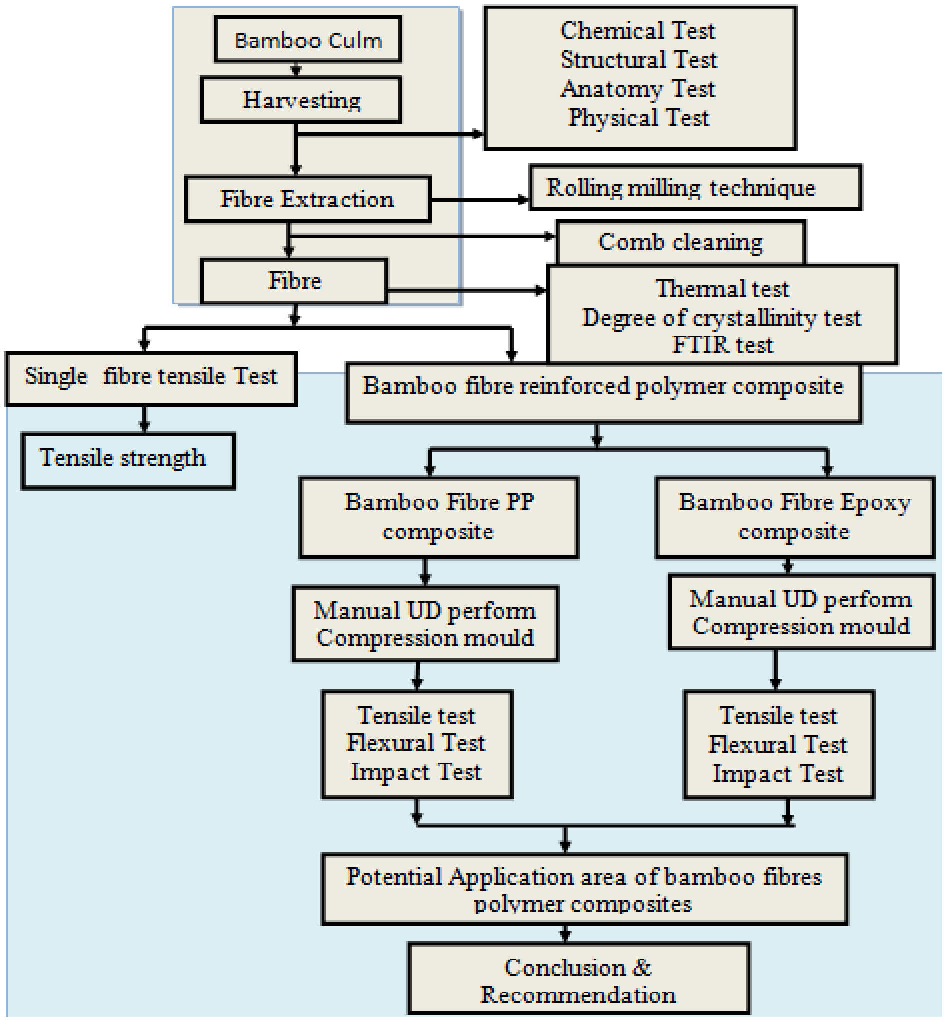


FIGURE 3.1: Flow chart of the research activities

3.1.1 Harvesting of the selected bamboo plant

The image of Ethiopian bamboo species are shown in Figures 3.2 (a), (b), and (c). Three Ethiopian bamboo species were studied in the current dissertation work: Injibara (*Y. alpina*), Kombolcha (*bambusa oldhamii*), and Mekaneselam (*Y. alpina*) bamboo plants were harvested on February, 11/2020, and November, 22/2020, respectively. Three representatives of bamboo plants were harvested at each age of one, two, and three years old within two months. The age of the bamboo culm was known by experienced field personnel using its color and sheath in the culm. The culm was later subdivided into three parts such as the bottom, middle, and top portions based on the criteria of internodes length greater than 25cm and outer diameter greater than 3cm.

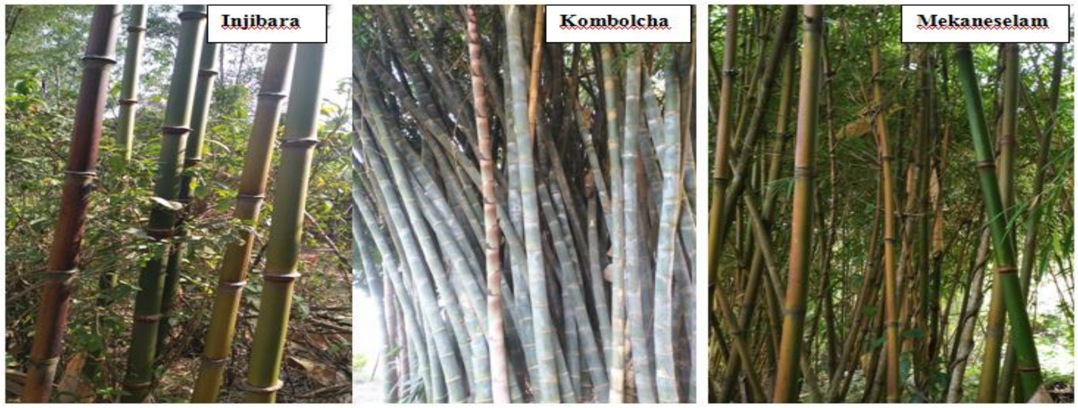


FIGURE 3.2: Ethiopian bamboo species (a) Injibara, (b) Kombolcha, (c) Mekaneselam.

3.1.2 Description of the study area

The geographic location and climatic conditions of the testing sites are described in Table 3.1. The Injibara region is the high altitude at sea level next to the Mekaneselam region, but Kombolcha is a low altitude and high maximum temperature.

Table 3. 1 Geographic location and climatic conditions of the testing sites (Birara et al., 2018; Abate Shiferaw, 2012)

Name of testing sites	Administrative location of the testing site				Climate, Average value		
	Zone	Region	Lat-Long	Alt.(m)	AV. RF (mm)	Max. Temp.(°C)	Min. Temp.(°C)
Injibara	Awi	Amahara	10°59′N 36°55′E	2540–2865	1813	24	14
Kombolcha	S/ wollo	Amahara	11°5′N 39°44′E	1842 - 1915	1027	26	20
Mekaneselam	S/ wollo	Amahara	10°45′N 38°45′E	2605-3000	1048	21	10

3.1.3 Culm age determination method

The age of bamboo culm was known by experienced field personnel. As presented in Table 3.2, the ages of the culm are identified based on culm color, bud break, branches, and sheath. Identifying the age of bamboo culms by their color is possible with new and young culms, but becomes more difficult with older culms. One-year-old culms have a distinct sheen, which is common in green, yellow, and black bamboo varieties. Bamboos with green culms have a dark green color when they are one year old, but the color gradually fades and becomes murky as the culms age. Year after year, one has carefully observed the pattern of color changes in the culms of a species in a specific environment or location. At best, observing the color of culms can provide hints as to whether the culm is young, mature, or old.

Table 3. 2: Age determination method of Ethiopian bamboo species (Mulatu, 2018).

	Injibara (*Y. alpina*)
Ages	Morphological description
First Year	Culm sheath: It is possible to find it at 2–3 basal nodes of the culm.
	Bud break and branches: Except at the basal 3–4 nodes, the large branch bud on the culm node breaks
	Culm: The basal 6–9 nodes have a brown to whitish pubescent ring, and the basal 4–5 nodes usually have a ring of adventitious roots.
Second year	Culm sheath: Mostly not present on the culms, it is possible to present on the basal 1–2 nodes
	Bud break and branches: Except for 4–5 basal nodes, almost all culm node buds develop thick, stout branches.
	Culm: On the basal 3–4 nodes, a brown to whitish ring and adventitious roots may be present. Not quite as dark green.
Third Year	Culm sheath: Absent
	Bud break and branches: Buds on the basal 3–5 culm nodes are usually dead and rotten.
	Culm: On the culm's basal 2–3 nodes, dead adventitious root rings may be present. The internodal surface is smooth and deep bottle green (hookers green).
	Kombolcha (*Bambusa oldhamii*)
First Year	Culm sheath: Except for the thin tip, the culm sheath covers all nodes.
	Bud break and branches: There is no bud break at the culm node, but there are 2–4 tip buds on the culm that produce drooping large leaves directly on the nodes, and there are no branches.
	Culm: Green, straight, branchless culm with drooping tips and 2–4 leaves.
Second year	Culm sheath: The sheath remains on the lower two-thirds of the culm, and the blade is loosely fitted.
	Bud break and branches: buds on the one-third upper portion of the culm nodes break and produce many thin ranches.
	Culm: Green
Third Year	Culm sheath: Only survive on the basal one-third of the culm (3–5 internodes). The blade of the culm sheath was shed off and was mostly black..
	Bud break and branches: Further buds break up to two-thirds of the culm, and many thin branches with fewer leaves.
	Culm: Dull dark green
	Mekaneselam (*Y. alpina*)
First Year	Culm sheath: Usually not found on the culm, but may be found on the basal 1–2 nodes and is tightly fitted.
	Bud break and branches: The culm node branch bud breaks acropetally, producing a stout branch, while 3–8 buds in the lower mid-culm zone remain dormant.
	Culm: The internode is a dark green color with a slight whitish bloom that comes off easily with a finger. A ring of small adventitious roots may form around basal 1–2 nodes. A brown to dark woolly band can be found just above the 1–3 basal nodes.
Second year	Culm sheath: Absent
	Bud break and branches: Almost all of the branch buds, including those that were dormant the first year, become active and produce branches on the lower mid-zone.
Third Year	Culm: A slight whitish bloom may be present; rubbing removes it.
	Culm sheath: Absent
	Bud break and branches: Branchy sprouts in a branch complement the basal 1–4 nodes of the culm generally die and shed off, leaving black scars.
	Culm: Green throughout, except for yellowish stains at the lower part of the internodes.

3.1.4 Harvesting seasons

The region of Amhara state was found between 8°45'N and 13°45' N latitude and 35° 46' and 40° 25' E longitude. The total area of the region is predicted at 156,960 km^2. The climatic condition of the Amhara region, based on altitude, was categorized into "Kola" (hot zone) - below 1500 m.a.s.l, and it covers 31% of the region, "Woyina Dega" (warm zone) - between 1500-2500 m.a.s.l covering 44% and "Dega" (cold zone) - between 2500-4620 m.a.s.l and it covers 25% of the region. The mean annual temperature of the region was between 15 °C and 21 °C. But in the valleys and marginal areas, the temperature exceeds 27 °C.

The climatic condition of the Amhara region, based on rainfall, temperature, and relative humidity, is categorized into three groups such as rainy seasons (June–September), cold seasons (October–January), and dry seasons (February–May). The average annual temperature of the rainy, cold, and dry seasons is 12–21°C, 9–23°C, and 12–30 °C, while the average annual rainfall is 897–1267 mm, 105–223 mm, and 93–174 mm, and the average annual relative humidity is 62–80%, 52–58%, and 50–60%, respectively (Ayalew et al., 2012).

The current research work on bamboo plants is harvested during the periods of cold and dry seasons, which are (October–January) and (February–May). However, harvesting months in the rainy seasons are not good for the development of plant growth and the plants contain a high amount of starch content in the culm, which is not a required property for the fibres.

3.2 Structural measurements bamboo culm

Structural measurements of the culms were taken during the harvesting week before any significant size reductions occurred as a result of moisture loss. For each Internode along the entire culm, the length (between the middle points of the enclosing nodes) and the outer diameter (at the middle of the Internode) were measured. The culm wall thickness was measured in the middle of the Internode. The bamboo plants are cut using a flat sward. A digital vernier caliper was used to measure the diameter and wall thickness, and a steel rule measure was used to measure the length.

The maximum fibre length of the extracted fibres will be determined by the Internodal length. Long fibres are preferred for making unidirectional composites with uniformly oriented fibres; shorter fibres are more difficult to align. The total amount of fibres that can be extracted is affected by the thickness of the culm. Because of these two factors, only certain internodes with minimum length and wall thickness will be suitable for industrial-scale fibre extraction for UD composite production. The minimum internodal length and thickness of the culm were presented in Table 3.3, to assess the fraction of the culm suitable for industrial-scale fibre extraction. All internodes that met both criteria were found in the center of the culm (classified as the middle segment). Internodal numbers below and above the middle were labeled as bottom and top segments.

Table 3. 3: Criteria setting for the division of bamboo culm along with the height

Age	position	Injibara	Kombolcha	Mekaneselam
1 year	Bottom	Below	Below	Below
	Middle	thickness >6 mm and I. length>30 cm	thickness >8 mm and I. length>25 cm	thickness >5 mm and I. length>45 cm
	Top	Above	Above	Above
2 year	Bottom	Below	Below	Below
	Middle	thickness >8 mm and I. length>35 cm	thickness >10 mm and I. length>28 cm	thickness >7 mm and I. length>47 cm
	Top	Above	Above	Above
3 year	Bottom	Below	Below	Below
	Middle	thickness > 9 mm and I. length>30 cm	thickness >12 mm and I. length>32 cm	thickness >9mm and I. length>50 cm
	Top	Above	Above	Above

I. length= Internodal length

3.3 Bamboo fibres extraction method

Bamboo culm was cut from the nodes across a cross-section, then the internodes were split along the longitudinal into strips width of 30 mm. The strips were then passed through the two steel rods in the rolling mill under slight pressure and at low speed. One-third of the inner and outer parts of the culm are removed after enough rolling, then the middle part of the rolled culm is combed using different sizes of comb for separate fibres. For two weeks, the obtained fibers were sun-dried, and their length ranged above 250 mm (Osorio et al., 2011).

The extraction process and extracted fibres are presented in Figures 3.3 and 3.4, respectively. The fibres were extracted from the middle section of the internode. Fibre extraction was performed in the same week of harvest. The cleaning step is carried out, which entails brushing the fibres with the addition of water to remove residual parenchyma. Finally, the fibres were dried for at least one week at 60 °C after extraction before being used to make composites.

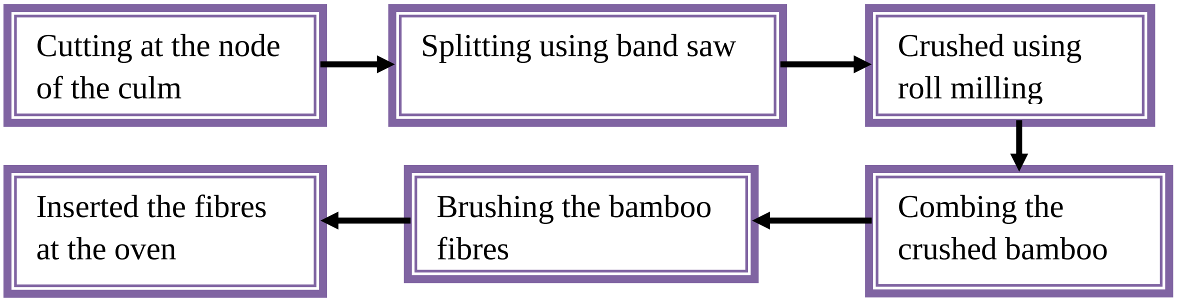


FIGURE 3.3: Extraction of bamboo fibre

FIGURE 3.4: Extracted bamboo fibres (a) Injibara, (b) Kombolcha, (c) Mekaneselam

3.4 Bamboo fibres properties test

The testing procedures for fibres density, thermal properties, degree of crystallinity, and functional groups of the fibres are presented in detail in the following section.

3.4.1 Fibres density measurement

Fibres grinding mill and pycnometer are presented in Figure 3.5(a–d). Gas pycnometer measurements were performed to determine the density of the fibres, using a Quantachrome multi pycnometer model MVP-D160-E with helium gas at a pressure of 1.5 bar as displacement medium. The fibres were dried before milling for 1 week in an oven at 60 °C. By milling the fibres with a centrifugal mill, type Retsch ZM100 (Gemini BV, Netherlands), all the particles became smaller than 250 µm. The fibre dust was dried in a vacuum oven for at least 5 hours at 30 °C before measuring. The measured density can be considered as the cell wall density of the bamboo fibre (Rude et al., 2000).

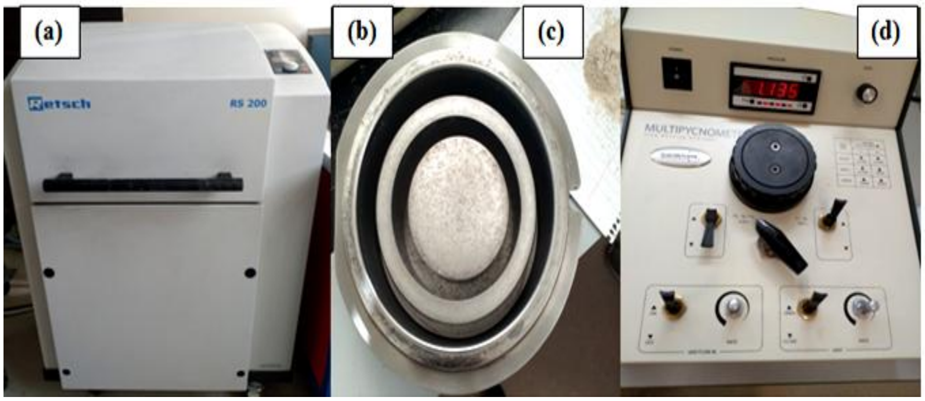


FIGURE 3.5: Fibre density measurement (a) centrifugal grinding machine, (b) grinding wheel, (c) fibres powder, (d) density measurement of pycnometer

3.4.2 Fibres thermal properties measurement

The thermal properties of fibres measuring equipment are presented in Figure 3.6. TGA characterizes weight loss or gains due to decomposition, oxidation, or dehydration, to determine the thermal stability and oxidative stability of material at temperatures up to 500 °C. Usually, the first derivative of the TGA curve (DTG) is also calculated to identify the points of the greatest rate of change on the weight loss curve.

Thermogravimetric analysis (TGA) for bamboo technical fibres was carried out on a SDT Q600 T.A and the model of the machine is Netzsch STA 449F3 Jupiter. The experiment is carried out under an inert atmosphere at a flow rate of 20mL/min. and a heating rate of 5 °C/min. For the TGA measurements, samples between 5 and 12 mg were tested. TGA/DTG curves for bamboo fibres in argon environments are used during thermal analysis. The samples of the powder are prepared using the same preparation procedure as the pycnometer samples prepared in section 3.4.1 (Bücheler et al., 2016).

FIGURE 3.6: Thermogravimetric analysis (TGA)

3.4.3 Degree of crystallinity measurement

The degree of crystallinity measuring setup is presented in Figure 3.7. The samples of the powder were prepared using the same preparation procedure as the pycnometer and TGA samples prepared in sections 3.4.1 and 3.4.2.

For the reflection (R) measurement a Bruker D8 Advance goniometry was used (Bragg-Brentano geometry), equipped with a copper Kα (λ = 0.154189 nm) X-ray source operating at 40 mA and 40 kV in line focus and a Malvern Panalytical Empyrean diffractometer. Data were collected over an angular range of 5– 60° 2θ using a Lync Eye-XE-T detector with a step size of 0.04° 2θ and a counting time of 0.1s per step. Data reduction was performed with the origin lab 2019 software. The degree of crystallinity (DOC) was calculated from the total areas under the defined degree of crystallinity and amorphous components. The empirical method proposed by (Nam et al., 2016) was applied to calculate the crystallinity using Eq. (3.1):

$$\text{Degree of crystallinity} = \frac{Crystalline\ area}{Crystalline\ Area + Amorphous\ Area} \qquad (\text{Equ. } 3.1)$$

FIGURE 3.7: XRD testing setup of bamboo fibres

3.4.4 FTIR test

The equipment for the FTIR test is indicated in Figure 3.8. The samples of the powder are prepared using the same preparation procedure as the pycnometer and TGA samples prepared in sections 3.4.1 and 3.4.2.

FTIR Spectroscopy is an analytical technique used to identify organic materials using the range of the wavelength. The FTIR analysis method uses infrared light to scan test samples and observe chemical properties based on the functional group. The samples of bamboo powders were finely ground and oven-dried at 60 ^{O}C for 5 hrs. FTIR spectrometer Varian model 670 equipped with Mercury Cadmium Telluride (MTC) and deuterated using BRUKER OPUS 6 5 FTIR spectrometer for wave numbers ranging 4000–400 cm^{-1}, resolution 4 cm^{-1}, scan mode transmittance, and the number of scans 32 (Bakri et al., 2016).

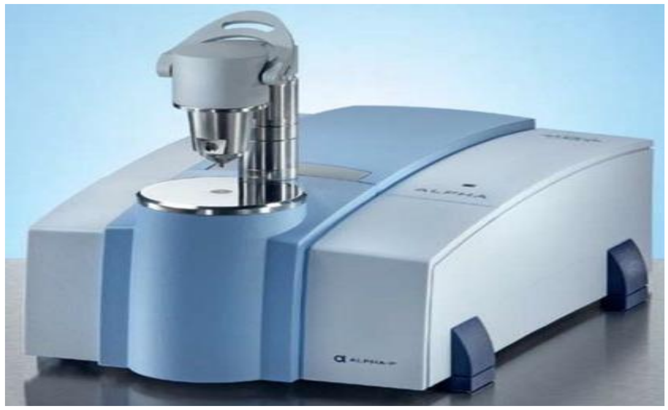


FIGURE 3.8: FTIR test of bamboo fibres

3.5 Physical properties test

The physical properties of the bamboo culm are very important for structural application and fibres extraction. The physical properties were influenced by the type of bamboo species, age, and harvesting seasons. The measurement methods for moisture content, basic density, and culm shrinkage are presented in sections 3.5.1, 3.5.2, and 3.5.3, respectively.

3.5.1 Moisture content measurement

Six specimens are prepared from each height at the bottom, middle and top parts to evaluate moisture contents. 18 experiments are performed at each age of 1, 2, and 3 years old in the bamboo culm. A total of 54 experiments were performed to evaluate the moisture contents of the culm aged from 1-3 years old. The samples were weighed with an analytical balance accuracy of 0.00001 g and dried in the model of the thermo oven OMH 750 an oven at 105±2 °C for 72 hours until a constant weight was attained, then the moisture content of the samples was calculated according to (ASTMD5229, 2004) as follows:

$$MC = \frac{M_{1-M_2}}{M_1} x100\ \% \qquad \text{(Eqn. 3.2)}$$

Where:

MC is the moisture content (%)
M_1 is the initial weight of the wet sample (gm)
M_2 is the dried weight sample (gm)

3.5.2 Basic density measurement

18 specimens were prepared from each age of 1, 2, and 3 years–old, and 6 specimens were prepared from each height at the bottom, middle, and top positions. Each bamboo specimen was prepared to the size of 25 mm × 25 mm × t. Basic density was determined based on oven-dry weight and green volume. The specimens are weighed in analytical balance before being oven-dried. Then, the specimens were dried in the model of the thermo oven OMH 750 oven-dried for 72 hours at 105±2 °C until a constant weight was attained. Then, the specimens were weighed in the analytical balance after being oven-dried. The green volume of the specimen was measured using digital vernier calipers. (ASTM, 2014a) reported that basic density was calculated according to the following formula:

$$BD = \frac{ODW\ (Kg)}{GV(\mathrm{m}^3)} \qquad \text{(Eqn. 3.3)}$$

Where:

BD is basic density (Kg/m^3)

ODW i$s\ ovendry\ weight\ (Kg)$

GV is $Green\ volume(m^3)$

3.5.3 Culm shrinkage measurement

The testing specimens were prepared using a CNC milling machine and presented in Figure 3.9. Six specimens are prepared from each height at the bottom, middle, and top parts. at each age of 1, 2, and 3 years old. 54 experiments proceed to evaluate shrinkage (radial, tangential and longitudinal) at each age of the culm. Each specimen was prepared in the size of 30 mm × 20 mm × t. Culm shrinkage was determined based on the green dimension and oven-dry dimension that were before and after the oven-dried, respectively. The specimens were dried in the model of the thermo oven OMH 750 oven-dried for 72 hours at 105±2 °C until a constant weight was attained. Then, the size of the specimens was measured using digital vernier calipers (ASTM C356, 1997). Linear shrinkage stated that culm shrinkage was calculated according to the following formula:

$$\mathrm{SHCM} = \frac{GD-ODD}{GD} x100\% \qquad \text{(Eqn. 3.4)}$$

Where:

SHCM is shrinkage in culm (%)

GD is $Green\ dimension$ (mm)

ODD is $oven\ dry\ dimension$ (mm)

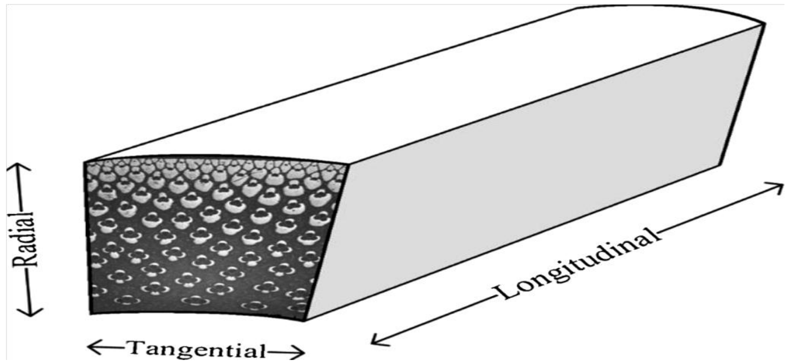


FIGURE 3.9: Samples of radial, tangential and longitudinal shrinkage of the culm

The longitudinal direction is the direction of the fiber; the tangential direction is the direction of the culm's circumference, and the radial direction is the direction of the culm's wall thickness. Dimensions of the beam are 30×20×t mm with t the thickness of the culm wall.

3.6 Chemical composition test

Chemical constituents of the bamboo culms have influenced the application area like structural, construction, biofuel, and fibres board production. The main chemical constituents of bamboo culms are cellulose, hemicelluloses, lignin, and extractives. Strips of bamboo were cut into small pieces using scissors, then grind using a higher-duty coffee grinder mill in powder form. The powder was sieved in the sieve size of 425 and 375 μm. The sample size of the particles was passed through in a sieve size of 425 μm and laid down on a sieve size of 375 μm. The current studies have applied the methods of gravimetric methods to evaluate the chemical constituents of the culm. The gravimetric methods were selected for chemical constituent analysis in considered economically suitable for developing countries because of cheap and mostly available on the shelf (Ayeni et al., 2015). The current research study measured the chemical composition using gravimetric weight methods. Various types of chemicals and types of equipment were used for measuring the chemical constituent of bamboo species in Ethiopia (SK et al., 2016).

3.6.1 Holocellulose content measurement

As shown in Figure 3.10, two gm of oven-dry extractive-free bamboo powder samples were put in 250-milliliter flasks with small watch glass covers. Following that, 80 milliliters of distilled water, 0.5 milliliters of cold glacial acetic acid, and 1 gram of $NaClO_2$ were applied to the samples. The flasks were then placed in a water bath kept at 70–80°C. Every hour for three hours, 0.5 milliliters of cold glacial acetic acid and 1 gm of $NaClO_2$ were added to the flasks, and the contents were constantly mixed thoroughly. The flasks were cooled for three hours until the temperature reached 25°C. Before recycling, the flask mixture was then filtered into known-weight glass crucibles. The residues were thoroughly rinsed (SK et al., 2016). The percentage of Holocellulose content was calculated as follows:

$$\text{Holocellulose} = \frac{W_{2-W_1}}{Orginal\ weight\ of\ the\ samples} \times 100\% \qquad \text{(Eqn.3.5)}$$

W_2 - Stands for the weight of crucible + sample.
W_1 - Stands for the weight of the empty crucible
.

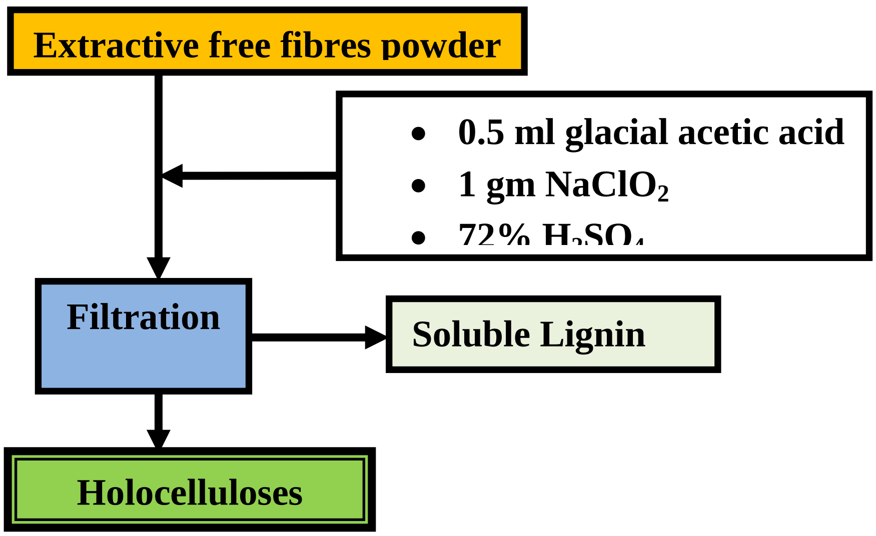


FIGURE 3.10: Holocellulose content measurement

3.6.2 Celluloses content measurement

As shown in Figure 3.11, two gm of oven-dried Holocellulose samples were put in 250 ml beakers with small watch glass covers. The samples were then thoroughly mixed for 5 minutes after being treated with 10 ml of 17.5% NaOH. 15 ml of 17.5% sodium hydroxide solution was added to the reaction mixture in three equal portions (3-5 ml) at 5-minute intervals with constant stirring. After 30 minutes of allowing the specimens to react with the solution, 33 ml of distilled water was added to each flask and left for another hour. Vacuum suction was used to filter the contents of the beakers into glass crucibles of known weight. The residues from each flask were washed with 100 ml of 8.3% NaOH first, then with water (SK et al., 2016). The following formula was used to obtain cellulose in bamboo species in Ethiopia.

$$\text{Cellulose \% (Based on Holocellulose=100)} = \frac{W_2}{W_1} \times 100 \qquad \text{(Eqn. 3.6)}$$

W_2=Weight of the oven-dry cellulose residue
W_1 =Weight of the original oven-dry Holocellulose sample.

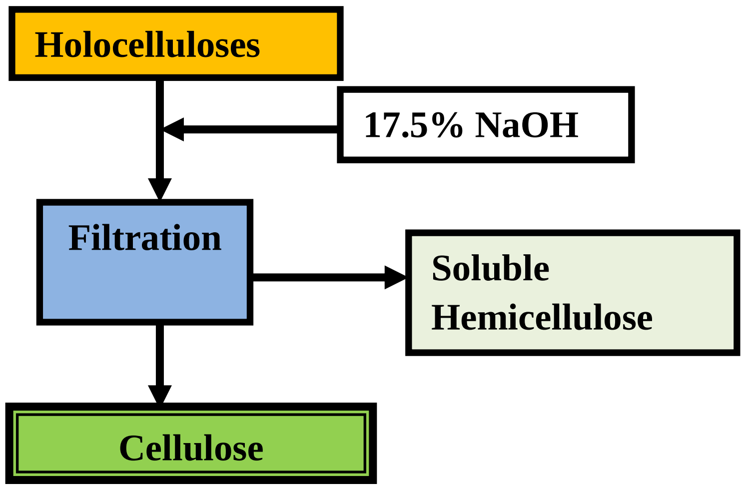


FIGURE 3. 11: Flow chart in the evaluation of cellulose content

3.6.3 Lignin content measurement

As shown in Figure 3.10, in 100 ml beakers, 1gm oven-dried extractive-free dust was put. In each beaker, 15 ml of cold sulfuric acid (72%), glacial acetic acid, and sodium chlorite were slowly added while stirring and thoroughly mixed. The reaction was stirred frequently for two hours. After two hours, the specimens were transferred by washing them with 560 ml of distilled water into 2,000 ml flasks, diluting the sulfuric acid concentration to 3%. For four hours, the flasks were placed on hot plates. The beakers is removed from the hot plate, then the contents of the beakers were allowed to settle. The contents of the flasks were filtered into known-weight glass crucibles and washed with distilled water. The residues were oven-dried at 105±2°C (SK et al., 2016). The following formula was used to obtain the lignin content in bamboo species in Ethiopia:

$$\text{Lignin \%} = 100x \frac{W_2 - W_1}{Orginal\ weight\ of\ the\ samples} \quad \text{(Eqn. 3.7)}$$

W_2- Stands for the weight of the crucible + sample.

W_1- Stands for the weight of the empty crucible.

3.6.4 Extractive content measurement

As shown in Figure 3.12, 60ml of acetone with 1gm oven-dry samples of bamboo powder are mixed and inserted in the water bath at 100 °c for 2 hrs. The mixed solution is washed with distilled water and dried in the oven at 105 ±2°C until a constant weight was obtained.

The crucibles were then cooled in a desiccator and weighed until they reached a constant weight (SK et al., 2016). In Ethiopia, the extractive content of bamboo species was determined using the following formula:

$$\text{Extractives content } \% = 100 \times \frac{W_2}{W_1} \qquad \text{(Eqn.3.8)}$$

W_2 - Stands for the oven-dry weight of the sample.

W_1 - Stands for the weight of the crucible with sample-Weight of an empty crucible

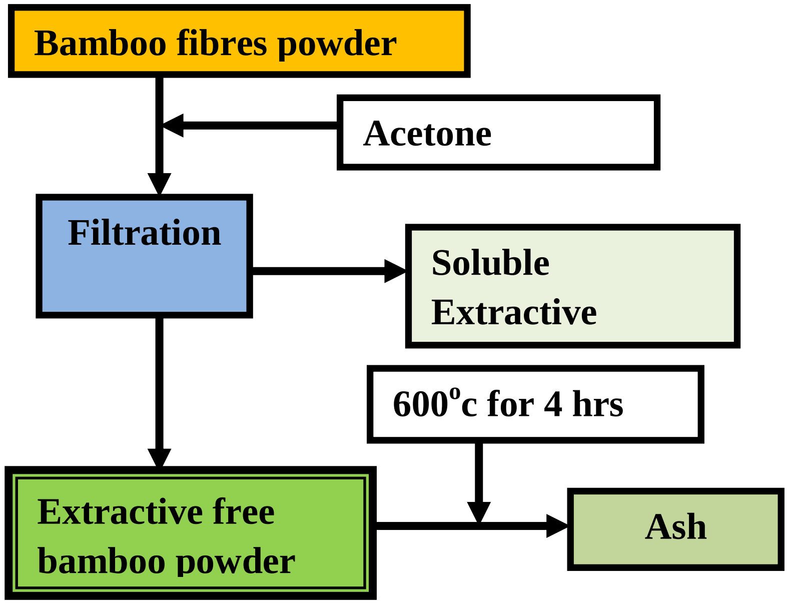


FIGURE 3. 12: Evaluation of extractive content

3.6.5 Ash content measurement

As shown in Figure 3.12, two gm of oven-dry (OD) samples of bamboo powder were placed in the crucible. Crucibles with contents were placed in the muffle furnace and ignite for 4 hours. The temperature of the final ignition was 600°C. Removed the crucibles with their contents to a desiccator, replaced the cover loosely, cooled, and weighed accurately (Mansor et al., 2019). The following formula was used to obtain the ash percent of bamboo species in Ethiopia:

$$\text{Ash } \% = 100\, x \frac{W_2 - W_1}{Orginal\ weight\ of\ the\ samples} \qquad \text{(Eqn.3.9)}$$

W_2 - Stands for the weight of the crucible + sample.

W_1- Stands for the weight of an empty crucible

3.7 Single bamboo fibres tensile measurement

Before tensile testing, the fibers were visually selected to ensure that there were no defects along their length. To ensure a good grip and straight position between the clamps, both ends of the fiber sample were glued with cyanoacrylate adhesive onto a paper frame that was cut after being clamped by the testing machine's jaws. Special care was taken during handling to avoid introducing new flaws and altering flaw distributions. The opening of the paper frame was determined by the length of the tensile test samples.

3.7.1 Tensile test setup

Figure 3.13 depicts the frame dimensions for test gauge lengths of 15 mm, 25 mm, 30 mm, 40 mm, and 50 mm, as well as the position of the fibre within the frame. The frame allows for easier sample mounting and fiber alignment in the grips, while the abrasive paper reduces fiber slippage during the test. Tensile tests were carried out on an Instron model of 5943 equipped with a 100 N load cell in a conditioned environment at 50% RH and 21ºC following the (ASTM Internasional, 2003). The frame was gripped pneumatically with a gripping force of 200 N. To straighten the fiber, a crosshead displacement rate of 1.5 mm/min., and a pre-load of 0.01 N was applied. When calculating strain from crosshead displacement, fibre straightness is critical.

Samples were loaded until mechanical failure which is defined as the point at which the specimen could no longer support the externally applied load. Forces and displacements of the testing machine were directly registered on a chart recorder using an acquisition system. Tensile strength was calculated as the ratio of the maximum applied load to the specimen's cross-sectional area. It should be noted that the samples broken near the edge of the clamps were excluded from the analysis after the tensile test for fibres. As shown in Figure 3.14, technical bamboo fibres connect many elementary fibres that determine the mechanical strength. As the length of the bamboo fibres increases, the likelihood of a weak link formation increases, with the fibres breaking at a specific joint (Tomczak et al., 2007). As a result, the strength increases, and a different fracture type can occur, particularly at different testing gauge lengths.

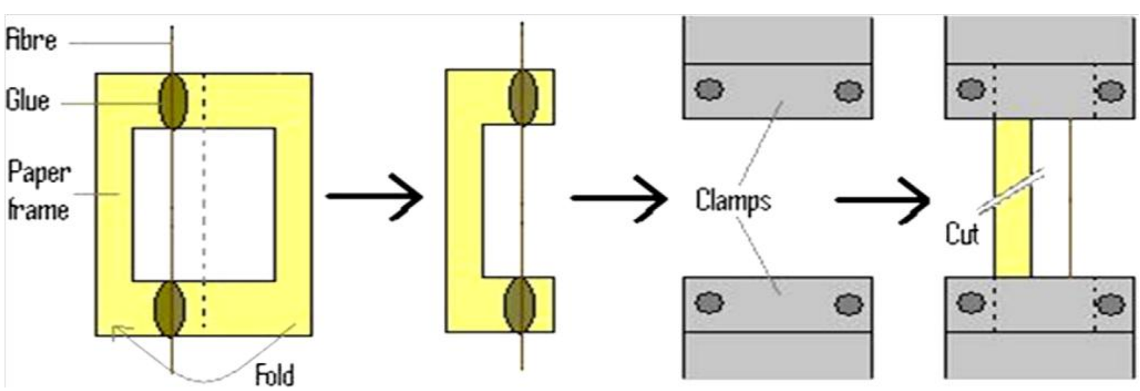


FIGURE 3.13: Use a paper frame to put the fibre straight between the screwed clamps

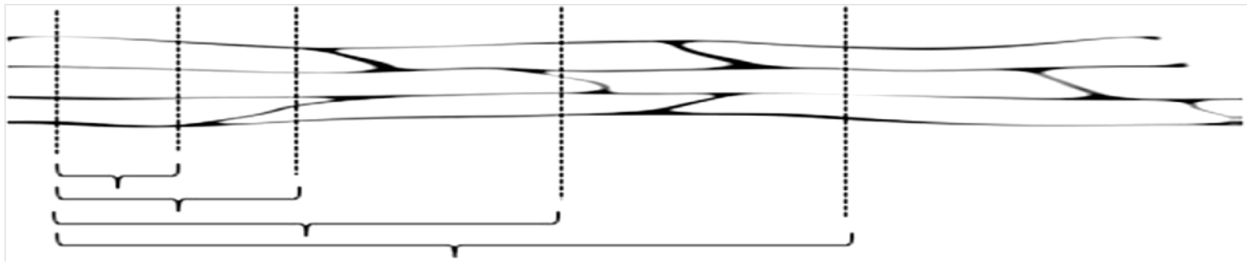


FIGURE 3. 14: Arrangements of elementary fibre through a technical fibre

3.7.2 Cross-sectional area measurement

The fibre cross-section of the tensile-tested fibers was determined using a gravimetric method. As a result, after milling the fibres, the cell wall density was measured using a gas pycnometer. The apparent weight of Ethiopian bamboo fibres was used to calculate the cross-sectional area. The weight of the fibers is determined using a digital balance with an accuracy of 0.00001 gm. The diameter of the fiber was calculated from the area by assuming a circular shape (Depuydt et al., 2017).

$$A = \frac{m}{\rho l} \quad \text{(Eqn.3.10)}$$

In the above equation, m is the fibre mass, ρ is the fibre density and l is the fibre length. The fibre mass was determined with an analytical balance (Mettler AT 261 DeltaRange, Mettler Toledo) accurate to 10^{-5} gm. Forty samples were tested at five gauge lengths (15 mm, 25 mm, 30 mm, 40 mm, and 50 mm). The coefficient of variations of fibre diameter (CVFD) is the average value of diameter variation coefficients of 40 fibres at each gauge length.

3.7.3 Weibull strength distribution

Bamboo fibers have a significantly higher variation in diameter between fibers and within a fiber when compared to synthetic fibers (Abdul Khalil et al., 2012). As a result, natural fibers exhibit significant strength variation, which is correlated with fiber diameter and length. In other words, there is no specific value that represents their strength. This necessitates the use of an efficient method for evaluating fiber strength and predicting its size dependence (F. Wang et al., 2014). Brittle fiber tensile strength is commonly described using weakest link statistics, which are based on the assumption that the material is composed of smaller elements that are linked together. If any of these elements, or "links," fails, the material is considered to have failed (Sharma et al., 2020). Brittle fiber strength has a typical distribution due to the severity of flaws. This statistical variability is frequently examined using the Weibull cumulative distribution function.

$$P(\sigma) = 1 - \exp\{-\left(\frac{V}{V_0}\right)\left(\frac{\sigma}{\sigma_0}\right)^{\beta}\} \quad \text{(Eqn. 3.11)}$$

where P is the probability of failure. β is the Weibull modulus or the shape parameter, which measures the variability of the fibre strengths. The strength distribution with a lower Weibull modulus tends to perform a larger scatter. σ_0 is the characteristic Weibull strength or the scale parameter that corresponds to a reference gauge volume V_0. V is the fibre volume. For a constant tested volume, Eqn. (3.11) is reduced to

$$P(\sigma) = 1 - \exp\{-\left(\frac{\sigma}{\sigma_0}\right)^{\beta}\} \quad \text{(Eqn. 3.12)}$$

The unknown cumulative probability of failure P can be estimated from the observations: N samples are ranked in ascending order, i = 1– N. σ denotes the i^{th} smallest observation (i = 1 corresponds to the smallest, and i = n corresponds to the largest). Then, an empirical estimator of P is the expectation of σ based on a statistical approximation technique:

$$P = \left(\frac{i}{n+1}\right) \quad \text{(Eqn. 3.13)}$$

Taking the double natural logarithms of both sides in Eqn. (3.12), the rearrangement of the Weibull distribution gives the following equations (Defoirdt et al., 2010),

$$\ln\left(\ln\left(\frac{1}{1-\mathrm{p}}\right)\right) = \beta\ln(\sigma) - \beta\ln(\sigma o) \quad \text{(Eqn. 3.14)}$$

Hence, the scale and shape parameters can be obtained from a plot of $Y = \ln\left(\ln\left(\frac{1}{1-\mathrm{p}}\right)\right)$ versus X = ln(σ), which should produce straight line with gradient β and intercept σo at Y = 0. Although the above conventional Weibull model is widely applied to uniform brittle and polymeric fibres, it does not always adequately describe the fibre strength and the dependence of the strength on the fibre volume for many natural fibres, because they are notably different from man-made fibres, particularly in their variable geometrical structures such as the between-fiber and within-fiber diameter variations. Therefore, a modified form of Eqn. (3.11) was suggested by (Sharma et al., 2020)

$$p = 1 - exp[-\left(\frac{L}{L_0}\right)^{\gamma}\left(\frac{\sigma}{\sigma_0}\right)^{\beta} \qquad \text{(Eqn. 3.15)}$$

where L_0 is the reference length and L is the fiber gauge length. From (1), the average strength is a power function of gauge length L

$$\sigma_2 = \sigma_1\left(\frac{L_2}{L_1}\right)^{(-\gamma/\beta)} \qquad \text{(Eqn. 3.16)}$$

The conventional (equation (3.11)) and many modified Weibull models (Eqn. (3.15), etc) are widely applied to uniform brittle and polymeric fibers (H. Wang et al., 2014).

$$\sigma = \sigma_0\left(\frac{L_2}{L_1}\right)^{-(1/\beta)} \Gamma\left(1 + \frac{1}{\beta}\right) \qquad \text{(Eqn. 3.17)}$$

If a material's strength was determined by weak-link statistics, longer fibers have more links than shorter fibers and are more likely to encounter a more severe flaw along the fiber (Shao et al., 2013). Longer fibers also have lower average fracture strengths than shorter fibers. In other words, as the size of the materials increases, their strength decreases (Aydin, 2013). As a result, weak-link scaling predictions assume that the strength of any fiber can be scaled. Based on a single estimate of a weak-link point at a predetermined fiber gauge length (Virk et al., 2009). Considering Eqn. (3.17) for the same probability of failure for two specimens with identical stress distributions, the strength values obtained at any given gauge length can be scaled to predict the strength of another length of fiber and for a similar probability of failure as follows (Edy Pramono et al., 2015) :

$$\frac{\sigma_2}{\sigma_1} = \left(\frac{L_2}{L_1}\right)^{1/\beta} \qquad \text{(Eqn. 3.18)}$$

Eqn. (3.15) can be changed as follows:.

$$ln[-ln(1 - p)] = \gamma lnL - \gamma lnL_0 + \beta ln\sigma - \beta ln\sigma_0 \qquad (Eqn. 3.19)$$

and hence the Weibull modulus and characteristic strength can be obtained from a plot of $ln[-ln(1 - p)]$ versus ln(σ) which should produce a straight line, with gradient (β) and intercept σ_0 at $ln[-ln(1 - p)]$= 0 (F. Wang et al., 2014). The sensitivity parameter (γ) represents the fibre diameter variations(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985)(Watson et al., 1985). The tensile properties of wool fibre with the employment of the modified Weibull distribution (Zhang et al., 2002; Xia et al., 2009).

3.8 Bamboo fibres reinforced polymer composites

The strengths of bamboo fibre reinforced polymer composites were influenced by the quality of fibres extraction, composite manufacturing method, bamboo species type, fibres volume fraction, and the orientation and alignment of the fibres. The current research studies considered the factors which affect the quality of the fibres and their composites. The fibres qualities were influenced by the ages, harvesting seasons, and types of bamboo species. The manufacturing and testing procedures of bamboo fibres reinforced polymer composites were reviewed in detail as follows:

3.8.1 Composite production methods

Compression molding was used to manufacture the UD BFEPCs. The impregnated fibre was placed into a multi-cavity mold with their fitting upper molds to produce the samples. This method is used to eliminate variations during processing conditions. The technique allowed us to maintain the fibre alignment and patterns while also providing a good surface quality on both sides of the composite. A 40% fibre volume fraction was aimed for and verified by weight measurements after manufacturing.

First, the fibres were pre-dried for 24 hrs at 60 ºC, then cut into a length of 25 cm and weighed to calculate the fibre volume fraction. To create a unidirectional composite, the fibres were placed in the mold cavity where a vacuum film was previously laid (see Figure 3.15(a) to (c)). After that, the resin was degassed and poured on top of the fibers. The vacuum film was then removed. The counter-mold is then put on top. The entire assembly is then placed inside a heated press for consolidation. Following curing, the samples are demoulded and ready for testing at 21 °C±2 °C, and 50% relative humidity.

Figure 3.15 depicts a modified version of the setup used by (Trujillo et al., 2014) and the samples were geometrically comparable. Because the mass of the fibres in the mold was precisely controlled, the fibre volume fraction can be controlled by imposing a precise specimen thickness with spacers, as shown in Figure 3.15(c). The width of the specimen was determined by the width of the mold. In this manner, unidirectional composite samples with small cross-sections were created, which typically results in a low number of defects and good control over the orientation of the fibres (Bensadoun et al., 2017; Delphine E C Depuydt, Sweygers, Appels, et al., 2019).

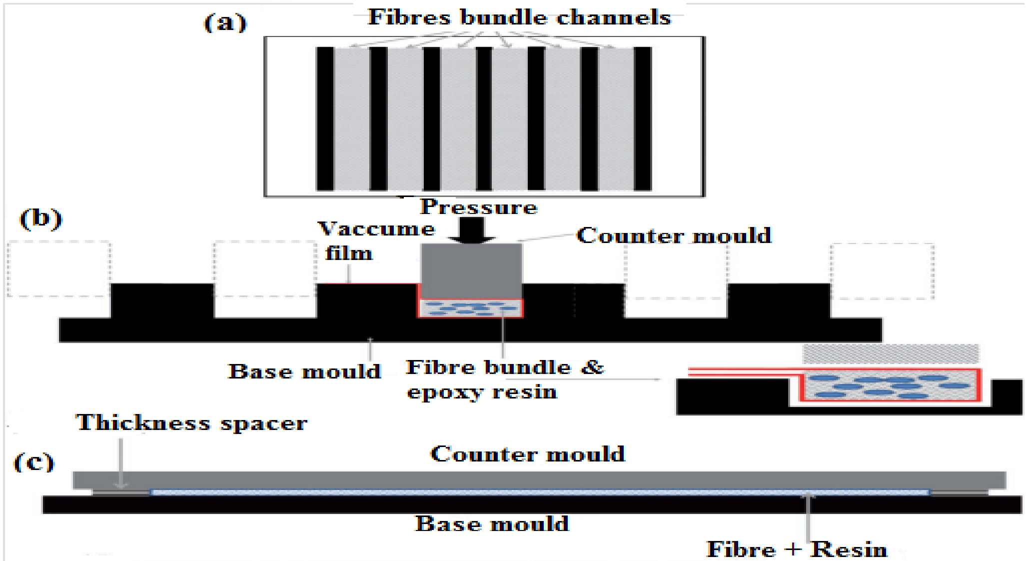


FIGURE 3. 15: Impregnated fibre bundle test (a) top view, (b) Front view, and (c) longitudinal cross-section view

3.8.2. Fibres volume fraction calculation

The calculation of the fibre volume fraction (Vf) was performed in the following way and according to the (Prapavesis et al., 2020) standard:

$$Vf = \frac{m_f/\rho_f}{V_C} \quad \text{(Eqn.3.20)}$$

where m_f is the mass of the fibres ($m_f = V_f * V_c * \rho_f$), V_C is the volume of the composite and ρ_f is the density of the fibres.

3.8. 3 Back-calculation of the fibre properties

Using the methodology developed for carbon fibers (ISO 10618:2004), the properties of the bamboo fibres as they were present and behave in a composite can be determined from the strength and stiffness of the impregnated fibre bundles. The fibre properties can be calculated backward from the measured composite properties of this impregnated fiber bundle using the following formulae, which were the inverted formulae of the well-known "rule of mixture" (Gibson, 2016; Bensadoun et al., 2017):

$$Ef = \frac{Ec - Em * (1 - Vf)}{Vf} \quad (Eqn. 3.21)$$

$$\sigma u,f = \frac{\sigma c - \sigma' m * (1 - Vf)}{Vf} \qquad (Eqn. 3.22)$$

where E_f is the longitudinal modulus of the fibre, Em is the modulus of the matrix and V_f is the fibre volume fraction, σ_f is the longitudinal strength of the fibre and σ'm the stress in the matrix at the failure strain, which can be calculated assuming linear elastic deformation of the matrix up to the moment of fibre (and hence composite) failure: $\sigma'_m = E_m * \varepsilon_{u,c}$. Eqn. (3.22) is valid only when the fibres fail first, meaning that they have a lower failure strain than the matrix. For this reason, the matrix needs to have sufficiently high ductility.

3.8.4. Resin preparation

The bamboo fibres were dried for at least 4 days at 60 °C before production and weighing. The epoxy and hardener resins are presented in Figure 3.16. As a matrix, Epikote 828 LVEL epoxy with a 1,2-diaminocyclohexane (Dytek DCH-99) hardener from Hexion was used as a substitute. The ratio of epoxy to hardener is 100:15.2. The mixed resin was degassed in the vacuum oven for 10 minutes. Curing was done at 75°C for 1 hour, followed by a subsequent post-curing of 1 hour at 150°C. Composites of 250 x 10 x 2 mm were made with a target volume fraction of 40% fibres, which was calculated based on the weight and measured density of the fibres. The neat resin system has a tensile strength of 70 MPa, a tensile stiffness of 2.7 GPa, and a strain-to-failure of 4.1% (Perremans et al., 2018).

FIGURE 3.16: Resin for composite manufacturing (a) Epoxy 828, (b) hardener

3.8.5 Resin degassing

The vacuum oven for degassing is presented in Figure 3.17. The resin and the hardener were mixed in proportions 100:15.2. Some air bubbles were found to be suspended in the solution. The solution was degassed under vacuum at 1 bar absolute, with a piece of 'Scotch–Brite' to act as a bubble nucleation agent. Bubble nucleation usually stopped after degassing for 15 minutes.

FIGURE 3.17: Vacuum thermo oven

3.9 Mechanical strength measurement

The testing procedure and machine setup of mechanical strength of bamboo fibres reinforced polymer composites are presented as follows:

3.9.1 Bamboo fibres reinforced epoxy composites (BFEPCs)

<u>Tensile strength measurement</u>

Tensile test samples were prepared and measured according to the standard ASTM D3039 (ASTM, 2014b). For the tests, an Instron model of 4467 machines with a load cell of 30 kN was used, and a crosshead speed of 2 mm/min. was applied. The gauge length between the two clamps was set at 150 mm, and an extensometer with a gauge length of 25 mm was employed for measuring accurately the elongation of the composites. The use of end tabs was not necessary because there was no failure close to the clamps, instead, the samples were mechanically clamped using sandpaper in the grips to prevent slippage. The tensile test setup is shown in Figure 3.18. All specimens were conditioned at room temperature (21°C± 2°C and 50±2% RH) for at least 24 hours before testing.

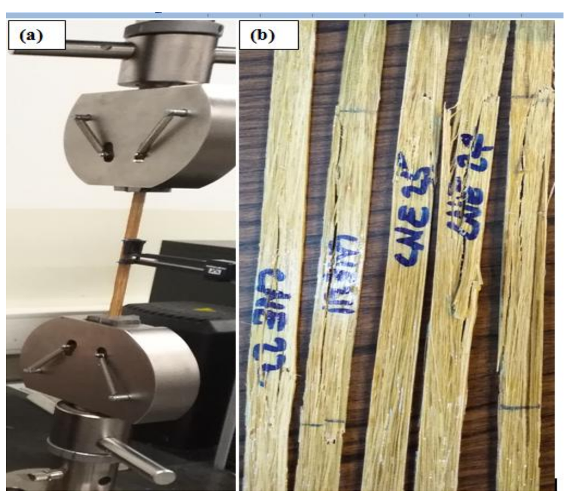


FIGURE 3.18: (a) Set-up of the tensile test machine, (b) Mode of failure

Flexural strength measurement

Flexural three-point bending tests (3PBT) were conducted in longitudinal fibre direction and performed on a universal testing machine an Instron model of 4426 according to ASTM (see Figure 3.19) (ASTM, 2015). The bending modulus of each sample was determined by calculating the slope of the stress-strain curve between 0.1 and 0.3% of the strain. The crosshead speed was set at 1mm/min, and a 1kN load cell was used during the test. The load and the flexural displacement were registered during the complete test. At least five samples were tested in each species, age, and season. sample dimensions of composites 60 x 10 x 2 mm were made with a target volume fraction of 40 % fibres, which was calculated based on the weight and measured density of the fibres.

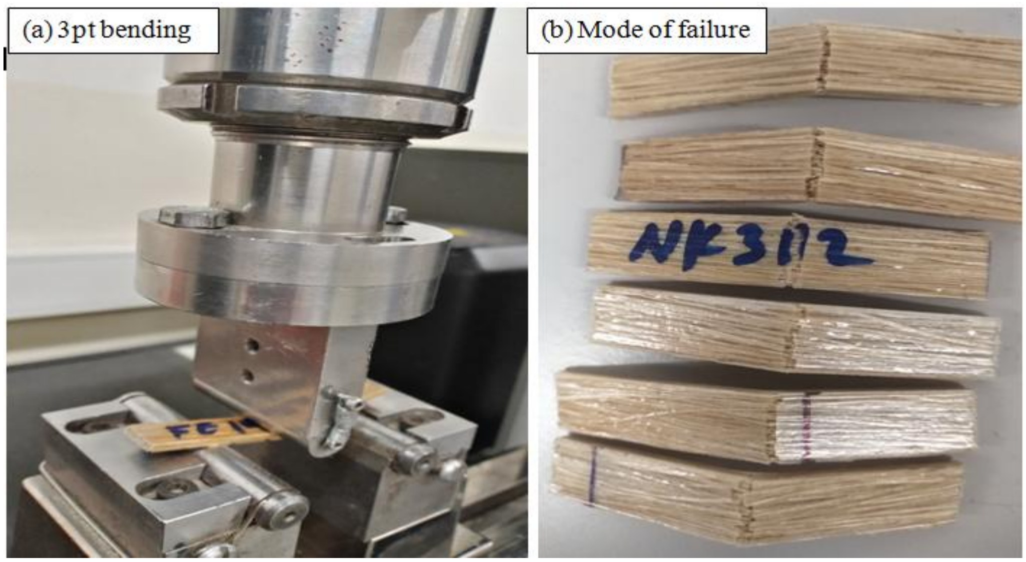


FIGURE 3.19: (a) Set-up for three-point bending test, (b) Mode of failure

Impact strength measurement

The pendulum continues to swing up after breaking the specimen to a height somewhat lower than that of a free swing. The energy lost by the pendulum was measured as the impact energy of the specimen. As shown in Table 3.4, samples were prepared and evaluated according to ISO 180 IZOD standards. The impact testing was tested in the flat-wise direction. Striking velocity, fall angle, and hammer weight were applied at 3.5 m/sec., 124.34 degrees and 1.84 kg respectively used during the test. Nine samples were prepared in the dimension of 4x10x80 mm for one setup during testing (ISO 179-1, 2010). The setup of the impact test is presented in Figure 3.20.

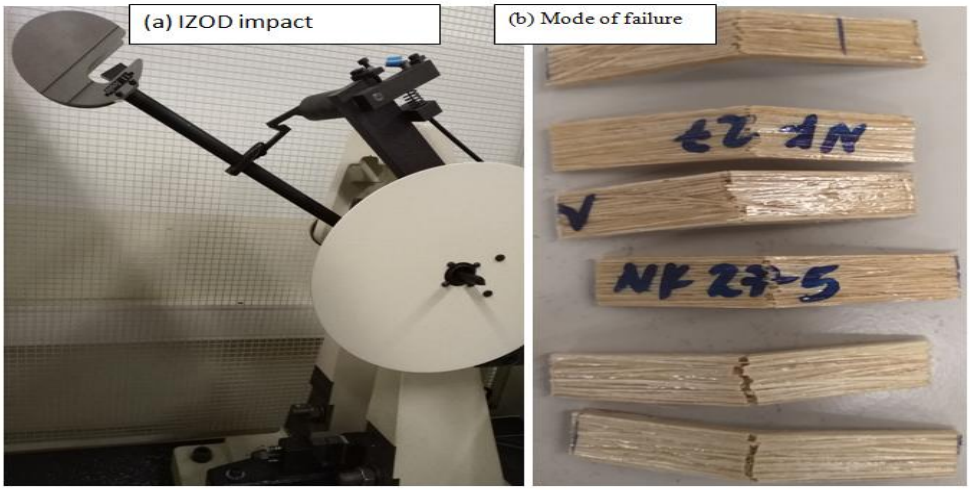


FIGURE 3.20: (a) Set up of Izod impact test, (b) Mode of failure

Table 3. 4: Standard methods of measuring unnotched Izod impact strength

Standard	ASTM D4812 ISO 180 (ISO 179-1, 2010)
Specimen	The sample dimension of composite 80x10x4 mm was prepared with a target volume fraction of 40 % fibres, which was calculated based on the weight and measured density of the fibres.
Conditioning	The bamboo fibres were dried for at least 4 days at 60°C before production and weighing. Curing was done at 75°C for 1 hour followed by a subsequent post-curing of 1 hour at 150°C. The testing room shall be conditioned at 23ºC±2ºC and 50 ± 5% R.H during testing.
Machine parameters	The Izod impact test measures the impact strength of a vertical cantilevered specimen hit by a swinging hammer. The Izod test exerts bending forces on the specimen and the absorbed energy is measured. Impact energy is expressed in [KJ/m2]. Impact testing was tested in the flatwise direction and striking velocity, fall angle, and hammer weight, were applied at 3.5 m/sec., 124.34 degrees and 1.84 kg respectively used during the test. The model of the impact machine is Q-Impact 5 impact testers

3.9.2 Bamboo fibres reinforced polypropylene composites (BFPPCs)

The mechanical strengths of BFPPCs were investigated using the ASTM standard. The composites' manufacturing and testing are presented in detail as follows.

Polypropylene (PP)

Polypropylene (PP) film with a density of 900 kg/m³ and 20 μm thickness was supplied by Propex GmbH (Germany). The shaping, melting and coefficient of thermal expansion is 115.7 ºC, 160.6ºC, and 62.7–73.2x10^{-6}/k respectively. The Young´s modulus, strength, and strain to failure are 1.6–1.8 GPa, 55–65 MPa, and >300%, respectively.

Preparation of bamboo fibre prepregs

For the preparation of bamboo fibre prepregs, special care was taken to accurately align and evenly distribute the fibres in a unidirectional (UD) array. The bamboo fibres were subsequently stabilized by mechanical clamping, as seen in Figure 3.21(a). Two layers of polypropylene film were attached to the fibres on both sides using a hot press as seen in Figures 3.21(b-c). The hot press adjusted a temperature of 170 °C, a compression pressure of 15 bar, and a waiting time of 10 seconds, enough time to pre-impregnate the bamboo technical fibres with the polymer (Figure 3.21 d). A Teflon® sheet was placed in between the polymer and the hot plate during this operation to avoid the adhesion of the film to the plate. The average areal density of the fibres used in the prepregs was 250 g/m^2 ± 20 g/m^2.

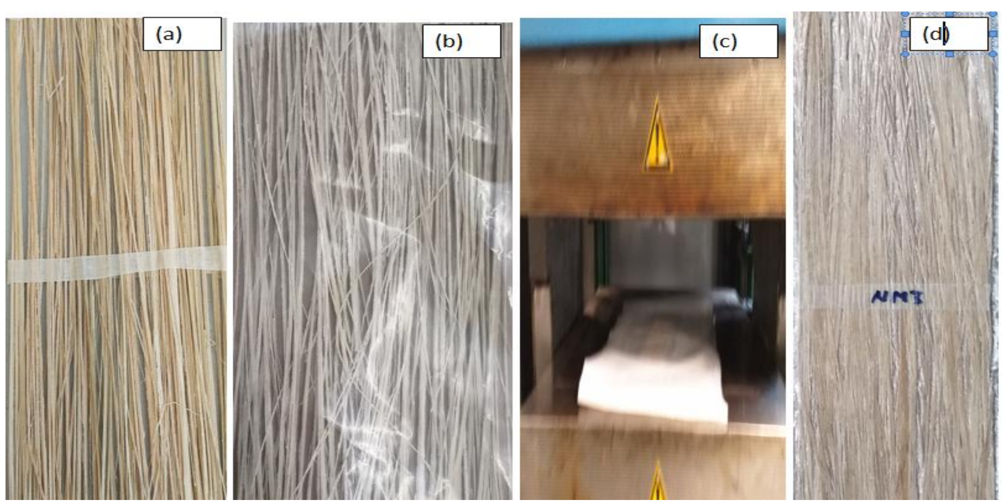


FIGURE 3. 21: Preparation of fibre prepregs with PP thermoplastic polymers (a) UD of fibres, (b) UD fibres with PP film, (c), hot press machine, (d) prepregs of BFPPCs

Composite preparation method of BFPPCs

The preparation of BFPPCs is presented in Figure 3.22 (a–e). The prepregs were dried in an oven at 65°C for at least 72 hrs and subsequently placed in a desiccator to avoid moisture absorption, before composite production.

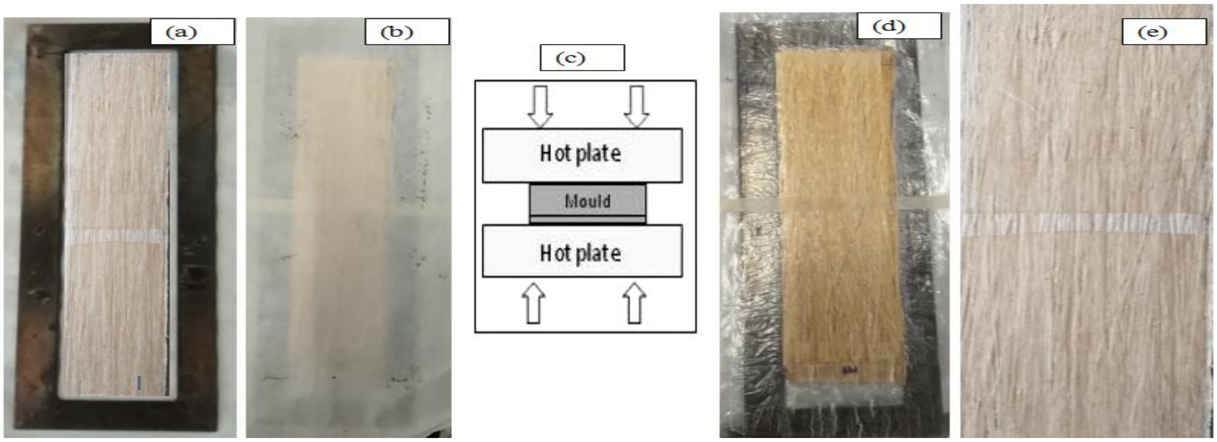


FIGURE 3.22: Preparation of BFPPCs: a) BFPP prepreg, b) the stacking sequence of prepregs and PP films to target 40% V_f, c) compression molding, and d), Produced composite sample.

Bamboo fibre with polypropylene (BFPP) was prepared by compression molding (Pinette hot press). Unidirectional bamboo prepregs (6 layers) and thermoplastic films of PP were intercalated and placed into a cavity mold of 250 x 60 mm Figure 3.22 (a) and (b). Fibre volume fraction (V_f) was targeted at 40% by weight measurements. The preheating and consolidation temperature of the Pinette hot press machine were adjusted to 165 ºC, and 180ºC respectively with a waiting time of 5 minutes and compression pressure of 20 bar.

<u>Sample preparation for testing</u>

After the production of the BFPP (25 x 6 cm), samples with average dimensions of 50, 14.4±0.2, and 1.85±0.1 mm, were cut using a low-speed bending saw machine (see Figure 3.23 (a-d). All specimens were kept at standard room conditions (21°C ± 2°C and 50 ± 2 %RH) for at least 24 hours before testing.

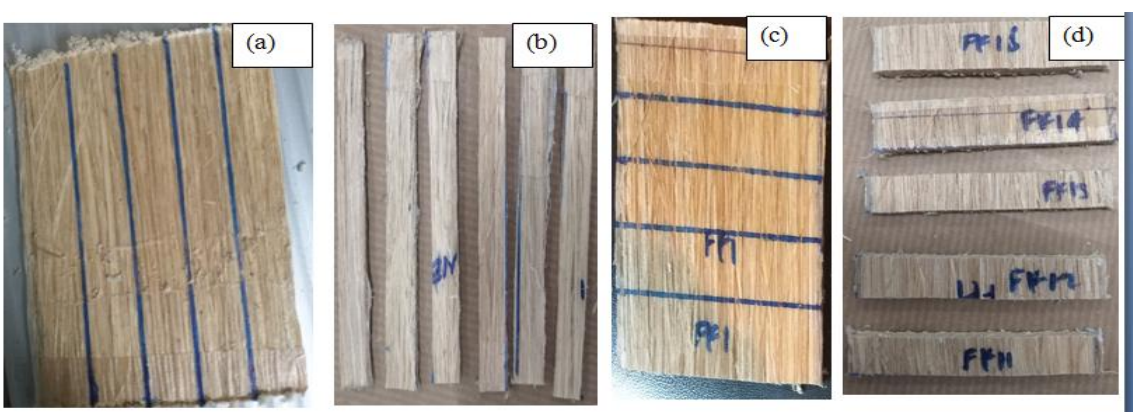


FIGURE 3. 23: three-point-bending test composite samples in the longitudinal direction (a & b), and transverse direction of the fibres (c & d).

The BFPPCs samples had 0° and 90° fibre orientation in Figure 3.23 (b) and (d) respectively, to evaluate longitudinal and transverse properties. The longitudinal disposition was evaluated to determine the flexural properties such as flexural strength and flexural stiffness. The transversal direction was carried out to estimate the interface strength between the polymer and the thermoplastic matrix. Young's modulus was calculated from the slope at the beginning of the stress-strain curve, between 0.1 and 0.3% of deformation.

Tensile strength measurement

The tensile strength testing procedures and setup of the machine are based on ASTM 3039 standards. The details of the work procedure and machine setup reports were presented in section 3.9.1

Flexural strength measurement

The tensile strength testing procedures and setup of the machine are based on ASTM 790 standards. The details of the work procedure and machine setup reports were presented in section 3.9.1

Impact strength measurement

The tensile strength testing procedures and setup of the machine are based on ASTM D4812 ISO 180 standards. The details of the work procedure and machine setup reports were presented in section 3.9.1

3.10 Statistical analysis

Experimental statistical analysis was done using Stat. software version 12. The results were tabulated and one-way ANOVA was employed to determine the significance of the difference among the mean values of the different groups. A Scheffes post-hoc test was applied to find the difference between the mean values in mechanical strength, chemical, and physical properties. Orginlab.95-64 was used for modeling different figures and analyzing the experimental results of XRD, TGA, and FTIR tests. Moreover, it analyzed the coefficient and R-square value of the properties of Ethiopian bamboo species in terms of the effect of age and harvesting months.

CHAPTER –4

CHARACTERIZATION AND MEASUREMENT OF PROPERTIES OF ETHIOPIAN BAMBOO SPECIES

Introduction

The current research study is to characterize and measure the properties of Ethiopian bamboo species using the factors of age and harvesting months. Not only the structural features, physical properties, chemical properties, single fibres strength, and mechanical properties of bamboo fibres epoxy and polypropylene composites are described in detail and briefly in this chapter, but also the fibres density, degree of crystallinity, fibres thermal properties and anatomical property are described in this chapter. Fiber-reinforced polymer composites are heterogeneous materials. They consist of reinforcing fibres embedded in a continuous matrix. While the fibres provide strength and stiffness to the composite, the matrix transmits externally applied loads to the fibres and protects the fibres from external damage.

4.1 Result and discussion on structural properties of bamboo

The three considered bamboo species with 1-3 years old culm show several different structural characteristics. The measured size of culm size, the number of internodes, culm outer diameter, culm internode length, and culm wall thickness are presented in Table 4.1. The range of culm outer diameter, culm Internode length, and culm wall thickness of Injibara is 36-51 mm, 35-40 cm, and 9-11 mm, respectively. The ages 1 and 2 years old Injibara has 29% and 10% lower culm diameter, moreover, 26% and 3% lower culm Internodal length than 3 years old, respectively, whereas 2 years old has 24% higher culm diameter and culm Internodal length than 1-year-old.

The range of culm outer diameter, culm Internode length, and culm wall thickness of Kombolcha is 78-120 mm, 27-36 cm, and 10-15 mm, respectively. Kombolcha in the ages of 1 and 2 years old has a 35% and 26% lower culm diameter, as well as, 25% and 11% lower culm Internodal length than 3 years old, respectively, whereas 2 years old have a 12% higher culm diameter and 13% higher culm Internodal length than 1-year-old. The culm outer diameter, culm Internode length, and culm wall thickness of Mekaneselam are 39-43 mm, 47-54 cm, and 8-11 mm, respectively.

The ages 1 and 2 years old Mekaneselam has 9% and 5% lower culm diameter, moreover, 13% and 6% lower culm Internodal length than 3-years-old respectively, whereas 2 years old has 5% higher culm diameter and 8% higher culm Internodal length than 1-year-old.

Kombolcha has 58% and 64% higher outer diameters than Injibara and Mekaneselam, respectively. Whereas Injibara bamboo has a 16% higher outer diameter than Mekaneselam. Moreover, Kombolcha and Injibara is 33% and 26% lower culm Internodal length than Mekaneselam, respectively. Whereas Injibara has a 10% higher culm Internodal length than Kombolcha. Furthermore, Kombolcha has a 26% higher culm wall thickness than Injibara and Mekaneselam.

Table 4. 1: Summary results of structural characteristics of bamboo culm in Ethiopia.

Structural Properties	Injibara bamboo			Kombolcha bamboo			Mekaneselam bamboo		
	Ages in year			Ages in year			Ages in year		
	1	2	3	1	2	3	1	2	3
Culm lenth (cm)	722	822	832	1029	1084	1234	8388	9370	9850
Number of internodes	18	21	26	32	35	39	20	23	28
Internode length (cm)									
Bottom	29	31	32	23	28	31	42	48	51
Middle	47	49	50	30	36	45	54	57	62
Top	28	37	38	27	31	32	46	47	48
Culm diameter (mm)									
Bottom	52	62	68	92	103	128	53	54	56
Middle	38	50	55	84	88	121	37	38	41
Top	17	27	29	59	76	111	27	30	31
Culm wall thickness (mm)									
Bottom	12	14	15	13	18	21	12	14	17
Middle	8	9	11	10	12	14	8	9	10
	6	7	8	8	9	11	5	6	7

Culm height, Diameter at breast height, and basal wall thickness of *P. nigra Boryana* (PNB) are 7.7±0.9 m, 3.8±0.1 cm, and 7.2±0.8 mm; *P. aureosulcata Spectabilis* (PAS) is 7.3±1.5 m, 3.9±0.2 cm, and 7.3±2 mm; *P. vivax* (PV) is 11.7±1.2 m, 7.4±0.8 cm, and 10.7±1.9 mm, and; *P. vivax McClure Jiantonging* (PVMJ) is 10.4±0.8 m, 6.2±0.3 cm and 10.8±0.4 mm, respectively. Injibara and Mekaneselam are higher culm height, outer diameter, and wall thickness compared to PNB and PAS, however, they are lower culm height, outer diameter, and wall thickness compared to PV and PVMJ. Whereas the structural characteristics of Kombolcha bamboo are higher culm height, outer diameter, and wall thickness compared to

PNB, PAS, PV, and PVMJ (Delphine E C Depuydt, Billington, Fuentes, et al., 2019). The average diameter, wall thickness, and Internodal length of *G. angustifoliais* are 5.9–11.5 cm, 0.9–1.8 cm, and 20–33 cm, respectively. Injibara and Mekaneselam are similar wall thickness, smaller culm outer diameter, and higher culm internodal length compared to *G. angustifoliais*. Whereas Kombolcha is a higher average diameter, and wall thickness compared to *G. angustifoliais*, but it has a similar culm Internodal length (E. Trujillo, 2014).

4.1.1 Culm internodal length

The culm Internodal length of Ethiopian bamboo species such as Injibara, Kombolcha, and Mekaneselam are presented in Figure 4.1. The Internodal length of Bamboo species is increased when the number of internodes increased up to the middle, then their Internodal length is decreased from the middle to the top position. The culm Internodal length of Injibara and Mekaneselam 100% satisfied the minimum requirement of internode length for fibre extraction. The minimum Internodal length for fibre extraction is settled above 25 cm culm Internodal length based on unidirectional continuous bamboo fibre composite production. Mekaneselam is a higher Internodal length compared to Injibara and Kombolcha, as well as, Injibara is a higher culm Internodal length compared to Kombolcha.

The ages 2 and 3 years old bamboo have similar culm internodal lengths, but their culm Internodal length is higher than 1-year-old. The culm Internodal length of PNB is 5.88%, 17.95%, and 20.00% lower than Injibara, and 31.91%, 37.25%, and 40.47% higher than Mekaneselam at the ages of 1, 2, and 3 years old, respectively. The culm Internodal length of PAS is 3.17%, 13.85%, and 16.00% lower than Injibara, and it is 29.01%, 33.69%, and 37.40% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively.

The culm Internodal length of PV is 9.74%, and 12.00%, lower than Injibara at the ages of 2, and 3 years old, and 25.63%, 30.53%, and 34.41% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively.

The culm Internodal length of PVMJ is 6.41%, and 8.75%, lower than Injibara at the ages of 2, and 3 years old, and 24.99%, 29.94%, and 33.86% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively. The culm Internodal length of PNB is 15.63% and 3.13% higher, whereas PAS is 20.83% and 5.65% higher, as well as, PV is 24.23% and 10.03% higher, moreover, PVMJ is 24.48% and 10.79 higher than Kombolcha at the ages of 1, 2, and 3 years old, respectively (Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

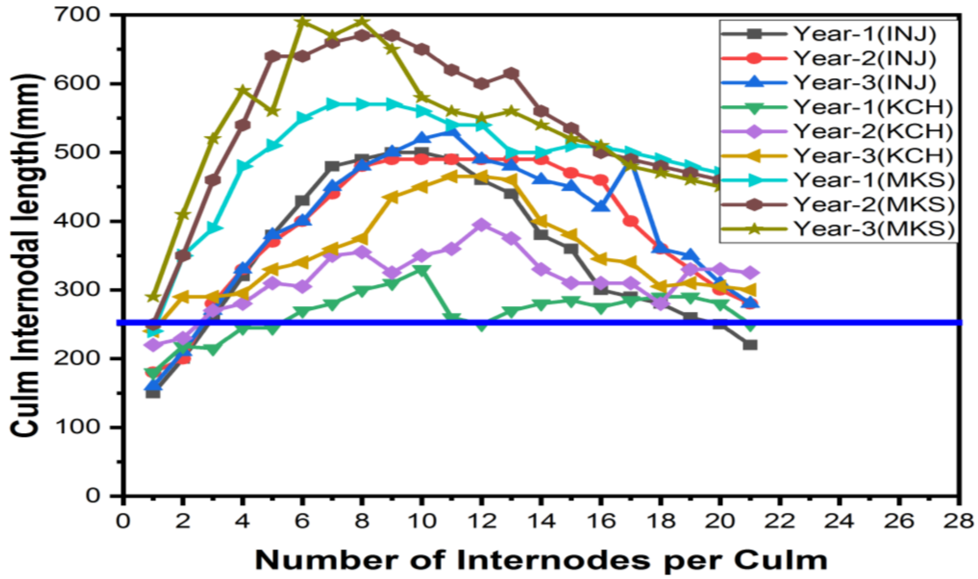


FIGURE 4.1: Internodal length variation along the bamboo culms in the function of the Internodes number, with the limit criterion for fibre extraction at 25 cm.

4.1.2 Culm outer diameter

The culm outer diameter of Ethiopian bamboo species such as Injibara, Kombolcha, and Mekaneselam are presented in Figure 4.2. The culm outer diameter of Bamboo species is decreased when moved from bottom to top along the culm height. The culm outer diameter of Kombolcha bamboo 100% satisfied the minimum requirement for fibre extraction when it determined the middle section of the culm.

Mekaneselam bamboo has a similar culm outer diameter for all ages years old and above 67% number of bamboo culm can satisfy the minimum criteria of a 3cm culm outer diameter. Above 81% number of the bamboo culm of Injibara bamboo have satisfied the minimum requirement of culm outer diameter. The minimum culm outer diameter for fibre extraction is settled above 3 cm culm outer diameter based on the required amount of fibre extraction. Kombolcha is the highest culm outer diameter compared to Injibara and Mekaneselam, as well as, Injibara bamboo is a higher culm outer diameter compared to Mekaneselam. The ages 2 and 3 years old of Injibara bamboo have similar culm outer diameter, but their culm outer diameter is higher compared to 1 year old.

The outer culm diameter of PNB is 22.24% and 29.01% lower than Injibara at the ages of 2 and 3 years old, and 54%, 67.17%, and 70% higher than Kombolcha, as well as 7.69%, 11.54%, and 15.69% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively. The outer culm diameter of PAS is 20.09% and 27.02% lower than Injibara at the ages of 2 and 3 years old, and 52.75%, 58.43%, and 69.17% lower than Kombolcha, as well as 5.13%, 9.09%, and 13.35% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively. The outer culm diameter of PV is 37.37%, 18.77%, and 12.65% higher than Injibara and 31.58%, 28.59%, and 25.09% higher than Mekaneselam at the ages of 1, 2, and 3 years old, respectively. However, the outer culm diameter of Kombolcha is 27.2%, 35.96%, and 52.5% higher than PV at the ages of 1, 2, and 3 years old, respectively. The outer culm diameter of PVMJ is 30.19%, 9.22%, and 0.59% higher than Injibara and 23.53%, 20.19%, and 16.17% higher than Mekaneselam at the ages of 1, 2, and 3 years old respectively. However, the outer culm diameter of Kombolcha is 34.84%, 42.69%, and 57.5% higher than PV at the ages of 1, 2, and 3 years old, respectively (Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

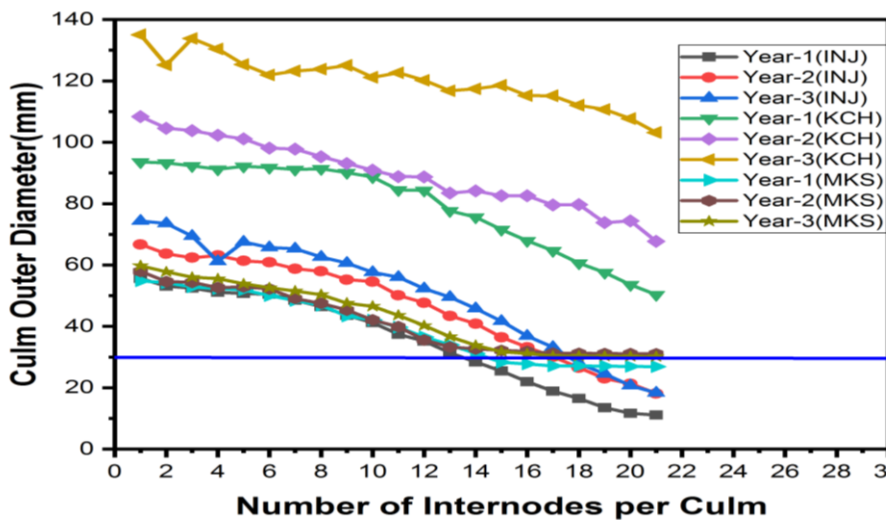


FIGURE 4. 2: Internodal outer diameter variation along the bamboo culms in the function of the Internode number, with the limit criterion on the outer diameter of 3 cm.

4.1.3 Culm wall thickness

The culm wall thickness of Ethiopian bamboo species such as Injibara, Kombolcha, and Mekaneselam are presented in Figure 4.3. The culm wall thickness of bamboo species is decreased when moving from bottom to top along the culm height. For ages, 3 years old Kombolcha bamboo is a higher culm wall thickness compared to ages 1 and 2 years old.

Mekaneselam and Injibara have a similar culm wall thickness in all ages of bamboo culm, but Kombolcha bamboo has a higher culm wall thickness compared to Mekaneselam and Injibara bamboo. The culm wall thickness of PV and PVMJ is 19.72% and 7.4% higher than Injibara, and 22.87% and 10.46% higher than Mekaneselam at the ages of 1 and 2 years old, respectively. However, it is 4.68% lower than Injibara and Mekaneselam at the ages of 3 years old, respectively. The culm wall thickness of Kombolcha is 16.92% and 29.55% higher than PV and PVMJ at the ages of 2 and 3 years old, respectively. However, the outer culm wall thickness of PV and PVMJ is 4.35% higher than Kombolcha PV at the ages of 1 and 2 years old, respectively. The culm wall thickness of PNB and PAS is 16.96%, 28%, and 36.45% lower than Injibara and 30.3%, 44.62%, and 53.03% lower than Kombolcha, as well as 13.57%, 25.54%, and 36.45% lower than Mekaneselam at the ages of 1, 2, and 3 years old, respectively (Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

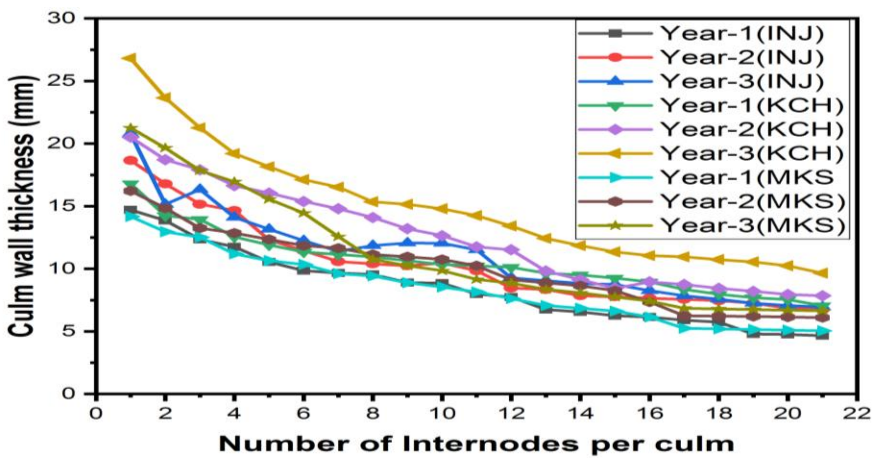


FIGURE 4.3: Culm wall thickness variation along the bamboo culms in the function of the internode number.

In general, the culm Internodal length, outer diameter, and wall thickness of Ethiopian bamboo species such as Injibara, Kombolcha, and Mekaneselam are presented in Figures 4.1, 4.2, and 4.3, respectively. Mekaneselam has a higher culm Internodal length compared to Kombolcha and Injibara bamboo, however, it has a lower outer diameter and wall thickness compared to them. Kombolcha has a higher culm outer diameter compared to Injibara and Mekaneselam bamboo, but it has the lowest culm Internodal length compared to them. The structural characteristics of Ethiopian bamboo species are the fittest for bamboo fibre composite production since they are fulfilled the minimum requirement of culm Internodal length and outer diameter.

4.1.4 Structural statistical modeling

The coefficient of the linear fit for the culm outer diameter and wall thickness versus the number of Internodes are presented in Table 4.2. The slope of the culm outer diameter and wall thickness are a negative relationship with the number of internodes. Injibara has a higher negative slope compared to Kombolcha and Mekaneselam, however, it has the lowest intercept value. Kombolcha has a higher intercept value both in culm outer diameter and culm wall thickness compared to Injibara and Mekaneselam. The R-square of the culm outer diameter for Injibara, Kombolcha, and Mekaneselam are 94–97%, 88–98%, and 92-95%, whereas the R-square of the culm wall thickness for Injibara, Kombolcha, and Mekaneselam are 84–94%, 88–94%, and 86-96%, respectively. R-square of the culm outer diameter has a good linear fit compared to the culm wall thickness.

Table 4. 2: Coefficients of the linear fit: (a) Culm outer diameter (mm) = a*number of Internodes (N) + b, and (b) Culm wall thickness (mm) = a*number of Internodes (N) + b.

.Bamboo species	Ages (Yr)	(a) Linear fit for Outer diameter versus number of Internodes				(b) Linear fit for wall thickness versus number of Internodes			
		Coefficients		R - square	Adj. R-square	Coefficients		R - square	Adj.R-square
		a	b			a	b		
Injibara	1	62.38	-2.45	0.97	0.97	13.57	-0.47	0.95	0.94
	2	74.09	-2.51	0.95	0.95	15.94	-0.51	0.85	0.84
	3	81.42	-2.79	0.94	0.94	16.88	-0.53	0.86	0.85
Kombolcha	1	103.9	-2.24	0.89	0.88	14.59	-0.37	0.91	0.89
	2	109.6	-1.82	0.98	0.98	19.32	-0.63	0.94	0.94
	3	133.7	-1.22	0.88	0.88	22.82	-0.71	0.87	0.88
Mekaneselam	1	58.35	-1.71	0.95	0.95	13.27	-0.44	0.96	0.96
	2	58.42	-1.55	0.92	0.92	15.23	-0.48	0.96	0.96
	3	61.89	-1.73	0.95	0.95	18.81	-0.71	0.87	0.86

4.1.5 Characteristics of fibres properties

Characteristics of anatomical properties of fibres

The optical microstructure of the Injibara, Kombolcha, and Mekaneselam bamboo are presented in Figures (4.4–4.6). Vascular bundles of the bamboo fibre are very dense on the outer and more sparse on the inner surface in all bamboo species. Injibara and Kombolcha bamboo have the same vascular bundle structure. Based on the classification of four basic types of vascular bundles by (Watson et al., 1985), the considered species can be assigned as follows: Injibara and Kombolcha bamboo consist of vascular bundles of type I and Mekaneselam bamboo out of vascular bundles of type III, see Figure (4.4–4.6).

All the samples were prepared in the same way, and no reason for this difference is known to the authors. Therefore it is assumed a similar preparation of characteristics of this species. The effect of ages and bamboo species on the microstructure are presented in Figures (4.4–4.7). The microstructure of the bamboo species observed that the fibre strand possesses lower contrast with the matrix. This is because the fibres are less mature, having a larger lumen and resembling more the open structure of the parenchyma (Sánchez & Rodríguez, 2018).

When the bamboo matures, the microstructure image of the vascular bundle formed more dense fibre bundles in the regions. The microstructure image of the bamboo species is more open space when the ages of the bamboo decrease.

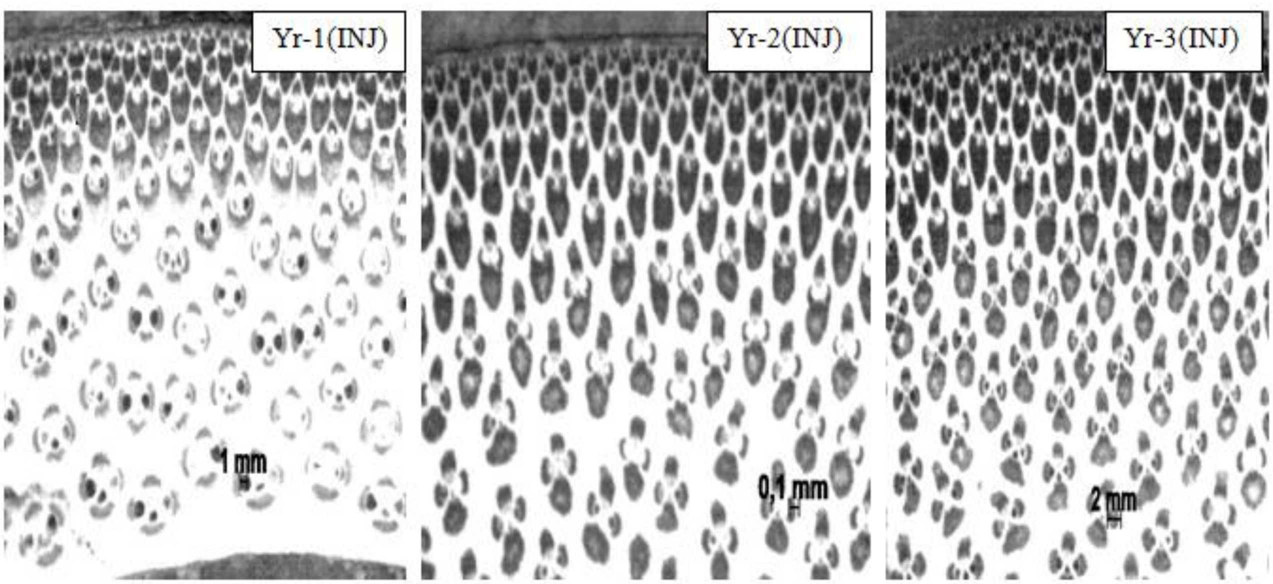


FIGURE 4.4: Microstructure of Injibara bamboo from ages of 1-3 years old

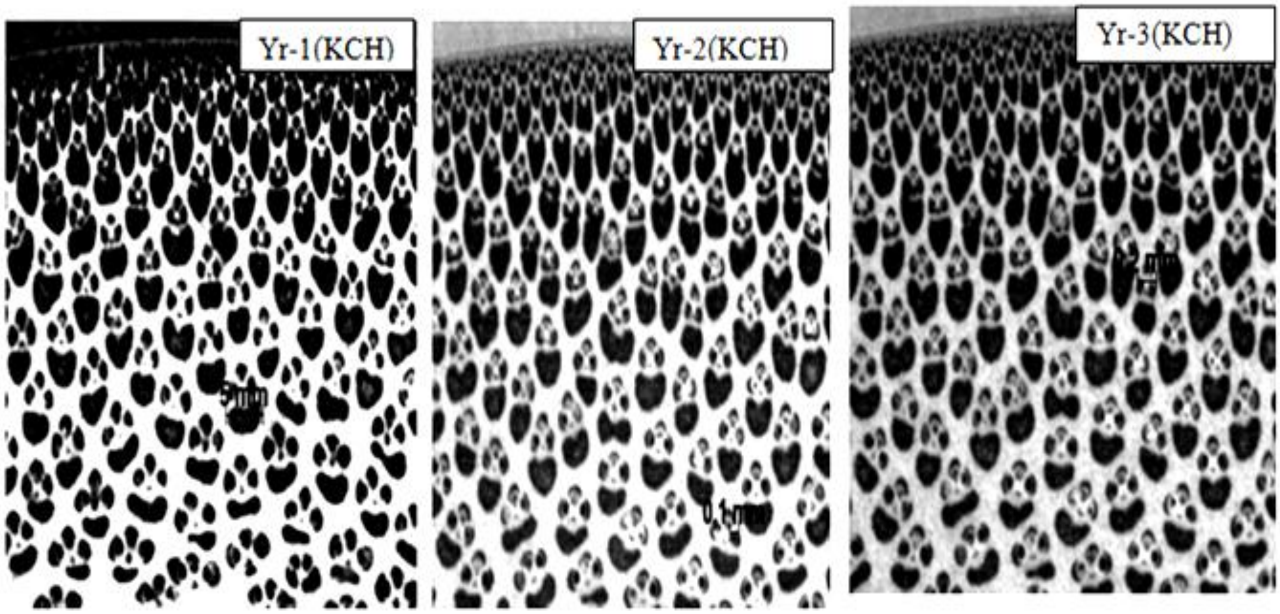


FIGURE 4.5: Microstructure of Kombolcha bamboo from ages of 1-3 years old

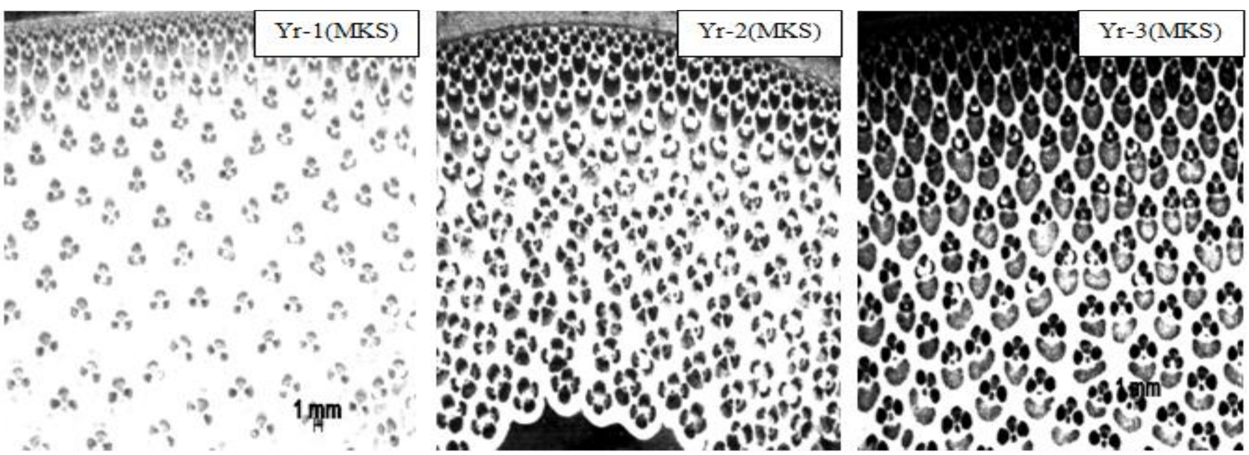


FIGURE 4.6: Microstructure of Mekaneselam bamboo from ages of 1-3 years old

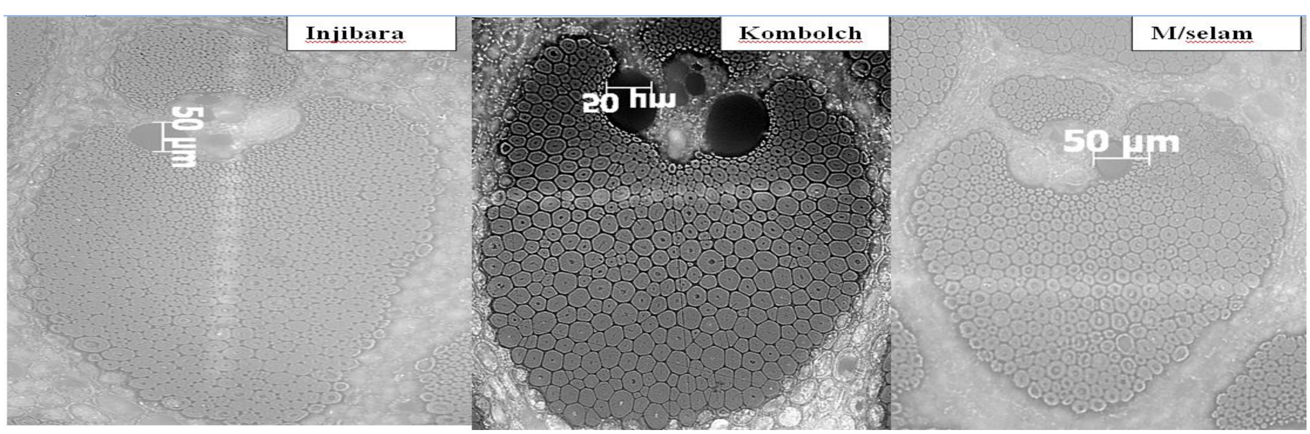


FIGURE 4.7: Vascular bundles of (a) Injibara (b) Kombolcha (c) Mekaneselam bamboo

Characteristics of fibres density

The densities of the Ethiopian bamboo species fibre with the effect of the ages are presented in Table 4.3. The range of the measured fibre densities (ρf) for Injibara, Kombolcha, and Mekaneselam bamboo have 1.35–1.38g/cm³, 1.35–1.36g/cm³, and 1.34–1.36 g/cm³ respectively. The densities of Ethiopian bamboo fibres have low density compared to other bamboo species so it is the best for the low-weight application area of composite materials.

The ages of 1-year-old bamboo fibres have a low density compared to 2 and 3 years old. The difference between the three bamboo species is considered low (maximum 2%). The fibres densities of GAK and DMM are 4.25%, 2.12%, and 3.55 higher than Injibara, and 4.25%, 3.55%, and 3.55% higher than Kombolcha, as well as 4.96%, 3.55%, and 3.55% higher than Mekaneselam bamboo at the ages of 1, 2, and 3 years old, respectively.

The fibres density of PNB is 2.17 %, 0.00%, and 1.45 % higher than Injibara, and 2.17%, 1.45%, and 1.45% higher than Kombolcha, as well as 2.89%, 1.45%, and 1.45% higher than Mekaneselam bamboo at the ages of 1, 2, and 3 years old, respectively. The fibres density of PAS is 5.59 %, 3.49%, and 4.89% higher than Injibara, and 5.59%, 4.89%, and 4.89% higher than Kombolcha, as well as 6.29%, 4.89%, and 4.89% higher than Mekaneselam bamboo at the ages of 1, 2, and 3 years old, respectively.

The fibres density of PV is 6.29 %, 4.19%, and 5.59% higher than Injibara, and 6.29%, 5.59%, and 5.59% higher than Kombolcha, as well as 6.99%, 5.59%, and 5.59% higher than Mekaneselam bamboo at the ages of 1, 2, and 3 years old, respectively. The fibres density of PVMJ is 8.16 %, 6.12%, and 7.48 % higher than Injibara, and 8.16%, 7.48%, and 7.48% higher than Kombolcha, as well as 8.84%, 7.48%, and 7.48% higher than Mekaneselam bamboo at the ages of 1, 2, and 3 years old, respectively (Delphine E C Depuydt, Billington, Fuentes, et al., 2019).

Table 4. 3: The density of the Ethiopian bamboo species.

Bamboo species	Ages(Yrs)	ρf(g/cm³)	Refe.
Injibara	1	1.35±0.004	Study
	2	1.38±0.003	Study
	3	1.36±0.004	Study
Kombolcha	1	1.35±0.003	Study
	2	1.36±0.001	Study
	3	1.36±0.004	Study
Mekaneselam	1	1.34±0.003	Study
	2	1.36±0.003	Study
	3	1.36±0.005	Study
GAK	(1-3)	1.41±0.03	(Delphine E C Depuydt, Sweygers, Appels, et al., 2019)
DMM	(1&3)	1.41±0.02	(Delphine E C Depuydt, Sweygers, Appels, et al., 2019)
PNB	(2-4)	1.38±0.01	(Delphine E C Depuydt, Sweygers, Appels, et al., 2019)
PAS	—	1.43±0.02	(Delphine E C Depuydt, Billington, Fuentes, et al., 2019)
PV	—	1.44±0.03	(Delphine E C Depuydt, Billington, Fuentes, et al., 2019)
PVMJ	—	1.47±0.01	(Delphine E C Depuydt, Billington, Fuentes, et al., 2019)

Degree of crystallinity

The effect of age on the percentage of the degree of crystallinity of the bamboo species is presented in Table 4.4. The ages of 2 years old of Injibara, Kombolcha, and Mekaneselam bamboo have a higher degree of crystallinity compared to 1 and 3 years old, but it's the measured-low degree of crystallinity at the age of 1 year old. The highest value of the degree of crystallinity of Injibara, Kombolcha, and Mekaneselam have measured at 5%, 12%, and 3% higher than the lowest, respectively. The degree of crystallinity of Injibara bamboo have measured 10%, and 7% higher than Kombolcha and Mekaneselam, respectively. Whereas the degree of crystallinity of Mekaneselam bamboo measured 3% higher than Kombolcha.

Injibara, Mekaneselam, and Kombolcha bamboo are listed from the highest to the lowest value of the degree of crystallinity, respectively. Ethiopian bamboo species is a higher degree of crystallinity compared to *Neosinocalamus affinis* of (55%) (Nishiyama et al., 2003). The degree of crystallinity of Injibara, Kombolcha, and Mekaneselam bamboo fibres at the ages of 1– 3 years are 69–73%, 58–66%, and 66–68%, respectively.

Table 4. 4: Measurement of degree of crystallinity of Ethiopian bamboo species

	Injibara			Kombolcha			M/selam		
	Ages (Yrs)			Ages (Yrs)			Ages (Yrs)		
Crystalinity (%)	1	2	3	1	2	3	1	2	3
Degree of crystallinity	69	73	72	58	66	62	66	68	67
Amorphous	31	27	28	42	34	38	34	32	33

Injibara bamboo fibres

The effect of age on the degree of crystallinity of Injibara bamboo fibres is presented in Figure 4.8. The age of 2 years old of bamboo fibres has high intensity of transmission and degree of crystallinity compared to 1 and 3 years old, whereas the age of 1-year-old of bamboo fibre is the lowest intensity of transmission and degree of crystallinity. The degree of crystallinity and amorphousness of Injibara bamboo fibres at 2θ is 21.82 and 15.76 respectively. However Injibara bamboo has some silicon content at 2θ of 34.94. The degree of crystallinity of Injibara bamboo fibres at the ages of 1, 2, and 3 years has 20%, 25%, and 24% higher than *Neosinocalamus affinis* of (55%) (Nishiyama et al., 2003) and 22%, 26%, and 25% higher than Moso bamboo fibres (53.7%) (Chen et al., 2015), moreover, 7%, 12%, and 10% higher than bamboo pulp fibres (64.3%), respectively(Wei et al., 2016).

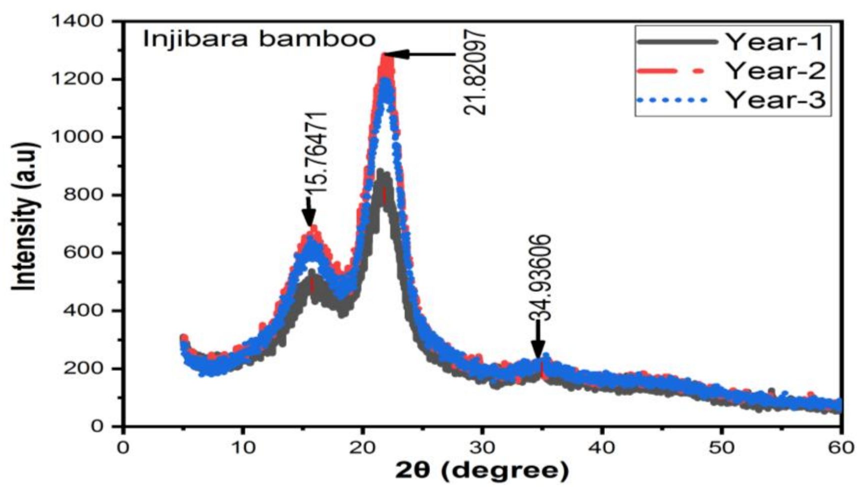


FIGURE 4.8: Degree of crystallinity of Injibara bamboo fibres

Kombolcha bamboo fibre

The effect of age on the degree of crystallinity of Kombolcha bamboo fibre is presented in Figure 4.9. The age of 2-year-old of bamboo fibres has high intensity of transmission and degree of crystallinity compared to 1 and 3 years old, whereas the age of 1-year-old of bamboo fibre is the lowest intensity of transmission and degree of crystallinity. The crystallinity and amorphous of Kombolcha bamboo fibres at 2θ are 21.94 and 15.46 respectively. However, Kombolcha bamboo fibre has some silicon content at 2θ of 35.26. The degree of crystallinity of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years has 5%, 17%, and 11% higher than *Neosinocalamus affinis* of (55%) (Nishiyama et al., 2003) and 7%, 19%, and 13% higher than Moso bamboo fibres (53.7%) (Chen et al., 2015), moreover, Kombolcha bamboo fibres at the ages of 1 and 3 years has 10% and 4% higher than bamboo pulp fibres, respectively, Moreover, Kombolcha bamboo fibres at the age of 2 years has 3% higher than bamboo pulp fibres, respectively. However, Kombolcha bamboo fibres at the ages of 1 and 3 years have 10% and 4% lower than bamboo pulp fibres (Wei et al., 2016).

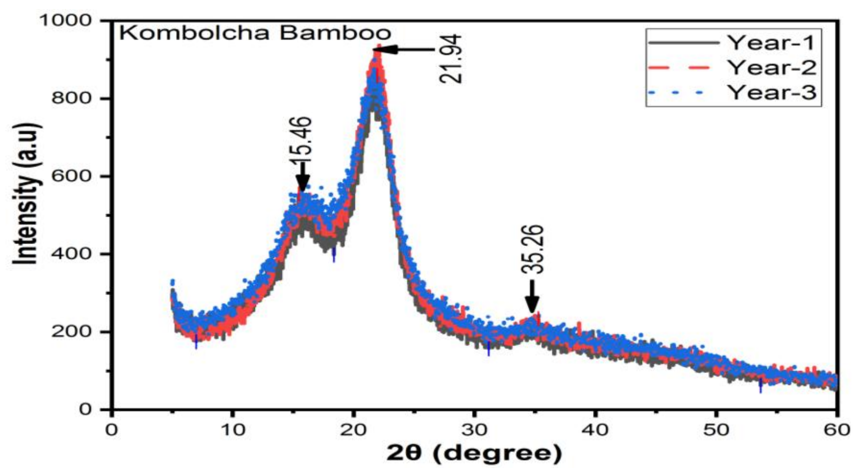


FIGURE 4.9: Degree of crystallinity of Kombolcha bamboo fibres

Mekaneselam bamboo fibre

The effect of age on the degree of crystallinity of Mekaneselam bamboo fibre is presented in Figure 4.10. Age of 2 years old bamboo fibres has high intensity of transmission and degree of crystallinity compared to 1 and 3 years old, whereas the age of 1 and 3 years old bamboo fibre has a similar intensity of transmission and degree of crystallinity. The degree of crystallinity and amorphous of Mekaneselam bamboo fibres at 2θ are 21.6 and 15.04 respectively. However, Mekaneselam bamboo fibre has some silicon content at 2θ of 34.7. The degree of crystallinity of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years has 17%, 19%, and 18% higher than *Neosinocalamus affinis* of (55%) (Nishiyama et al., 2003) and 19%, 21%, and 20% higher than Moso bamboo fibres (53.7%) (Chen et al., 2015), moreover, 3%, 5%, and 4% higher than bamboo pulp fibres (64.3%), respectively (Wei et al., 2016).

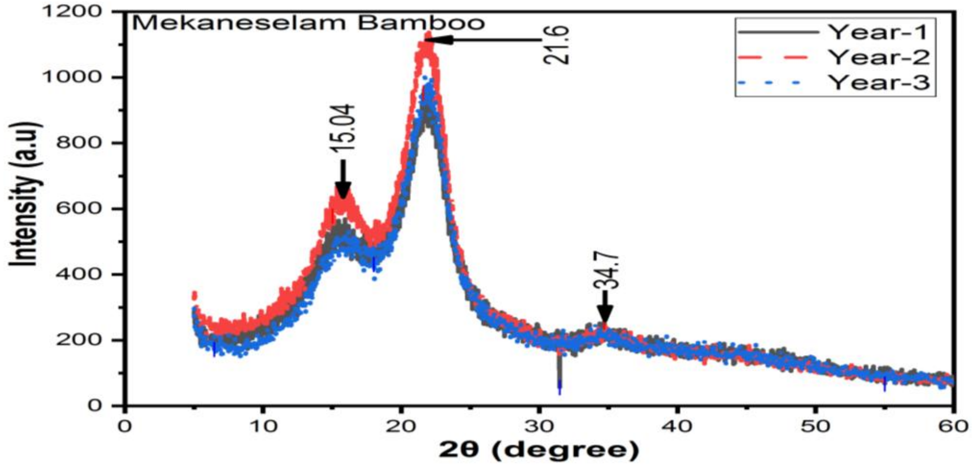


FIGURE 4.10: Degree of crystallinity of Mekaneselam bamboo fibres

Characteristics of the functional group of the fibres

Injibara bamboo fibres

The FTIR characterization of Injibara bamboo fibres on the effect of ages is presented in Figure 4.11 and Table 4.5. As a result, the band associated with the C–O ring of lignin at 1245–1268 cm–1 declined, as well as the band at 1740cm^{-1} associated with carboxylic groups present in pectins and hemicellulose almost disappears. Other significant changes include the reduction of peaks between 3200 and 3600cm^{-1}, which correspond to the reduction of some hydroxyl groups associated with the vibration modes of chemical substances such as carbohydrates and fatty acids found in fibers. The age of 3 years old of Injibara bamboo fibres has a high percentage of transmittance compared to ages 1 and 2 years old, whereas ages 1 and 2 years old are a similar percentage of transmittance. Cellulose, hemicelluloses, and lignin content of Injibara bamboo fibres are found in the different functional groups at the ages of 1-3 years old.

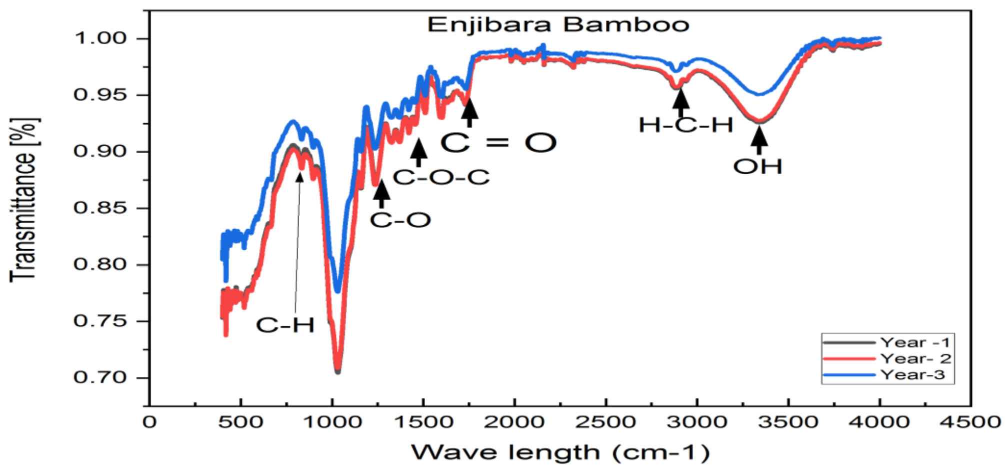


FIGURE 4.11: FTIR results for the obtained chemical structure of Injibara bamboo fibres

Kombolcha bamboo fibres

The effect of age on the chemical structure of Kombolcha bamboo fibres is presented in Figure 4.12 and Table 4.5. Infrared spectroscopy using the Fourier Transform is performed. Cellulose, hemicelluloses, and lignin of bamboo fibres are among the samples examined. The FTIR allows for identifying the chemical structure to characterize it. Each sample contains functional groups. The age of 3 years old has a high percentage of transmittance compared to the ages of 1 and 2 years old, whereas the percentage of transmittance in the ages of 1 and 2 years old is a similar functional group. Cellulose, hemicelluloses, and lignin content of Kombolcha bamboo fibres are found in different functional groups at the ages of 1-3 years old.

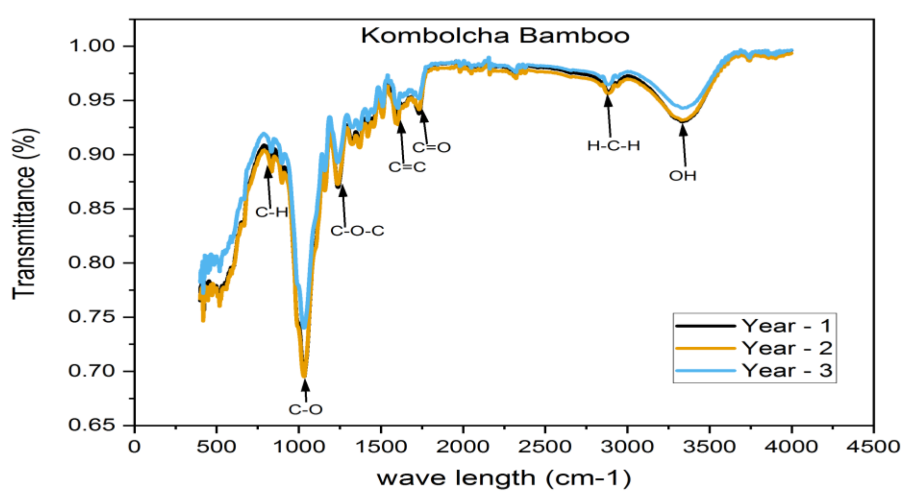


FIGURE 4.12: FTIR results for the obtained chemical structure of Kombolcha fibres

Mekaneselam bamboo fibres

The effect of age on the chemical structure of Mekaneselam bamboo fibres is presented in Figure 4.13 and Table 4.5. Infrared spectroscopy using the Fourier Transform is performed. Cellulose, hemicelluloses, and lignin contents of Mekaneselam bamboo fibres are among the samples examined. The FTIR allows for identifying the chemical structure to characterize it. Each sample contains functional groups. The age of 1-year-old of Mekaneselam bamboo fibres has a high percentage of transmittance compared to ages 2 and 3 years old, whereas the age of 2 years old is the smallest percentage of transmittance. Cellulose, hemicelluloses, and lignin contents of Mekaneselam bamboo fibres are found in different functional groups at the ages of 1–3 years old.

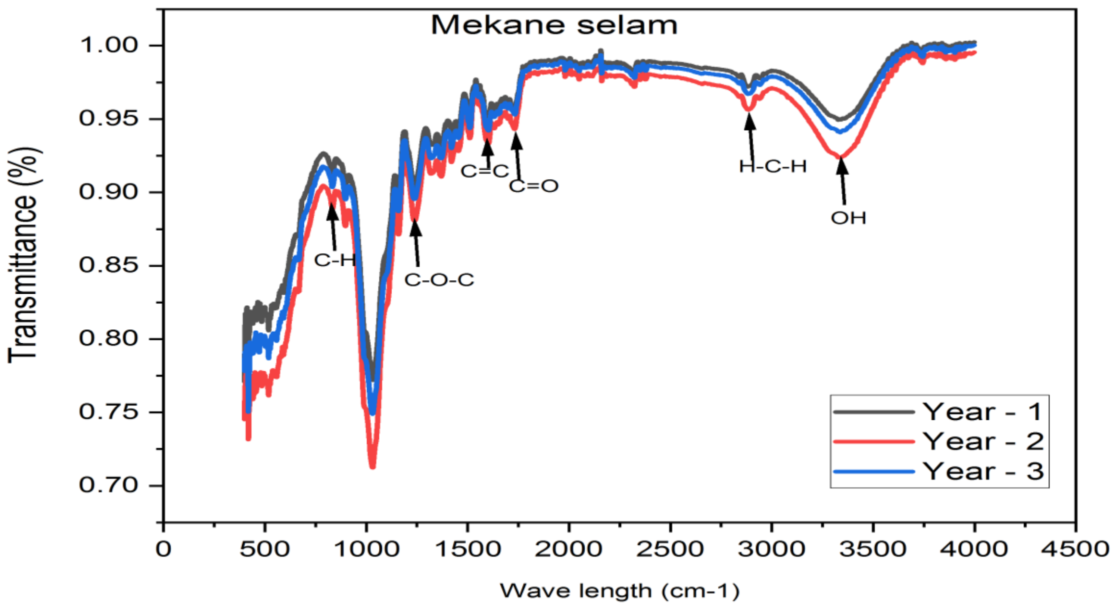


FIGURE 4.13: FTIR results for obtained chemical structure of Mekaneselam bamboo fibres

Table 4. 5: Absorption bands for functional groups of cellulose, hemicelluloses, and lignin contents (Morán et al., 2008).

Fiber components	Wave number (cm-1)	Functional group	Compounds
Cellulose	4,000–2,995	OH	Acid, methanol
	2,890	H–C–H	Alkyl, aliphatic
	1,640	Fiber–OH	Adsorbed water
	1,270–1,232	C–O–C	Aryl-alkyl ether
	1,170–1,082	C–O–C	Pyranose ring skeletal
	1,108	OH	C–OH
Hemicellulose	4,000–2,995	OH	Acid, methanol
	2,890	H–C–H	Alkyl, aliphatic
	1,765–1,715	C=O	Ketone and carbonyl
	1,108	OH	C–OH
Lginin	4,000–2,995	OH	Acid, methanol
	2,890	H–C–H	Alkyl, aliphatic
	1,730–1,700		Aromatics
	1,632	C=C	Benzene stretching ring
	1,613, 1,450	C=C	Aromatics skeletal mode
	1,430	O–CH3	Methoxyl–O–CH3
	1,270–1,232	C–O–C	Aryl-alkyl ether
	1,215	C–O	Phenol
	1,108	OH	C–OH
	700–900	C–H	Aromatic hydrogen

Characteristics of thermal properties of the fibres

As presented in Table 4.6, the thermogravimetric analyses (TG) and derivatives (DTG) curves under argon atmospheres for Ethiopian bamboo fibers. At temperatures below 105ºC, all samples show a progressive loss of mass, which is associated with the release of water. In the DTG curves, the decomposition of lignocellulosic compounds (hemicellulose, cellulose, and lignin) for all bamboo fibers confirmed only one distinct peak (Júnior et al., 2015).

As presented in Table 4.6, the first stage, second stage, third stage, and fourth stage of thermal decomposition of bamboo fibres indicate the moisture release, hemicelluloses, cellulose, and lignin decomposition of temperature, respectively.

Ages of 3 years old of Kombolcha bamboo have higher hemicellulose, cellulose, and lignin decomposition temperature compared to the ages 1 and 2 years old, whereas ages 1 and 2 years old have a similar decomposition of temperature. Furthermore, the age of 2 years old of Mekaneselam bamboo fibre has slightly higher hemicelluloses, cellulose, and lignin decomposition temperature compared to the ages 1 and 3 years old, whereas ages 1 and 3 years old have a similar decomposition of temperatures. At temperatures ranging from 10 ºC to 105 ºC, mass losses of 3.47–6.6%, 3.24–4.3%, and 3.47–5.21% were observed in Ethiopian bamboo species of Injibara, Kombolcha, and Mekaneselam bamboo fibres, respectively. The current results of moisture evaporation in Ethiopian bamboo fibres are similar compared to the values found in literature in the range between 3 and 7%.(Yang et al., 2010; Sebestyén et al., 2011).

The hemicellulose, cellulose, and lignin degradation temperature of Injibara bamboo fibre is 260-306 ºC, 319-328 ºC, and 390-410 ºC, whereas Kombolcha bamboo fibre is 273-285 ºC, 322-332 ºC, and 415-425 ºC, and Mekaneselam bamboo fibre is 283 ºC, 329-330 ºC, and 424 ºC respectively. The decomposition temperature of hemicellulose for Injibara bamboo fibres is higher than 7% and 8% of Kombolcha and Mekaneselam bamboo fibres, respectively. Whereas the decomposition temperature of cellulose for Kombolcha bamboo fibres is 3% and 2% higher than Injibara and Mekaneselam bamboo fibres, respectively.

In an inert environment, the degradation temperatures of hemicelluloses and celluloses for *G. angostfilo* were 288°C and 340°C, respectively, thus it is similar to the current studies of Ethiopian bamboo fibres. The decomposition temperature of hemicelluloses for natural fibres is 234–297°C (E. Trujiloo, 2014). The hemicelluloses are degraded at lower temperatures compared to celluloses and lignin due to their short molecular structure and low molecular weight (Azis et al., 2020).

At temperatures between 100 and 297 °C, some of the changes in the physical properties of the fibres can be explained in terms of alterations in either physical or chemical structures such as depolymerization, hydrolysis, dehydration, decarboxylation, and recrystallization. Aside from that, the formation of free radicals has been observed (Wei et al., 2016). In general, the contribution of hemicelluloses and cellulose to thermal degradation is much larger and significantly greater. In general, distinct peaks were realized in the literature, depending on the type of natural fiber treated (Yang et al., 2010).

Table 4. 6: Parameters obtained from TG/DTG curves of bamboo fibers at argon inert environment: temperature range of thermal degradation, and mass losses at 500ºC.

Bamboo Species	Ages (Yrs)	Decomposition temp. (°C)				Mass loss/(%)			
		1st stage	2nd stage	3rd stage	4th stage	1st stage	2nd stage	3rd stage	4th stage
Injibara	1	89	260	319	390	6.6	11.75	44.26	12.31
	2	100	284	328	410	3.47	22.34	34.45	10.96
	3	102	284	328	410	4.57	21.26	33.36	15.32
Kombolcha	1	102	273	326	415	3.24	19.71	30.74	19.07
	2	105	273	322	415	3.26	24.68	27.28	15.38
	3	102	285	332	425	4.3	20.35	26.2	24.47
Mekaneselam	1	103	281	329	424	3.47	20.14	34	14.28
	2	99	281	330	424	5.2	20.57	29.24	19.48
	3	102	281	329	424	4.13	18.62	28.13	21.45

Injibara bamboo fibres

As shown in Figure 4.14, the ages of 2 years old of Injibara bamboo fibres have higher decomposition temperatures of hemicelluloses, cellulose, and lignin compared to the age 1-year-old, whereas ages 2 and 3 years old have a similar decomposition of temperatures. Ages of 2 and 3 years old are also noted that the maturity of the culm improved with the thermal stability of the fiber, characterized by an increase in initial temperatures of degradation. Age of 2 years has a lower percentage of weight loss compared to 1 and 3 years. An increase in the initial degradation temperature (291.0 and 284.0 ºC) at the ages of 2 and 3 years old, respectively, compared with the *Bamboosa Vulgaris* fibers in their natural state (220 ºC), can be seen. Similar results were found by (Shah et al., 2017) who investigated the thermal behavior of the *Bamboosa Vulgaris*.

The initial degradation temperature of hemicelluloses Injibara bamboo fibres at the ages of 1, 2, and 3 years has 5%, 20%, and 14% higher than bamboo pulp fibres (Wei et al., 2016), 4%, 18%, and 12% higher than *Bambusoideae bamboo*(Júnior et al., 2015), 15%, 28%, and 23% higher than *Bamboosa Vulgaris* (Shah et al., 2017), and 9%, 23%, and 17% higher than bamboo fibres (Zhang et al., 2018), respectively.

The initial degradation temperature of cellulose of Injibara bamboo fibres at the ages of 1, 2, and 3 years has 11%, 9%, and 10% lower than bamboo pulp fibres(Wei et al., 2016), 16%, 14%, and 15% lower than *Bambusoideae bamboo*(Júnior et al., 2015), and 14%, 11% and 13% lower than bamboo fibres (Zhang et al., 2018), however, it has 6%, 9% and 8% higher than *Bamboosa vulgaris* (Shah et al., 2017), respectively.

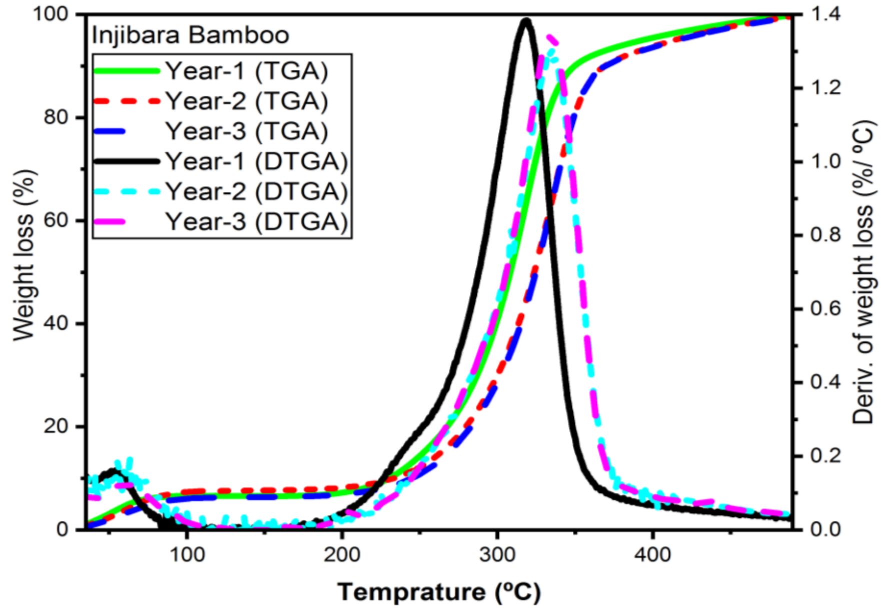


FIGURE 4.14: TGA/DTG results of Injibara bamboo fibres under argon environments

Kombolcha bamboo fibres

As shown in Figure 4.15, the age of 3 years old of Kombolcha bamboo fibres has a higher decomposition temperature of hemicellulose, cellulose, and lignin compared to the ages of 1 and 2 years old, whereas 1 and 2 years have a similar decomposition temperature of hemicellulose, cellulose, and lignin content. Ages of 2 years have a lower percentage of weight loss of mass compared to 1 and 3 years. Ages of 1 and 2 years old are also noted that early-stage improved with the thermal stability of the fiber, characterized by an increase in initial temperatures of degradation.

The initial degradation temperature of hemicelluloses of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years have 10%, 13%, and 7% higher than bamboo pulp fibres (Wei et al., 2016), 8%, 12%, and 6% higher than *Bambusoideae bamboo* (Júnior et al., 2015), 19%, 23%, and 17% higher than *Bamboosa Vulgaris* (Shah et al., 2017), and 14%, 17%, and 15% higher than bamboo fibres (Zhang et al., 2018), respectively. The initial degradation temperature of cellulose of Injibara bamboo fibres at the ages of 1, 2, and 3 years has 9%, 10%, and 6% lower than bamboo pulp fibres (Wei et al., 2016), 14%, 15%, and 11% lower than *Bambusoideae* *bamboo*(Júnior et al., 2015), and 11%, 12% and 8% lower than bamboo fibres (Zhang et al., 2018), however, it has 8%, 7% and 11% higher than *Bamboosa Vulgaris* (Shah et al., 2017), respectively.

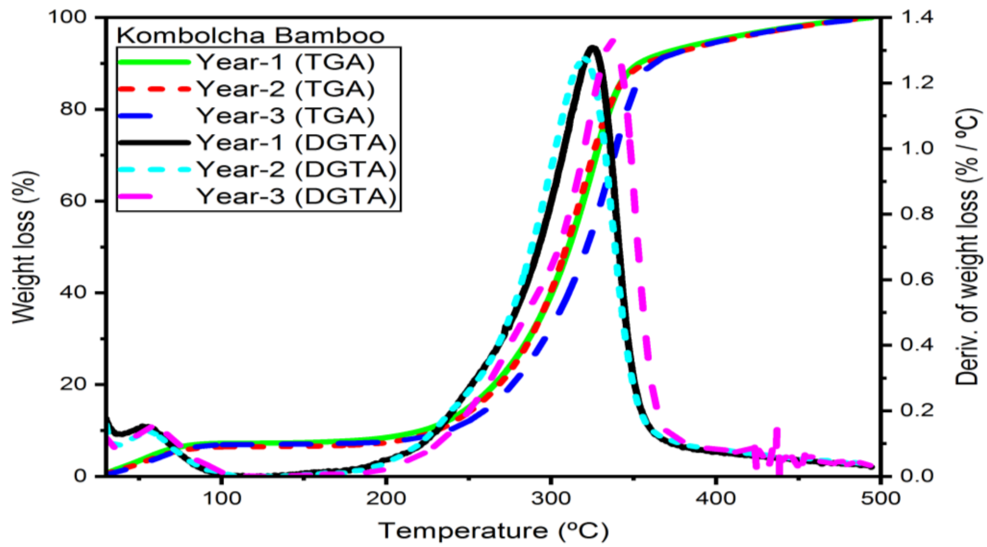


FIGURE 4.15: TGA/DTG results of Kombolcha bamboo fibres under argon environments

Mekaneselam bamboo fibres

The effect of age on the thermal decomposition of Mekaneselam bamboo fibres is presented in Figure 4.16. All ages of years old of Mekaneselam bamboo fibre have a similar decomposition temperature of hemicelluloses, cellulose, and lignin content, whereas ages 1-year-old have a higher percentage of weight loss of mass compared to 2 and 3 years.

The initial degradation temperature of hemicelluloses of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years have 12%, 13%, and 11% higher than bamboo pulp fibres (Wei et al., 2016), 11%, 12%, and 10% higher than *Bambusoideae bamboo* (Júnior et al., 2015), 22%, 23%, and 21% higher than *Bamboosa Vulgaris* (Shah et al., 2017), and 16%, 17%, and 15% higher than bamboo fibres (Zhang et al., 2018), respectively. The initial degradation temperature of cellulose of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years has 9%, 8%, and 9% lower than bamboo pulp fibres(Wei et al., 2016), 13%, 14%, and 13% lower than *Bambusoideae bamboo* (Júnior et al., 2015), and 11%, 10% and 11% lower than bamboo fibres(Zhang et al., 2018), however, it has 9%, 10% and 9% higher than *Bamboosa Vulgaris* (Shah et al., 2017), respectively.

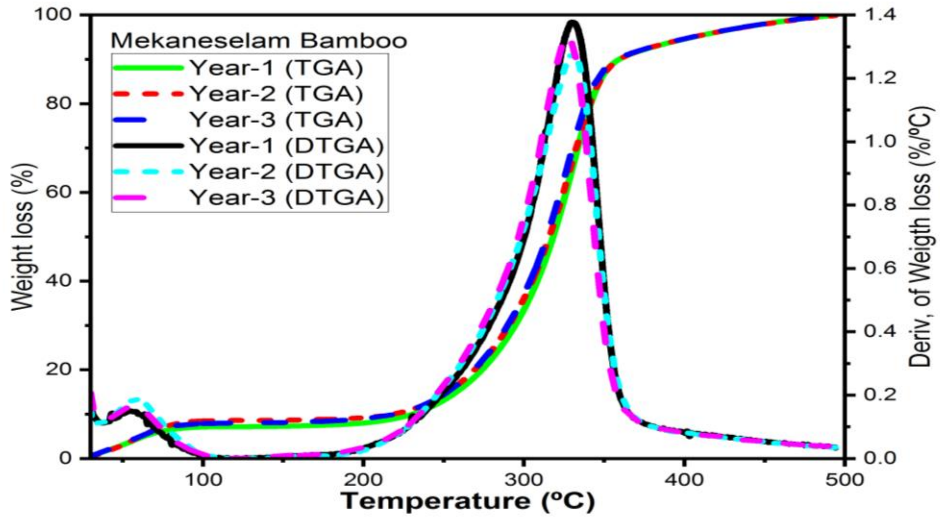


FIGURE 4.16: TGA/DTG results of Mekaneselam fibres under argon environments

4.1.6 Summary results of structural properties

All the structural, microstructural, thermal, and degree of crystallinity of bamboo fibres were studied on the influence of ages and Ethiopian bamboo species, which influence the culm structural features. The structural features have improved when the culm is old, but the internodal length, outer culm diameter, and culm wall thickness reduce their sizes from bottom to top position, whereas the Internodal length reaches its maximum in the middle of the culm, then decreases to the top of the culm along with its height. Kombolcha bamboo has a high breast height diameter and wall thickness compared to Injibara and Mekaneselam, but Mekaneselam bamboo culm has a larger internodal length compared to Injibara and Kombolcha. The Internodal length determined the length of bamboo fibres for the production of unidirectional continuous fibres composites. The outer diameter and culm wall thickness determined the quantities of fibres produced from the culm.

Factors of the culm ages satisfied the minimum criteria requirement of the breast height diameter (3 cm) and the Internodal length (25 cm), as set by the author for composite application. The structural features of bamboo species in Ethiopia are the best for fibre composite applications. The vascular bundles of Injibara and Kombolcha bamboo are type I structure and Mekaneselam bamboo is a type III structure. The microstructure of the vascular bundles is influenced by age maturation. Matured culm (3 years) has a dense vascular bundle, whereas young culm (1 year) has sparse vascular bundles.

The TGA results indicated that age 2 years old has higher thermal and degree of crystallinity properties compared to 1 and 3 years old. The moisture release, hemicelluloses, and cellulose decomposition temperature of Injibara bamboo is 89-102 ºC, 260-306 ºC, and 319-328 ºC, whereas Kombolcha bamboo fibre is 102-105 ºC, 273-285ºC, and 322-332 ºC, as well as, Mekaneselam bamboo fibres are 99-103 ºC, 283 ºC, and 329-330 ºC, respectively. In Ethiopia, bamboo species have a similar range of thermal decomposition temperatures each other and they have a similar range of thermal decomposition temperatures as found in the literature.

The XRD results show that the degree of crystallinity of Injibara, Kombolcha, and Mekaneselam bamboo fibres have 69–73%, 58–66%, and 66–68%, respectively. The degree of crystallinities of Kombolcha and Mekaneselam bamboo fibres have 11% and 7% lower compared to Injibara bamboo fibre, respectively. Bamboo species in Ethiopia have a high percentage of degree of crystallinity compared to other literature found. FTIR results approved that bamboo species in Ethiopia are lignocellulose fibres, which have found a different functional group on the bamboo fibres in a different wavelength.

4.2 Result and discussion on the physical properties of bamboo

Bamboo culms are used in structural applications such as fences, building houses, and furniture making. The structural applications of the bamboo culm are influenced by the moisture content, basic density, and culm wall shrinkage of the culm. The physical properties of Injibara, Kombolcha, and Mekaneselam bamboo are discussed in detail as follows:

4.2.1 Moisture content

The fiber extraction is influenced by the moisture content of the culm. When the more moisture content, the easier fiber extraction is on the culm, but the mechanical strength of the culm is reduced.

The moisture content of the culm in February

The influence of age, culm height, and bamboo species of the bamboo culm are indicated in Figure 4.17. In the present results, moisture content decrease when the culm age older and along the culm height go from the bottom to the top position. One-year-old Injibara bamboo culm at the bottom, middle, and top positions of Injibara bamboo culm has 26%, 23%, and 36%, whereas Kombolcha bamboo culm has 43%, 47%, and 49% higher, as well as Mekaneselam bamboo culm, has 10%, 22%, and 49% higher moisture content compared to 3 years old, respectively. Moreover, the bottom part of Injibara bamboo culm at 1, 2, and 3 years old has 38%, 39%, and 42% higher, whereas Kombolcha bamboo culm has 8%, 15%, and 11% higher, as well as Mekaneselam bamboo culm, has 21%, 23%, and 42% higher moisture content compared to the top parts, respectively. The highest to the lowest moisture content of bamboo species in Ethiopia are Mekaneselam, Injibara, and Kombolcha bamboo culm, respectively. Kombolcha bamboo culm is challenging to extract fibres from the culm because of the low moisture content and damage to the fibres during the extraction process.

The moisture contents of *Yushanina alpina* at the age of 2 (120.3%) are lower, but 3 (100.5%) is higher than the current value of bamboo species in Ethiopia at 1, 2, and 3 years old (Girma et al., 2018). The moisture contents of *Bambusa vulgaris* var. *vulgaris* at the ages of 1 (49.13%), 2 (40.07%), and 3 (39.73%) are lower, *Bambusa vulgaris* var. *striata at* ages of 1 (29.68%), 2 (29.43%), 3 (27.82%) are lower, *Bambusa balcooa* at the ages of 1 (56.86%), 2 (51.46%) and 3 (48.35%) is lower, *Bambusa tulda* at the ages of 1 (42.93%), 2 (48.76%) and 3 (38.60%) is lower, *Bambusa polymorpha* at the ages of 1 (68.14%), 2 (62.48%) and 3 (56.85%) is lower, *Dendrocalamus strictus* at the ages of 1 (49.02%), 2 (48.76%), and 3 (38.60%) is lower, as well as, *Bambusa bambos* at the ages of 1 (56.19%), 2 (49.64%) and 3 (41.34%) is lower than the current results of bamboo species in Ethiopia in 1, 2 and 3 years old, respectively (Selvan et al., 2017).

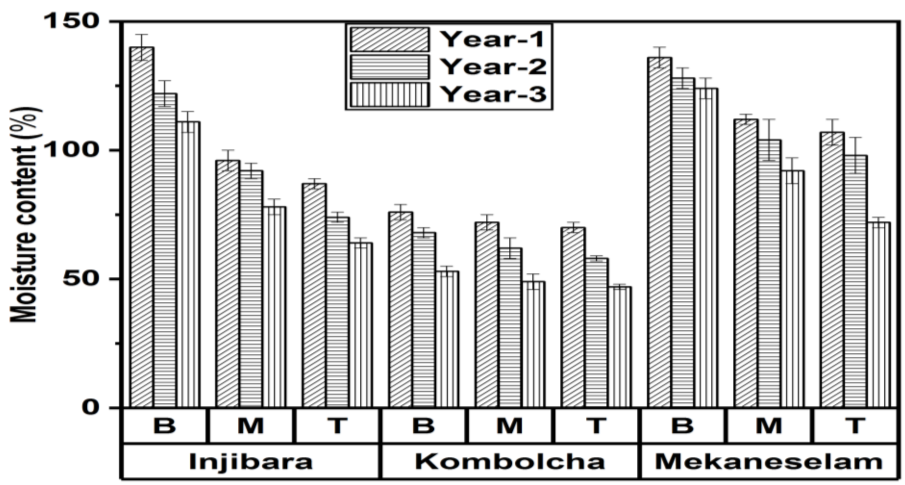


FIGURE 4.17: Moisture content a long culm height aged from 1-3 years old in February

The moisture content of the culm in November

The influence of age, height, and bamboo species of the bamboo culm are shown in Figure 4.18. One-year-old Injibara bamboo culm at the bottom, middle, and top positions of Injibara bamboo culm have 58%, 71%, and 75% higher, whereas Kombolcha bamboo culm has 28%, 45%, and 60% higher, as well as Mekaneselam bamboo culm, has 47%, 46%, and 59% higher moisture content compared to 3 years old, respectively. Moreover, the bottom position of

Injibara bamboo culm at the ages of 1, 2, and 3 years old have 43%, 45%, and 49% higher, whereas Kombolcha bamboo culm has 20%, 30%, and 36%, as well as Mekaneselam bamboo culm, has 22%, 26%, and 27% higher moisture content than the top position, respectively.

The moisture content of Mekaneselam bamboo culm at the age of 1, 2, and 3 years old has 8%, 21%, and 17% higher than Injibara bamboo and 7%, 4%, and 2 higher than Kombolcha, whereas Kombolcha bamboo has 1%, 17%, and 16% higher than Injibara.

The moisture content of Injibara bamboo at the age of 1, 2, and 3 years old in November has 38%, 17%, and 12% higher than in February, whereas Kombolcha bamboo in November has 55%, 54%, and 56% higher than February, and Mekaneselam bamboo in November has 32%, 24%, and 17% higher than February, respectively.

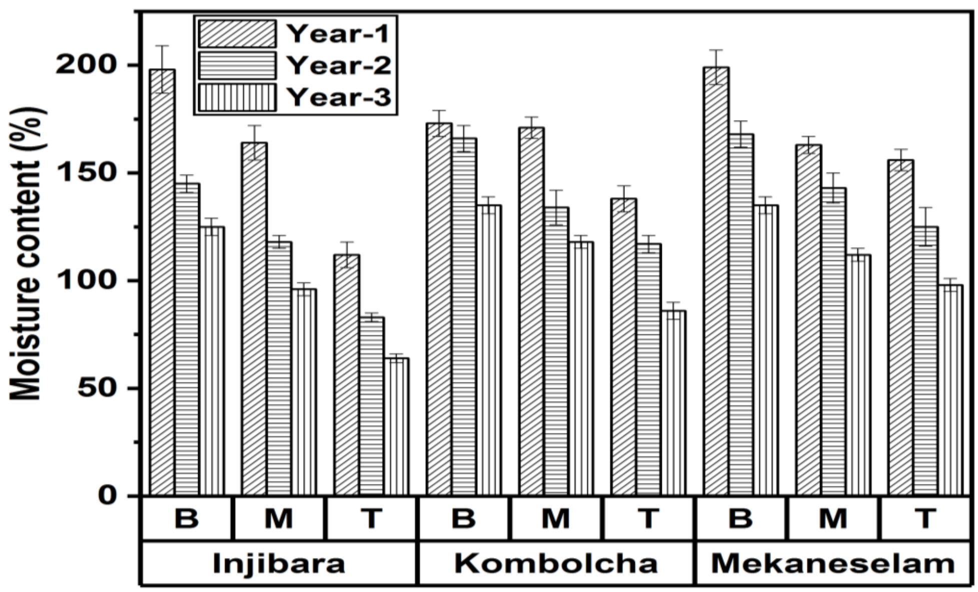


FIGURE 4.18: Moisture content a long culm height aged from 1-3 years old in November

4.2.2 Characteristics of basic density

<u>Basic density of the culm in February</u>

The effect of age, height and bamboo species of bamboo culm on the basic density are shown in Figure 4.19. In the present results, the basic density increase when the age of the culm is older and along the culm height goes from the bottom top position. Three years old Injibara bamboo culm at the bottom, middle, and top positions has 41%, 39%, and 19%, whereas Kombolcha bamboo culm has 55%, 50%, and 46%, as well as Mekaneselam bamboo culm, has 30%, 20%, and 23% higher basic density compared to one year old, respectively. The top position of Injibara bamboo culm at the age of 1, 2, and 3 years old has 47%, 35%, and 26%, whereas Kombolcha bamboo culm has 32%, 33%, and 17%, as well as Mekaneselam bamboo culm, has 27%, 19%, and 21% higher basic density compared to the bottom position, respectively.

The highest to the lowest basic density of bamboo species in Ethiopia are Kombolcha, Injibara, and Mekaneselam bamboo culm, respectively. The basic density content of Injibara bamboo at the age of 1, 2, and 3 years old in February is 32%, 25%, and 61% higher than in November, whereas Kombolcha bamboo in February is 51%, 32%, and 36% higher than November, and Mekaneselam bamboo in February is 20%, 12%, and 5% higher than November, respectively.

Kombolcha bamboo culm is suitable for manufacturing home furniture, building the house, and constructing fences during harvesting month in February. The basic density of Injibara bamboo culm at the age of 1, 2, and 3 years in February have 554 ±16Kg/m^3, 675±24 Kg/m^3, and 814±21Kg/m^3, whereas Kombolcha bamboo has 535± 15Kg/m^3, 687±23 Kg/m^3, and 825±27 Kg./m^3, and Mekaneselam bamboo has 463±17 Kg/m^3, 478±21 Kg/m^3, and 511±15 Kg/m^3, respectively.

The basic density of *Bambusa vulgaris* var. *vulgaris* at the ages of 1 (410.5 Kg/m^3) , 2 (426.4 Kg/m^3) and 3 (441.8 Kg/m^3) are lower, *Bambusa vulgaris* var. *striata* at the ages of 1 (390.0 Kg/m^3), 2 (410.0 Kg/m^3) and 3 (435.0 Kg/m^3) are lower, *Bambusa balcooa* at the ages of 1 (428.0 Kg/m^3), 2 (442.0 Kg/m^3) and 3 (466.0 Kg/m^3) is lower, *Bambusa tulda* at the ages of 1 (431.2 Kg/m3), 2 (446.8 Kg/m^3) and 3 (468.2 Kg/m^3) is lower, *Bambusa polymorpha* at the ages of 1 (416.7 Kg/m^3), 2 (428.4 Kg/m^3) and 3 (441.6 Kg/m3) is lower, *Dendrocalamus strictus* at the ages of 1 (432.3 Kg/m^3), 2 (448.7 Kg/m^3) and 3 (458.0 Kg/m^3) is lower, as well as, *Bambusa bambos* at the ages of 1 (422.2 Kg/m^3), 2 (438.8 Kg/m^3) and 3 (450.75 Kg/m^3) is lower than the current results of bamboo species in Ethiopia at the ages of 1, 2 and 3 years old (Selvan et al., 2017). The basic density of *Bambusa balcooa* and *Bambusa Tulda* aged from 2-4 years old have lower, however, *melocanna baccifera* and *Bambusa Salarkhanii* aged from 2-4 years old have higher than the current results of bamboo species in Ethiopia aged from 1–3 years old (KRISHNAKUMAR et al., 2017).

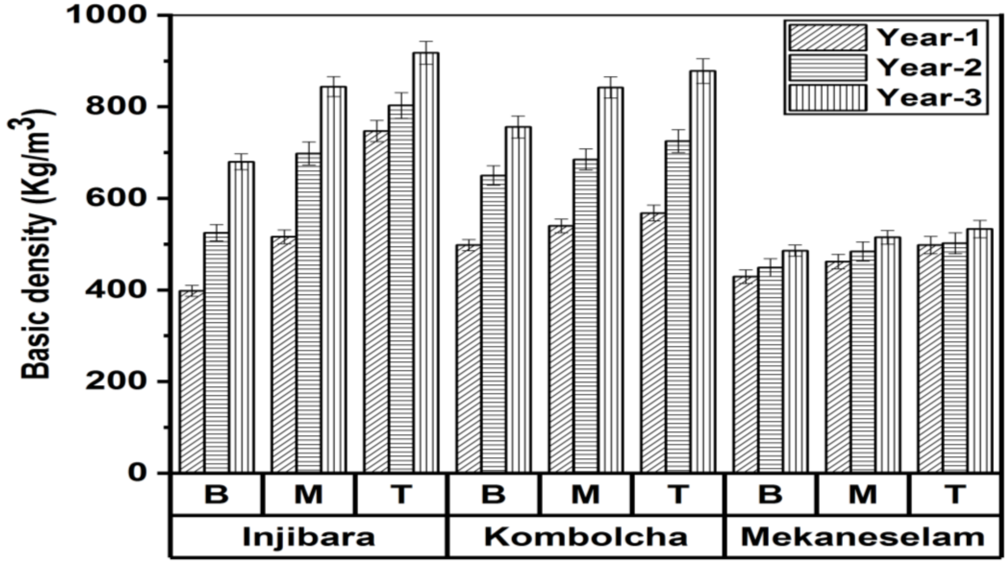


FIGURE 4.19: Basic density along culm height aged from 1-3 years old in February

Basic density of the culm in November

The influence of age, height, and bamboo species on the basic density are indicated in Figure 4.20. In the present studies, basic density increase when the culm age older and along the culm height go from the bottom to the top position. Three years old of Injibara bamboo culm at the bottom, middle, and top positions have 32%, 38%, and 23%, whereas Kombolcha bamboo culm has 34%, 36%, and 35%, as well as Mekaneselam bamboo culm, has 12%, 10%, and 7% higher basic density compared to one year old, respectively. Moreover, the top position of Injibara bamboo culm at 1, 2, and 3 years old has 30%, 16%, and 20%, whereas Kombolcha bamboo culm has 12%, 10%, and 14%, as well as Mekaneselam bamboo culm, has 14%, 11%, and 9% higher basic density compared to the bottom position, respectively. The highest to the lowest basic density of bamboo species in Ethiopia are Injibara, Kobmolcha, and Mekaneselam, respectively.

The basic density of Injibara bamboo culm at the age of 1, 2, and 3 years in November, it has 375±11Kg/m^3, 506±17 Kg/m^3, and 542±10Kg/m^3, whereas Kombolcha bamboo has 535± 14Kg/m^3, 687±23 Kg/m^3, and 825±27 Kg./m^3, and Mekaneselam bamboo has 463±17 Kg/m^3, 478±21 Kg/m^3, and 511±15 Kg/m^3, respectively. Injibara bamboo culm is suitable for manufacturing furniture, building the house, and constructing fences during harvesting month in February. Kombolcha bamboo culm is suitable for manufacturing home furniture, building houses, and constructing fences during harvesting month in February.

The mean basic density of *Yushania alpina* at the age of 1 (599.85 Kg/m^3), 2 (652.89 Kg/m^3), and 3 (666.85 Kg/m^3) years old has higher than the current results of Injibara and Mekaneselam bamboo at the ages of 1, 2 and 3 years old. The basic density of *Yushania alpina* at the age of 2 (652.89 Kg/m^3), and 3 (666.85 Kg/m^3) years old has lower than Kombolcha bamboo at the age of 2 and 3 years old, however, the basic density of *Yushania apina* at the age of 1 (599.85 Kg/m^3) year old has higher than Kombolcha bamboo (Girma et al., 2018).

Basic density increases when the culm age is older and goes from the bottom to the top along with the culm height (Morales et al., 2017). The mean basic density of *Gigantochloa levis* at the age of 2 (733 Kg/m^3) and 4 (751 Kg/m^3) years old has higher than the current research studies of Ethiopian bamboo, whereas along with culm height at the bottom (696.5 Kg/m^3), middle (750.5 Kg/m^3), and top (758.5 Kg/m^3) has lower than the current results of bamboo species in Ethiopia at the bottom, middle and top parts, respectively (Wang et al., 2010).

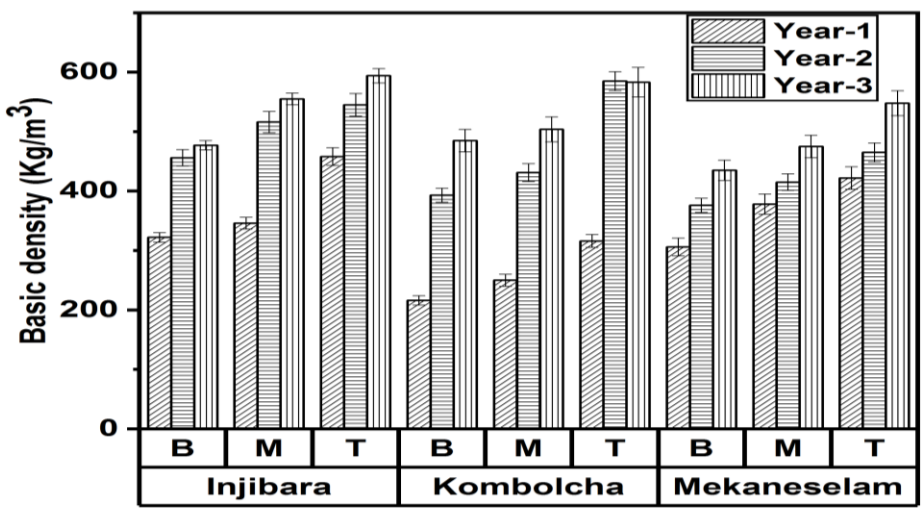


FIGURE 4.20: Basic density along the culm height aged from 1-3 years old in November.

4.2.3 Characteristics of culm shrinkage

As shown in Table 4.7, the radial and tangential shrinkage decrease from bottom to top across the height, and the bamboo culm become mature. The radial shrinkage of the bamboo culm is higher than the tangential shrinkage. The harvesting month of November is higher culm shrinkage than February.

Table 4.7: measurement of radial and tangential shrinkage of the bamboo culm

Bamboo Species	Age(Yrs)	Height	Radial shirnkage (%)		Tangential shirnkage (%)	
			February	November	February	November
Injibara	1	Bottom	18±1.4	19±1.7	12±1.1	15±1.2
		Middle	15±1.4	17±1.5	10±0.8	14±1.1
		Top	11±0.9	15±1.2	8±0.5	10±0.8
	2	Bottom	14±1.2	16±1.4	11±0.9	13±1.1
		Middle	11±0.8	13±1.2	9±0.7	11±0.9
		Top	9±0.7	11±1.3	7±0.5	9±0.7
	3	Bottom	12±0.9	14±1.2	10±0.8	11±0.9
		Middle	9±0.6	11±1.4	8±0.5	9±0.7
		Top	7±0.4	9±0.8	5±0.3	7±0.4
Kombolcha	1	Bottom	15±1.2	17±1.5	12±1.1	11±0.9
		Middle	12±0.9	15±1.2	11±0.8	10±0.8
		Top	9±0.7	12±1.3	9±0.7	9±0.7
	2	Bottom	12±1.1	15±1.2	10±0.9	10±0.8
		Middle	11±0.9	13±1.1	9±0.7	8±0.4
		Top	7±0.5	11±0.8	7±0.4	6±0.3
	3	Bottom	10±0.6	12±0.9	9±0.5	8±0.5
		Middle	8±0.5	10±0.8	7±0.4	6±0.4
		Top	7±0.4	9±0.7	5±0.3	5±0.3
Mekaneselam	1	Bottom	18±1.5	21±1.2	14±1.2	19±1.4
		Middle	14±1.2	19±1.3	12±1.1	15±1.2
		Top	10±0.8	16±1.3	11±0.9	12±1.1
	2	Bottom	16±1.3	18±1.2	12±1.1	18±1.6
		Middle	12±1.1	15±1.1	11±0.9	14±1.2
		Top	9±0.7	13±1.2	9±0.8	10±0.9
	3	Bottom	14±1.2	15±1.3	10±0.8	14±1.2
		Middle	11±0.8	12±1.1	8±0.5	10±0.8
		Top	7±0.5	10±0.8	7±0.4	8±0.4

Radial shrinkage of the culm in February

The influence of age, height, and species of bamboo culm on the radial shrinkage are indicated in Figure 4.21. The radial shrinkage decreases when the culm age older and along the culm height go from the bottom to the top. One-year-old Injibara bamboo culm at the bottom, middle, and top positions have 35%, 38%, and 33%, whereas Kombolcha bamboo culm has 37%, 38%, and 30% higher, as well as, Mekaneselam bamboo culm has 22%, 21%, and 30%

higher radial shrinkage compared to 3 years old, respectively. Moreover, the bottom position of Injibara bamboo culm at the age of 1, 2, and 3 years old has 40%, 44%, and 38% higher, whereas Kombolcha bamboo culm has 37%, 38%, and 31% higher, as well as, Mekaneselam bamboo culm has 44%, 43%, and 50% higher radial shrinkage compared to the top position, respectively. The highest to the lowest radial shrinkage of bamboo species in Ethiopia are Mekaneselam, Injibara, and Kombolcha, respectively.

The radial culm wall shrinkage of Injibara bamboo culm at the ages of 1, 2, and 3 years has 50%, 47%, and 23% higher; Kombolcha bamboo culm has 40%, 28%, and 13% higher, and Mekaneselam bamboo culm has 48%, 41%, and 32% higher than *Gigantochlo Scortechinii* (7.22%), respectively. Moreover, the radial culm wall shrinkage of Injibara bamboo culm at the age of 1 year has 21% higher, but at the age of 3 years has 20% lower and at the age of 2 years has a comparable value with *Bambusa vugaris*, respectively. The radial culm wall shrinkage of Kombolcha bamboo culm at the age of 1 year has 8% higher, but at the ages of 2 and 3 years has 14%, and 19% lower than *Bambusa vulgaris*, respectively. The radial culm wall shrinkage of Mekaneselam bamboo culm at the ages of 1 and 2 years has 17% and 6% higher, but at the ages of 3 years has 8% lower than *Bambusa vulgaris*, respectively (Anokye et al., 2014).

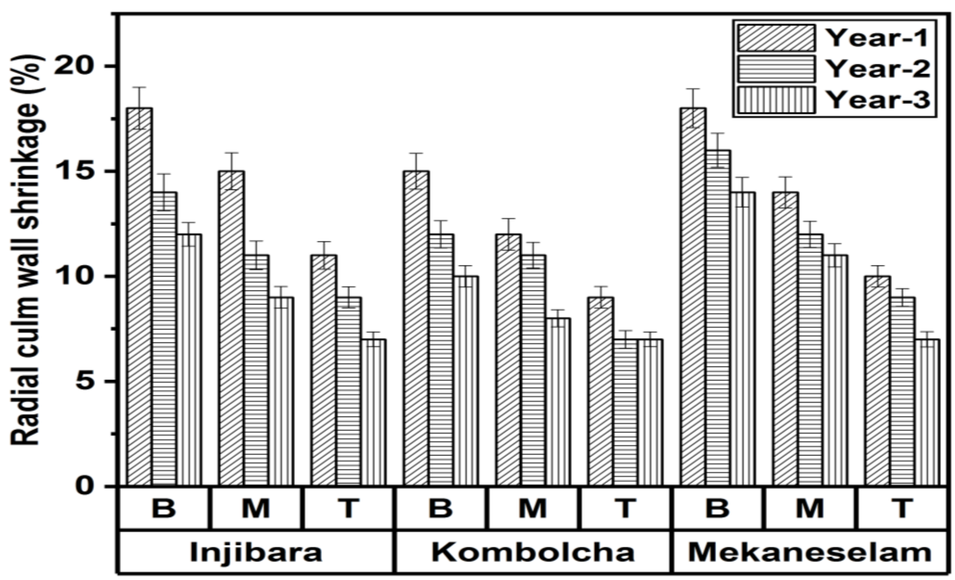


FIGURE 4.21: Radial shrinkage of a long culm height aged from 1-3 years old in February

Radial shrinkage of the culm in November

The effect of age, height and species of bamboo culm on the radial shrinkage are shown in Figure 4.22. One-year-old Injibara bamboo at the bottom, middle, and top position have 42%, 38%, and 43% higher, whereas Kombolcha bamboo has 33%, 38%, and 42% higher, as well as, Mekaneselam bamboo culm has 29%, 37%, and 38% higher radial shrinkage compared to 3 years old, respectively. The bottom position of Injibara bamboo at the age of 1, 2, and 3 years old has 26%, 33%, and 27% higher, whereas Kombolcha bamboo culm has 20%, 23%, and 30% higher, as well as Mekaneselam bamboo, has 24%, 28%, and 33% higher radial shrinkage compared to the top position, respectively.

The highest to the lowest radial shrinkage of bamboo species in Ethiopia are Mekaneselam, Injibara, and Kombolcha, respectively. The radial shrinkage of Injibara bamboo at the age of 1, 2, and 3 years old in November is 17%, 15%, and 18% higher than in February, whereas Kombolcha bamboo in November is 18%, 23%, and 20% higher than February, and Mekaneselam bamboo in November is 22%, 20%, and 17% higher than February, respectively. The radial shrinkage in wall thickness of *Gigantochloa levis* at the age of 2 (7.69%), 3 (5.21%), and 4 (5.60%) is lower than the current results of bamboo species in Ethiopia aged from 1-3 years old (Wang et al., 2010).

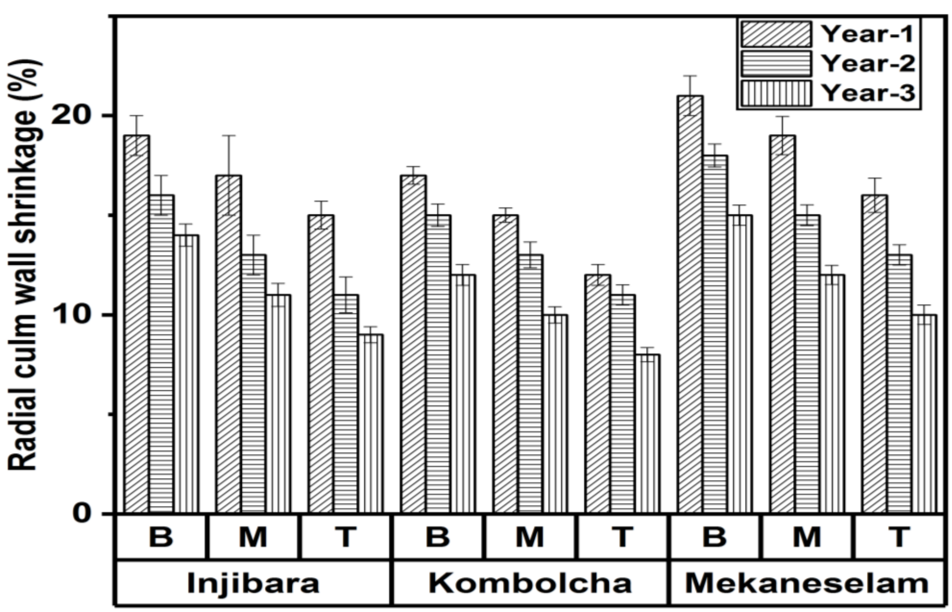


FIGURE 4.22: Radial shrinkage of ages from 1-3 years old in November.

Tangential shrinkage of the culm in February

The influence of age, height, and species of bamboo culm on the tangential shrinkage are indicated in Figure 4.23. One-year-old Injibara bamboo culm at the bottom, middle, and top positions have 23%, 20%, and 38% higher, whereas Kombolcha bamboo culm has 25%, 36%, and 44% higher, as well as Mekaneselam bamboo culm, has 29%, 33%, and 36% higher tangential shrinkage compared to 3 years old, respectively. Moreover, the bottom position of Injibara bamboo culm at the age of 1, 2, and 3 years old has 38%, 36%, and 50% higher, whereas Kombolcha bamboo culm has 25%, 30%, and 44% higher, as well as Mekaneselam bamboo, has 21%, 25%, and 30% higher tangential shrinkage compared to the top position, respectively. The highest to the lowest tangential shrinkage of bamboo species in Ethiopia are Mekaneselam, Injibara, and Kombolcha, respectively.

The tangential culm wall shrinkage of Injibara bamboo culm at the ages of 2 and 3 years has 10% and 23% lower; but at the age of 1 year old has comparable results with *Gigantochlo Scortechinii* (9.98%), respectively. Kombolcha bamboo culm at the ages of 2 and 3 years old has 13% and 30% lower, but at the age of 1 year old has comparable results with *Gigantochlo Scortechinii* (7.22%), respectively. Mekaneselam bamboo at the ages of 1 and 2 years old has 17% and 6% higher, but at the age of 3 years old has 17% lower than *Gigantochlo Scortechinii* (9.98%), respectively. The tangential culm wall shrinkage of Injibara bamboo culm at the ages of 2 and 3 years has 10% and 23% lower; but at the age of 1 year old has comparable results with *Bambusa vulgaris* (10.04%), respectively. Kombolcha bamboo culm at the ages of 2 and 3 years has 13% and 30% lower, but at the age of 1 year has comparable results with *Bambusa vulgaris* (10.04%), respectively. Mekaneselam bamboo culm at the age of 1 year old has 19% higher, but at the age of 3 years old has 17% lower, and at the age of 2 years old has comparable results with *Bambus vulgaris*, respectively (Anokye et al., 2014)..

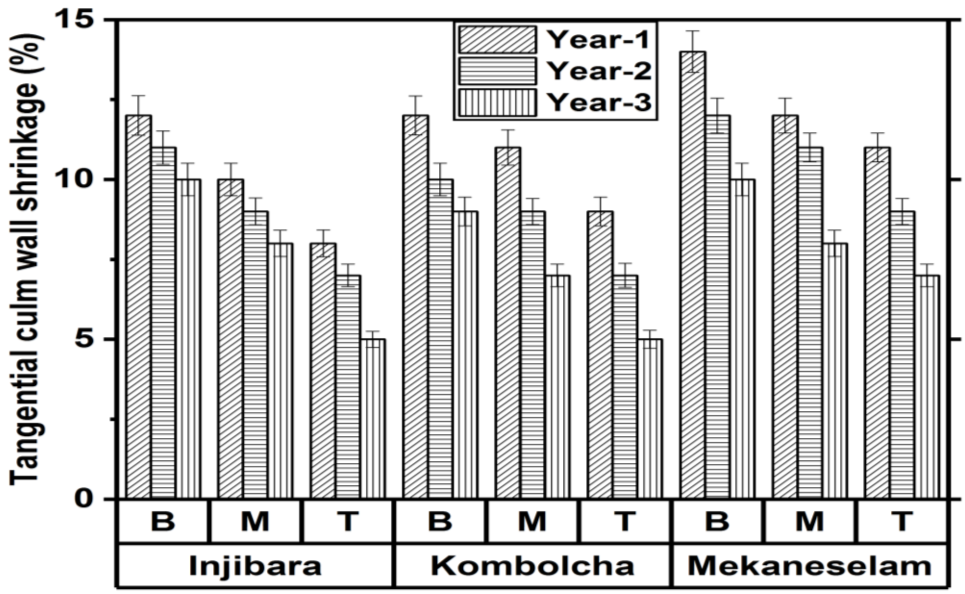


FIGURE 4.23: Tangential shrinkage of aged from 1-3 years old in February.

Tangential shrinkage of the culm in November

The influence of age, height, and species of bamboo culm on the tangential shrinkage are indicated in Figure 4.24. One-year-old Injibara bamboo culm at the bottom, middle, and top positions have 31%, 33%, and 33% higher, whereas Kombolcha bamboo culm has 27%, 40%, and 44% higher, as well as Mekaneselam bamboo culm, has 26%, 33%, and 38% higher tangential shrinkage compared to 3 years old, respectively. Moreover, the bottom position of Injibara bamboo culm at 1, 2, and 3 years old has 31%, 25%, and 33% higher, whereas Kombolcha bamboo culm has 18%, 33%, and 38% higher, as well as Mekaneselam bamboo culm, has 37%, 44%, and 46%higher tangential shrinkage compared to the top position, respectively. The highest to the lowest tangential shrinkage of bamboo species in Ethiopia are Mekaneselam, Injibara, and Kombolcha, respectively. The tangential shrinkage of Injibara bamboo at the age of 1, 2, and 3 years old in November is 23%, 18%, and 22% higher than in February, whereas Kombolcha bamboo in November is 2%, 11%, and 6% higher than February, and Mekaneselam bamboo in November is 20%, 28%, and 22% higher than February, respectively.

Kombolcha bamboo culm has the lowest shrinkage in radial and tangential directions, hence it is suitable for the manufacture of home furniture, building the house, and making fences. Therefore, Kombolcha bamboo culm has the lowest shrinkage in a radial and tangential direction, hence it is suitable for the manufacture of home furniture, building the house, and making fences. Radial shrinkage is higher shrinkage of the culm compared to tangential shrinkage.

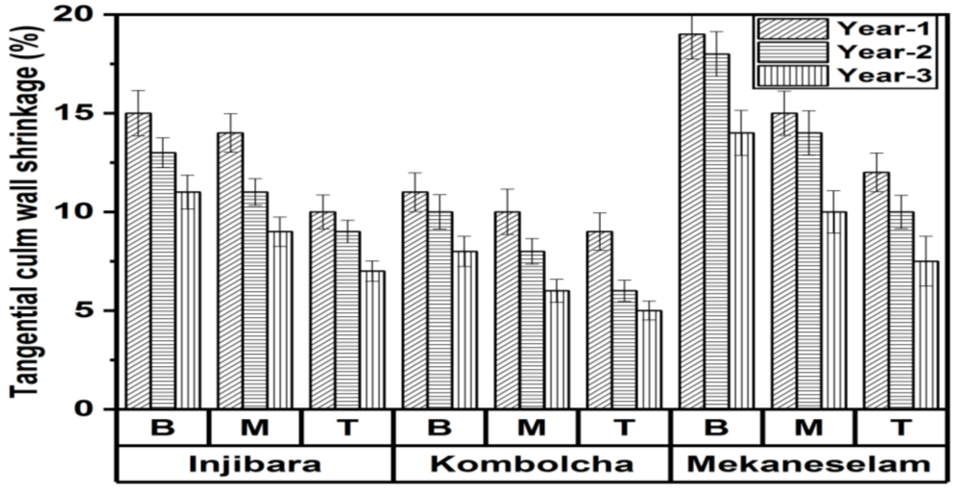


FIGURE 4.24: Tangential shrinkage at a long height aged from 1-3 years old in November

4.2.4 Physical properties of Injibara bamboo using ANOVA

Moisture content

As presented in Table 4.8, the linear regression of the moisture content of Injibara bamboo culm at the model and residual of $F(3,86)= 61.05$, $P= 0.0000$), and R- squared of 68% is statistically significant on the mean of moisture content. The linear equation of moisture content is calculated as follows:

Moisture content = 1.86Month–28.04Year–23.24Height+194.66

Table 4. 8: Statistical analysis of moisture content of Injibara bamboo

MC	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	1.86	0.51	3.66	0.000	0.85	2.86
Year	-28.04	2.79	-10.03	0.000	-33.59	-22.48
Height	-23.24	2.79	-8.31	0.000	-28.79	-17.68
cons.	194.66	8.86	21.96	0.000	177.04	212.28

Basic density

As presented in Table 4.9, the linear regression of the basic density of Injibara bamboo culm at the model and residual of $F(3,86)= 83.74$, $P= 0.0000$), and R- squared of 75% is statistically significant on the mean of basic density. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of basic density. The linear equation of basic density is calculated as follows:

Basic density= -17.53Month + 126.29Year + 119.01Height + 195.43.

Table 4. 9: Statistical analysis of the basic density of Injibara bamboo

BD	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	-17.53	2.73	-7.71	0.000	-22.05	-13.01
Year	126.29	12.53	10.08	0.000	101.37	151.19
Height	119.01	12.53	9.5	0.000	94.11	143.92
cons.	195.43	39.74	4.92	0.000	116.42	274.43

Radial shrinkage

As presented in Table 4.10, the linear regression of the radial shrinkage of Injibara bamboo culm at the model and residual of *F*(3,86)=48.77, *P*= 0.0000), and R- squared of 63% is statistically significant on the mean of radial shrinkage. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of radial shrinkage. The linear equation of radial shrinkage is calculated as follows:

Radial shrinkage= 0.28Month – 1.57Year – 1.81Height + 13.23.

Table 4. 10: Statistical analysis of radial shrinkage of Injibara bamboo

Rad	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.28	0.043	6.58	0.000	0.196	0.366
Year	-1.57	0.236	-6.66	0.000	-2.037	-1.101
Height	-1.81	0.236	-7.66	0.000	-2.274	-1.337
cons.	13.23	0.747	17.71	0.000	11.74	14.71

Tangential shrinkage

As presented in Table 4.11, the linear regression of the tangential shrinkage of Injibara bamboo culm at the model and residual of *F*(3,86)= 49.21, *P*= 0.0000), and R- squared of 63% is statistically significant on the mean of tangential shrinkage. Moreover, the harvesting month, age, and height are statistically significant on the mean of tangential shrinkage. The linear equation of tangential shrinkage is calculated as follows:

Tangential shrinkage= 0.28Month – 5.19Year – 3.89Height+ 30.87.

Table 4. 11: Tangential shrinkage of Injibara bamboo

Tangetial	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.28	0.09	2.78	0.007	0.079	0.475
Year	-5.19	0.55	-9.46	0.000	-6.29	-4.106
Height	-3.89	0.55	-7.11	0.000	-4.98	-2.805
cons.	30.86	1.74	17.72	0.000	27.405	34.33

4.2.5 Physical properties of Kombolcha bamboo using ANOVA

Moisture Content

As presented in Table 4.12, the linear regression of the moisture content of Kombolcha bamboo culm at the model and residual of *F*(3,86)= 639.63, *P*= 0.0000), and R- squared of 96% is statistically significant on the mean of moisture content. Harvesting year and culm height are statistically significant, but the harvesting month is not statistically significant on the mean of moisture content. The linear equation of moisture content is calculated as follows:

Moisture content = -0.053Month–11.36Year–3.65Height+91.93

Table 4. 12: Statistical analysis of moisture content of Kombolcha bamboo

MC	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	-0.053	0.049	-1.07	0.289	-0.151	0.0456
Year	-11.36	0.272	-41.69	0.000	-11.896	-10.813
Height	-3.65	0.272	-13.4	0.000	-4.192	-3.109
cons.	91.93	0.864	106.42	0.000	90.209	93.643

Basic density

As presented in Table 4.13, the linear regression of the basic density of Kombolcha bamboo culm at the model and residual of *F*(3,86)= 83.75, *P*= 0.0000), and R- squared of 75% is statistically significant on the mean of basic density. Moreover, the harvesting month, and age, are statistically significant, but culm height is not statistically significant on the mean of basic density. The linear equation of basic density is calculated as follows:

Basic density= -0.122Month + 115.15Year + 21.75Height + 144.37.

Table 4. 13: Statistical analysis of the basic density of Kombolcha bamboo

BD	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.122	1.341	0.09	0.928	-2.55	2.79
Year	115.149	7.393	15.57	0.000	100.45	129.85
Height	21.748	7.393	2.94	0.004	7.05	36.45
cons.	144.369	23.447	6.16	0.000	97.76	190.98

Radial shrinkage

As presented in Table 4.14, the linear regression of the radial shrinkage of Kombolcha bamboo culm at the model and residual of *F*(3,86)=297.42, *P*= 0.0000), and R- squared of 91% is statistically significant on the mean of radial shrinkage. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of radial shrinkage. The linear equation of radial shrinkage is calculated as follows:

Radial shrinkage= 0.048Month – 2.137Year – 3.21Height + 32.44.

Table 4. 14: Statistical analysis of radial shrinkage of Kombolcha bamboo

Radial	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.048	0.023	2.03	0.045	0.001	0.094
Year	-2.133	0.129	-16.51	0.000	-2.389	-1.876
Height	-3.205	0.129	-24.81	0.000	-3.462	-2.948
cons.	32.437	0.409	79.18	0.000	31.623	33.252

Tangential shrinkage

As presented in Table 4.15, the linear regression of the tangential shrinkage of Kombolcha bamboo culm at the model and residual of $F(3,86)=46.52$, $P= 0.0000$), and R- squared of 62% is statistically significant on the mean of tangential shrinkage. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of tangential shrinkage. The linear equation of tangential shrinkage is calculated as follows:

Tangential shrinkage= 0.119Month – 2.687Year – 1.86Height + 19.77

Table 4. 15: Statistical analysis of tangential shrinkage of Kombolcha bamboo

Tangential	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.119	0.05	2.33	0.022	0.018	0.221
Year	-2.68	0.28	-9.52	0.000	-3.24	-2.12
Height	-1.86	0.28	-6.6	0.000	-2.41	-1.29
cons.	19.77	0.89	22.16	0.000	17.99	21.55

4.2.6 Physical properties of Mekaneselam bamboo using ANOVA

Moisture Content

As presented in Table 4.16, the linear regression of the moisture content of Mekaneselam bamboo culm at the model and residual of $F(3,86)= 153.68$, $P= 0.0000$), and R- squared of 84% is statistically significant on the mean of moisture content. Harvesting month, year, and culm height are statistically significant on the mean of moisture content. The linear equation of moisture content is calculated as follows:

Moisture content = 5.51Month–13.67Year–22.69Height + 169.92

Table 4. 16: Statistical analysis of moisture content of Mekaneselam bamboo

MC	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	5.51	0.341	16.18	0.000	4.84	6.19
Year	-13.67	1.878	-7.28	0.000	-17.39	-9.93
Height	-22.69	1.878	-12.09	0.000	-26.43	-18.96
cons.	169.92	5.954	28.54	0.000	158.08	181.76

Basic density

As presented in Table 4.17, the linear regression of the basic density of Mekaneselam bamboo culm at the model and residual of *F*(3,86)= 153.06, *P*= 0.0000), and R- squared of 84% is statistically significant on the mean of basic density. Moreover, the harvesting month and culm height are statistically significant, but harvesting age is not statistically significant on the mean of basic density. The linear equation of basic density is calculated as follows:

Basic density= 16.38Month + 7.09Year + 24.54Height + 219.99.

Table 4. 17: Statistical analysis of the basic density of Mekaneselam bamboo

BD	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	16.38	0.794	20.62	0.001	14.8	17.96
Year	7.09	4.378	1.62	0.109	-1.61	15.8
Height	24.54	4.378	5.61	0.001	15.84	33.25
cons.	219.99	13.885	15.84	0.001	192.39	247.59

Radial shrinkage

As presented in Table 4.18, the linear regression of the radial shrinkage of Mekaneselam bamboo culm at the model and residual of *F*(3,86)=252.23, *P*= 0.0000), and R- squared of 90% is statistically significant on the mean of radial shrinkage. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of radial shrinkage. The linear equation of radial shrinkage is calculated as follows:

Radial shrinkage= 0.51Month – 2.55Year – 4.34Height + 25.29.

Table 4. 18: Statistical analysis of radial shrinkage of Mekaneselam bamboo

Rad	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.51	0.038	13.41	0.001	0.434	0.585
Year	-2.55	0.209	-12.16	0.001	-2.966	-2.133
Height	-4.34	0.209	-20.71	0.001	-4.757	-3.924
cons.	25.29	0.665	38.06	0.001	23.975	26.61

Tangential shrinkage

As presented in Table 4.19, the linear regression of the tangential shrinkage of Mekaneselam bamboo culm at the model and residual of $F(3,86)=122.82$, $P= 0.0000$), and R- squared of 81% is statistically significant on the mean of tangential shrinkage. Moreover, the harvesting month, age, and culm height are statistically significant on the mean of tangential shrinkage. The linear equation of tangential shrinkage is calculated as follows:

Tangential shrinkage= 0.39Month – 1.997Year – 3.03Height + 19.49

Table 4. 19: Statistical analysis of tangential shrinkage of Mekaneselam bamboo

Tangetial	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Month	0.39	0.039	9.78	0.000	0.31	0.469
Year	-1.99	0.219	-9.1	0.000	-2.43	-1.559
Height	-3.25	0.219	-13.78	0.000	-3.46	-2.589
cons.	19.49	0.696	28.01	0.000	18.11	20.876

4.2.7 Summary results of physical properties

Ages, harvesting seasons, and bamboo culm position significantly affect the moisture content, basic density, radial shrinkage, and tangential shrinkage. The moisture content increase from age 3 to 1 year and goes from the top to bottom position. 1-year-old Injibara, Kombolcha, and Mekaneselam bamboo culm have 40%, 30%, and 33% higher moisture content compared to 3 years old, whereas the bottom position of Injibara, Kombolcha, and Mekaneselam bamboo have 45%, 28%, and 25% higher moisture content compared to the top position in November, respectively.

The moisture content of Injibara bamboo at the age of 1, 2, and 3 years old in November is 38%, 17%, and 12% higher than in February, whereas Kombolcha bamboo in November is 55%, 54%, and 56% higher than February, and Mekaneselam bamboo in November is 32%, 24%, and 17% higher than February, respectively. Whereas the basic density increase when the culm age older and go from the bottom to the top along the height. Three years old of Injibara, Kombolcha, and Mekaneselam bamboo culm has 32%, 50%, and 24% higher basic density compared to 1 year old, whereas the top position of Injibara, Kombolcha, and Mekaneselam bamboo have 35%, 26%, and 22% higher basic density compared to bottom position in February, respectively. The basic density of Injibara bamboo at the age of 1, 2, and 3 years old in February is 32%, 25%, and 61% higher than in November, whereas Kombolcha bamboo in February is 51%, 32%, and 36% higher than February, and Mekaneselam bamboo in February is 20%, 12%, and 5% higher than November, respectively.

The radial and tangential shrinkage increases when the culm age younger and go from top to bottom along the height of the bamboo culm. 1-year-old Injibara, Kombolcha, and Mekaneselam bamboo culm have 29%, 24%, and 28% higher radial shrinkage compared to 3 years old, whereas the bottom position of Injibara, Kombolcha, and Mekaneselam bamboo have 41%, 29%, and 34% higher radial shrinkage compared to the top position in November, respectively. The radial shrinkage of Injibara bamboo at the age of 1, 2, and 3 years old in November is 17%, 15%, and 18% higher than in February, whereas Kombolcha bamboo in November is 18%, 23%, and 20% higher than February, and Mekaneselam bamboo in November is 22%, 20%, and 17% higher than February, respectively.

1 year old of Injibara, Kombolcha, and Mekaneselam bamboo have 32%, 37%, and 32% higher tangential shrinkage compared to 3 years old, whereas the bottom position of the culm has 29%, 28%, and 42% higher tangential shrinkage compared to the top position in November, respectively. The tangential shrinkage of Injibara bamboo at the age of 1, 2, and 3 years old in November is 23%, 18%, and 22% higher than in February, whereas Kombolcha bamboo in November is 2%, 11%, and 6% higher than February, and Mekaneselam bamboo in November is 20%, 28%, and 22% higher than February, respectively. Depending on the moisture contents and shrinkage in wall thickness considered, 3 years old and February of the culm are suited for structural application and furniture making, but the 2-year-old and November of the culm are suited for fiber extraction without damage to the fibers. The existence of water in the culm improves the easy extraction of the fibers from the culm.

Therefore, the moisture content of young's age of the bamboo culm is higher compared to old age due to the number and development of vascular bundles of the fibre sheath increased and the parenchyma of the bamboo culm decreased when the age of the bamboo culm becomes mature. The parenchyma of the bamboo culm absorbs and holds up large amounts of water like a sponge. The vascular bundles of the bamboo culm absorb and hold up low water moisture content during cell growth and development.

4.3 Result and discussion on the chemical properties of bamboo fibres

The chemical compositions of Ethiopian bamboo fibres and other bamboo species are presented in Table 4.20. From the highest to the lowest cellulose content are Injibara, Mekaneselam, and Kombolcha, respectively. From the highest to the lowest cellulose, hemicellulose, and lignin content are at the ages of 2, 3, and 1 year, respectively. The percentage of cellulose contents has a higher value recorded compared to hemicellulose contents. Kombolcha and Mekaneselam have higher lignin contents compared to hemicellulose contents, however, Injibara bamboo fibres have higher hemicellulose contents compared to lignin contents. The ash content is a lower value compared to extractive content.

Table 4. 20: chemical composition of bamboo fibres (Nahar et al., 2013; Cao et al., 2014; Li et al., 2015; Delphine E.C. Depuydt, Sweygers, et al., 2019; Martijanti et al., 2021)

B. species	Age (yrs)	Cellulose (%)	H.cellulose (%)	Lignin (%)	Extractive (%)	Ash (%)
GAK	1–3	54.6±1.2	14±0.3	31.4±1	0.7±0.5	0.6±0.1
	3–5	53.7±0.2	15.2±0.5	31±0.1	0.5±0.4	5.0±0.4
DMM	1	58.5±0.4	15.3±0.3	26.7±0.4	0.0±0.3	0.3±0.2
	3	50.4±0.3	16.8±0.1	32.8±0.7	9.7±0.6	0.1±0
PNB	0.75	52.8±1	17.9±1	29.3±0.5	7.9±0.6	0.2±0
	2–4	49.2±0.2	16.5±0.1	34.2±0.4	4.7±0.4	0.5±0.1
Bamboo Tali	–	46.91	17.29	21.3	–	–
Bamboo haur Hejo	–	52.3	19.15	20.01	–	–
Bambosa vulgaris	–	50.23±0.18	16.85±0.09	23.91±0.58	5.07±0.06	1.38±0.05
Dendrocalamophsis oldhami	2	45±0.1	26.1	20.9±0.1	3.9±0.1	1.5±0.2
Moso bamboo	1-5	44.64±2.9	23.65±2.53	20.35±1.84	–	–
Y. alpina	–	46.76±1.09	12.18±1.01	25.27±1.52	3.93±3.34	3.77±0.86
Injibara	1	51±1.7	20±1.2	19±1.0	4.5±0.2	2.1±0.1
	2	53±1.8	23±1.1	21±1.1	4.4±0.2	1.9±0.1
	3	52±1.8	22±1.0	20±1.0	3.9±0.2	1.6±0.1
Kombolcha	1	45.7±1.6	17±1.0	27±1.2	7.8±0.4	3.5±0.2
	2	48.7±1.5	19±0.9	29±1.1	7.3±0.5	3.1±0.1
	3	46±1.5	18±0.9	28±1.1	6.6±0.3	2.8±0.1
Mekaneselam	1	48.7±1.8	18±1.0	21±1.1	5.2±0.1	2.5±0.1
	2	51.7±1.6	20±1.0	24±1.1	5.1±0.2	2.0±0.1
	3	49.7±1.5	19±1.1	23±1.0	4.7±0.2	1.9±0.1

4.3.1 Measurements of chemical composition

Cellulose content

The influence of age and height on the cellulose content is shown in Figure 4.25. The cellulose content increases from the bottom to the top along with the height. The highest to the lowest cellulose content is at the ages of 2, 3, and 1 years, and in Injibara, Mekaneselam, and

Kombolcha bamboo, respectively. The mean cellulose contents of Injibara bamboo at the ages of 1, 2, and 3 years are 51±1.7%, 53±1.8%, and 52±1.8%, whereas Kombolcha bamboo fibres are 45.7±1.6%, 48.7±1.5%, and 46±1.5%, and Mekaneselam bamboo is 48.7±1.8%, 51.7±1.6%, and 49.7±1.5%, respectively. The cellulose content of 2-year-old Injibara, Kombolcha, and Mekaneselam bamboo fibres have 4%, 7%, and 6% higher compared to 1-year-old, respectively. The top parts of Injibara, Kombelcha, and Mekaneselam bamboo have 4%, 6%, and 6% higher cellulose content compared to the bottom at the ages of 2 years old, respectively.

Ages 1, 2, and 3 years of Injibara bamboo fibres have 10%, 8%, and 12% higher cellulose content than Kombolcha, and 5%, 3%, and 4% higher than Mekaneselam, whereas Mekaneselam bamboo fibres have 6%, 8%, and 7% higher cellulose content than Kombolcha, respectively.

As presented in Table 4.20, the cellulose content of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 6%, 3%, and 5% lower than GAK (1-3), 5%, 1%, and 3% lower than GAK (3-5), 13%, 9%, and 11% lower than DMM (1), respectively. However, it is 1%, 5%, and 3% higher than DMM (3), 4%, 7%, and 5% higher than PNB (2-4), 8%, 11%, and 10% higher than *Bamboo Tali*; 2%, 5%, and 3% higher than *Bambusa vulgaris*, 12%, 15%, and 13% higher than *Dendrocalamophsis oldhamii*, and 13%, 16%, and 14% higher than *Moso bamboo* (1–5), respectively. Moreover, it has a similar cellulose content to PNB (0.75), and *Bambusa haur Hejo*. Moreover, the cellulose content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years is 16%, 11%, and 16% lower than GAK (1-3), 15%, 9%, and 14% lower than GAK (3-5), 22%, 17%, and 21% lower than DMM (1); 9%, 3%, and 8% higher than DMM (3); 13%, 8%, and 13% higher than PNB (0.75); 7%, 1%, and 6% higher than PNB (2–4); 13%, 8%, and 13% is lower than Bamboo Haur Hejo, 9%, 3%, and 8% higher than *Bambusa vulgaris*, respectively. However, it is 1%, 8%, and 2% higher than *Dendrocalamophsis oldhami*, and 1.5%, 8%, and 3% higher than *Moso bamboo* (1–5), respectively. Moreover, it has a similar cellulose content to *Bambusa Tali*. Furthermore, the cellulose content of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years is 11%, 5%, and 9% lower than GAK (1–3), 9%, 4%, and 7% lower than GAK (3–5), 17%, 12%, and 15% lower than DMM (1), 8%, 2%, and 6% higher than PNB (0.75). respectively. However, it is 4%, 9%, and 6% higher than *Bamboo Tali*; 8%, 2%, and 6% higher than *Bamboo Haur Hejo*; 8%, 13%, and 9%

higher than *Dendrocalamophsis oldhami*; and 8%, 14%, and 10% higher than *Moso Bamboo* (1–5), respectively.

Moreover, it has a similar cellulose content to DMM(3), PNB(2-4), and *Bambosa vulgaris*.

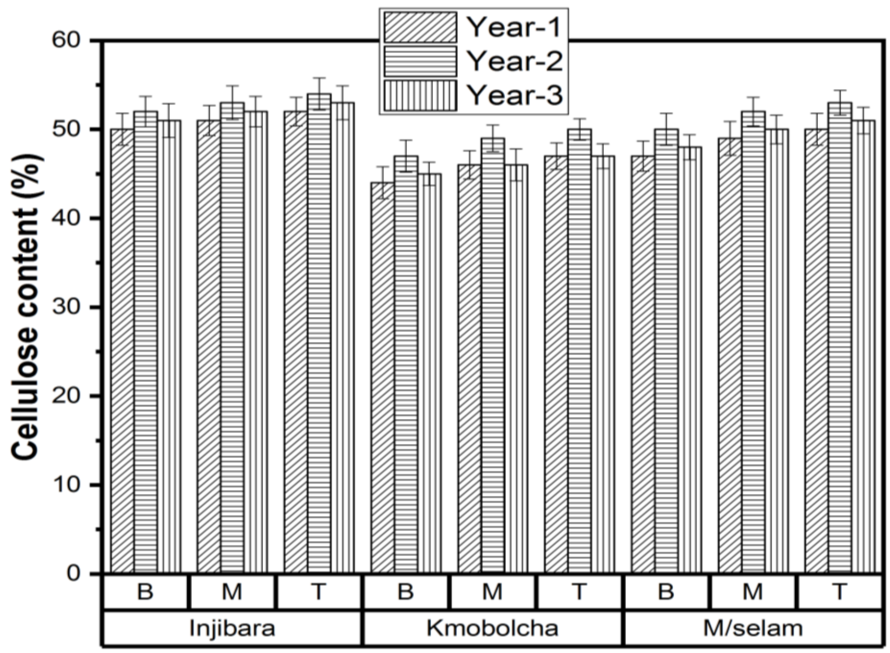


FIGURE.4.25: The effect of age and height on the cellulose content.

Hemicelluloses content

The effect of age and height on the hemicellulose content is shown in Figure 4.26. The hemicellulose content increases from the bottom to the top along the height. The highest to the lowest cellulose content is at the ages of 2, 3, and 1 year, respectively.

Injibara and Kombolcha bamboo fibres have the highest and lowest hemicellulose content, respectively. The mean hemicellulose contents of Injibara bamboo fibres at the ages of 1, 2, and 3 years are 20±1.12%, 23±1.1%, and 22±1.0%, whereas Kombolcha bamboo fibres are 17±1.0%, 19±0.9%, and 18±0.9%, and Mekaneselam bamboo fibres are 18±1.0%, 20±1.0%, and 19±1.1% respectively.

The hemicellulose content of 2-year-old (the highest) Injibara, Kombolcha, and Mekaneselam bamboo fibres is 13%, 10%, and 9% higher compared to 1-year-old (the lowest), respectively. The top part of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 10%, 8%, and 9% higher, whereas Kombolcha bamboo fibres are 16%, 14%, and 15% higher, and Mekaneselam bamboo fibres are 15%, 13%, and 14% higher in hemicellulose content compared to the bottom, respectively.

Ages 1, 2, and 3 years of Injibara bamboo fibres have 15%, 17%, and 18% higher hemicellulose content than Kombolcha, and 10%, 13%, and 14% higher than Mekaneselam, whereas Mekaneselam bamboo fibres have 6%, 5%, and 5% higher hemicellulose content than Kombolcha, respectively.

As presented in Table 4.20, the hemicellulose content of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 30%, 39%, and 36% higher than GAK (1–3); 24%, 34%, and 31% higher than GAK (3–5); 24%, 33%, and 30% higher than DMM (1); 16%, 27%, and 24% higher than DMM (3); 11%, 22%, and 19% higher than PNB (0.75); 18%, 28%, and 25% higher than PNB (2-4); 14%, 25%, and 21% higher than *Bamboo Tali*; 4%, 17%, and 13% higher than *Bamboo Haur Hejo*; 16%, 27%, and 23% higher than *Bambosa vulgaris*; and 39%, 47%, and 45% higher than *Y. alpina*; respectively. However, it is 23%, 12%, and 16% lower than *Dendrocalamophsis oldhami*; 15%, 3%, and 7% lower than *Bamboo Moso* (1–5), respectively.

Moreover, the hemicellulose content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years is 18%, 26%, and 22% higher than GAK (1–3); 11%, 20%, and 16% higher than GAK (3–5); 10%, 19%, and 15% higher than DMM (1); 1%, 12%, and 7% higher than DMM (3); a similar, 6%, and 5% higher than PNB (0.75); 3%, 13%, and 8% higher than PNB (2–4); a similar, 9%, and 4% higher than Bamboo Tali; 12%, a similar, and 6% higher than *Bamboo Haur Hejo*; 1%, 11%, and 6% higher than *Bambosa vulgaris*; and 28%, 36%, and 32% higher than *Y. alpina*, respectively.

However, it has 35%, 27%, and 31% lower than *Dendrocalamophsis oldhami*, and 28%, 36%, and 32% lower than *Bamboo Moso* (1–5), respectively.

Furthermore, the hemicellulose content of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years is 22%, 30%, and 26% higher than GAK (1–3); 16%, 24%, and 20% higher than GAK (3–5); 15%, 24%, and 19% higher than DMM (1); 7%, 16%, and 12% higher than DMM (3); a similar, 11%, and 6% higher than PNB (0.75); 8%, 18%, and 13% higher than PNB (2–4); 4%, 14%, and 9% higher than *Bamboo Tali*; 6%, 4%, and 1% higher than *Bamboo Haur Hejo*; 6%, 16%, and 11% higher than *Bambosa vulgaris*, and 32%, 39%, and 36% higher than *Y. alpina*, respectively. However, it has 31%, 23%, and 27% lower than *Dendrocalamophsis oldhami*, and 24%, 15%, and 20% lower than Bamboo Moso (1–5), respectively.

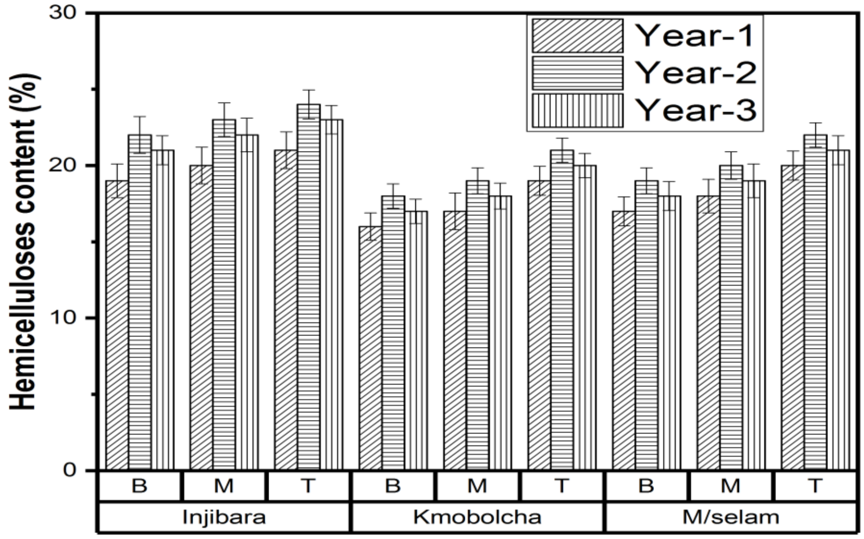


FIGURE 4.26: The effect of age and height on the hemicellulose content of fibres in Ethiopia.

<u>The lignin content</u>

The effect of age and height on the lignin content is shown in Figure 4.27. The lignin content increases from the bottom to the top along the height. The highest to the lowest cellulose content is at the ages of 2, 3, and 1 year old, respectively. Kombolcha and Injibara bamboo fibres have the highest and lowest lignin content, respectively. The mean lignin contents of Injibara bamboo fibres at the ages of 1, 2, and 3 years are 19±1.0%, 21±1.1%, and 20±1.0%, whereas Kombolcha bamboo fibres are 27±1.2%, 29±1.1%, and 28±1.1%, and Mekaneselam bamboo fibres are 21±1.1%, 24±1.1%, and 23±1.0%, respectively.

The lignin content of 2-year-old (the highest) Injibara, Kombolcha, and Mekaneselam bamboo fibres is 10%, 7%, and 13% higher than 1-year-old (the lowest), respectively. The top part of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 10%, 13%, and 9% higher, whereas Kombolcha bamboo fibres are 11%, 13%, and 13% higher, and Mekaneselam bamboo fibres are 9%, 8%, and 8% higher in lignin content compared to the bottom, respectively. The ages of 1, 2, and 3 years of Kombolcha bamboo fibres have 30%, 28%, and 29% higher lignin content than Injibara, and 22%, 17%, and 18% higher than Mekaneselam bamboo fibres, respectively. The highest and lowest percentage of lignin content are found in Injibara and Kombolcha bamboo fibres, whereas Mekaneselam bamboo fibres have 10%, 12%, and 13% higher lignin content than Injibara bamboo fibres, respectively.

As presented in Table 4.20, the lignin content of Injibara bamboo fibres at the ages of 1, 2, and 3 years has 39%, 33%, and 36% lower than GAK (1–3); 39%, 32%, and 35% lower than GAK (3–5); 29%, 21%, and 25% lower than DMM (1); 42%, 36%, and 39% lower than DMM (3); 35%, 28%, and 32% lower than PNB (0.75); 44%, 39%, and 42% lower than PNB (2-4); 5% lower, 5% higher, and 1% higher than *Bamboo Haur Hejo*; 21%, 12%, and 16% lower than *Bambosa vulgaris*; 25%, 17%, and 21% lower than Y. alpina; moreover, Injibara bamboo fibres at the age of 1and 3 years has 6% and 4% lower than *Dendrocalamophsis oldhami* and 7% and 2% higher than Bamboo Moso (1-5) as well as it 11% and 6%, but it is similar values with *Dendrocalamophsis oldhami* and *Bamboo Tali*, respectively.

Moreover, the lignin content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years is 14%, 8%, and 11% lower than GAK (1–3); 13%, 6%, and 10% lower than GAK (3–5); 17%, 12%, and 15% lower than DMM (3); 8%, 1%, and 4% lower than PNB (0.75); 21%, 15%, and 18% lower than PNB (2–4), however, it is 21%, 27%, and 24% higher than Bamboo Tali; 26%, 31%, and 28% higher than Bamboo Haur Hejo; 11%, 18%, and 15% higher than *Bambosa vulgaris*; 6%, 13%, and 10% higher than *Y. alpina*; 23%, 28%, and 25% higher than *Dendrocalamophsis oldhami*, and 25%, 30%, and 27% higher than Bamboo Moso (1–5), moreover, Injibara bamboo fibres at the age of 2 and 3 years has 8% and 5% higher than DMM (1), but one year has a comparable to DMM (1), respectively.

Furthermore, the lignin content of Mekaneselam bamboo fibres at the ages of 1, 2, and 3 years is 33%, 24%, and 27% lower than GAK (1–3); 32%, 23%, and 26% lower than GAK (3–5); 36%, 27%, and 30% lower than DMM (3); 28%, 18%, and 22% lower than PNB (0.75); 39%, 30%, and 33% lower than PNB (2-4); 16%, 5%, and 9% lower than *Y. alpina*. However, it has 21%, 10%, and 14% higher than DMM (1); and 5%, 16%, and 13% higher than Bamboo Haur Hejo; 23%, 28%, and 25% higher than *Dendrocalamophsis oldhami*, and 1%, 15%, and 11% higher than Bamboo Moso (1–5), respectively. Mekaneselam bamboo fibres at the age of 1 and 3 years have 12% and 1% higher than *Bambosa vulgaris*, but it comparable values with *Bambosa vulgaris* and *Bamboo Tali* and *Bambosa vulgaris* at the age of 2 and 1 years, respectively.

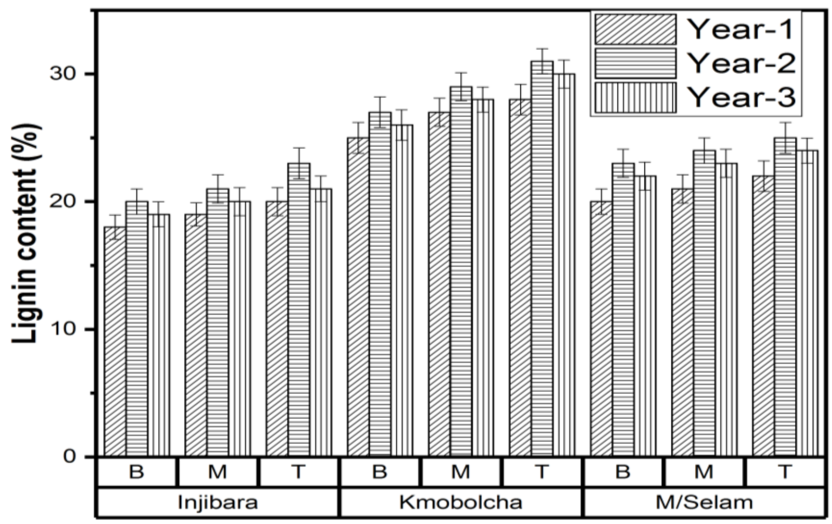


FIGURE 4.27: The effect of age and height on the lignin content of fibres in Ethiopia.

Extractive content

The effect of age and height on the extractive content is shown in Figure 4.28. The extractive content decreases from the bottom to the top along with the height and the age of the bamboo culm maturity. Kombolcha and Injibara bamboo fibres have the highest and lowest extractive content, respectively. The extractive contents of Injibara bamboo fibres at the ages of 1, 2, and 3 years are 4.5±0.2%, 4.4±0.2&, and 3.9±0.2%, whereas Kombolcha bamboo fibres are 7.8±0.4, 7.3±0.5, and 6.6±0.3, and Mekaneselam bamboo fibres are 5.2±0.1%, 5.1±0.2%, and 4.7±0.2%, respectively.

The extractive content of 1-year-old (the highest) Injibara, Kombolcha, and Mekaneselam bamboo fibres have 13%, 15%, and 10% higher than 3 years old (the lowest), respectively. The bottom part of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 10%, 11%, and 27% higher, whereas Kombolcha bamboo fibres are 14%, 10%, and 9% higher, and Mekaneselam bamboo fibres are 13%, 16%, and 10% higher extractive content compared to the top, respectively. The ages of 1, 2, and 3 years of Kombolcha bamboo fibres have 42%, 40%, and 41% higher extractive content than Injibara, and 33%, 30%, and 29% higher than Mekaneselam bamboo fibres, whereas Mekaneselam bamboo fibres have 13%, 14%, and 17% higher extractive content than Injibara bamboo fibres, respectively.

As presented in Table 4.20, the extractive content of the current research results is higher extractive content compared to GAK (1–3), GAK (3–5), *Y. alpina*, *Dendrocalamophsis* *oldhami*, and DMM (1). However, they are lower extractive contents compared to DMM (3), PNB (0.75), PNB (2-4), and Bambusa vulgaris.

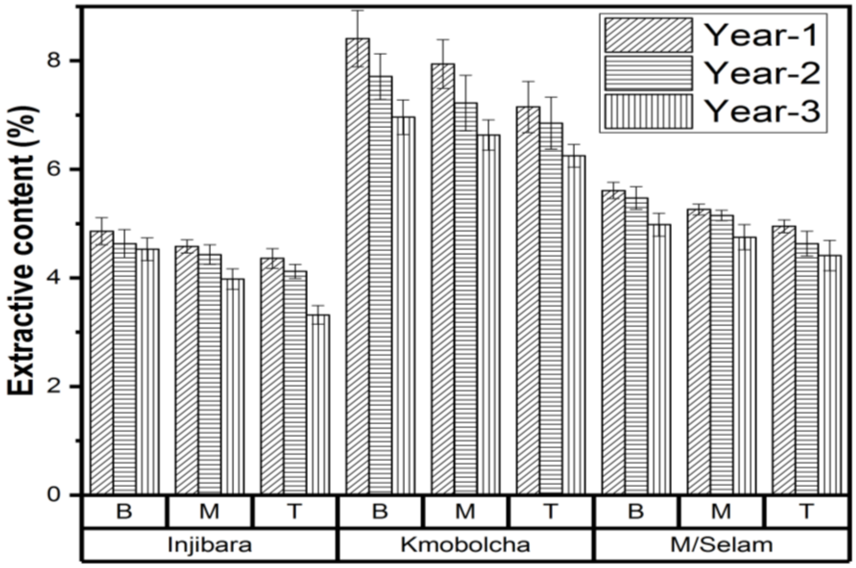


FIGURE 4.28: The effect of age and height on the extractive content of fibres in Ethiopia

Ash-content

The effect of age and height on the ash content is shown in Figure 4.29. The ash content decreased from the top to the bottom along with the height, and the age of the bamboo culm matured. Kombolcha and Injibara bamboo fibres have the highest and lowest ash content, respectively. The ash contents of Injibara bamboo fibres at the ages of 1, 2, and 3 years are 2.1±0.1%, 1.9±0.1%, and 1.6±0.1%, whereas Kombolcha bamboo fibres are 3.5±0.2%, 3.1±0.1%, and 2.8±0.1%, and Mekaneselam bamboo fibres are 2.5±0.1%, 2.0±0.1%, and 1.9±0.1% respectively.

The ash content of 1-year-old (the highest) Injibara, Kombolcha, and Mekaneselam bamboo fibres is 24%, 20%, and 24% higher than 3 years old (the lowest), respectively. The top part of Injibara bamboo fibres at the ages of 1, 2, and 3 years is 17%, 32%, and 50% higher, whereas Kombolcha bamboo fibres are 8%, 18%, and 19% higher, and Mekaneselam bamboo fibres are 15%, 22%, and 27% higher in ash content compared to the bottom, respectively. The ages of 1, 2, and 3 years of Kombolcha bamboo fibres have 40%, 39%, and 43% higher ash content than Injibara, and 29%, 35%, and 32% higher than Mekaneselam bamboo fibres, respectively, whereas Mekaneselam bamboo fibres have 16%, 5%, and 16% higher ash content than Injibara bamboo fibres, respectively.

Bambosa vulgaris bamboo has 1.38% of ash content, which is a lower ash content than Injibara, Kombolcha, and Mekaneselam bamboo fibres (Nahar et al., 2013). *Y. alpina* at the age of 3 years old has 3.77% of ash content, which has a higher ash content than Injibara, Kombolcha, and Mekaneselam bamboo fibres (Mahelete Tsegaye et al., 2020). *G. atroviolacea* bamboo has 3.29% of ash content, which has a higher ash content than Injibara, Kombolcha, and Mekaneselam bamboo fibres. However, *G. apus* and *G. levis have* 2.45%, and 2.46% of ash content respectively, which they have a lower ash content than Injibara, Kombolcha, and Mekaneselam bamboo fibres (Purbasari et al., 2016). *Dendrocalamopsis oldhami* bamboo has 1.5% of ash content, which has lower ash content than Injibara, Kombolcha, and Mekaneselam bamboo fibres (Cao et al., 2014).

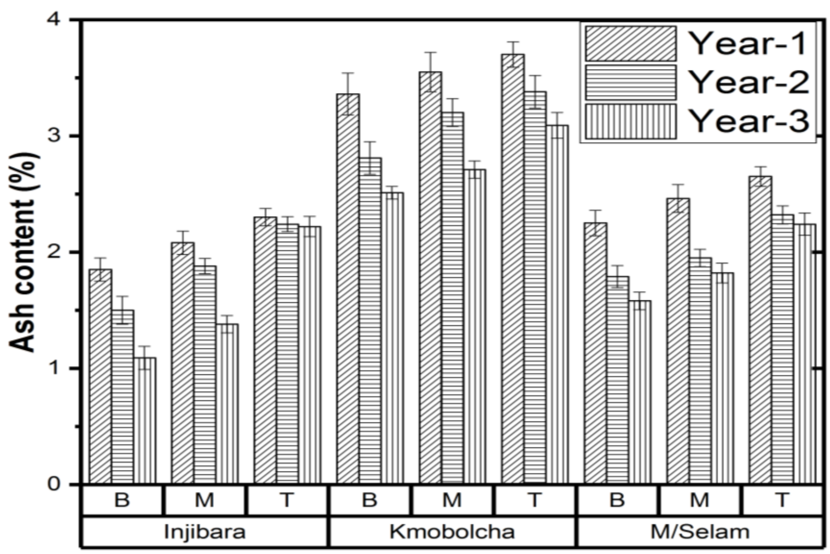


FIGURE 4. 29: The effect of age and height on the ash content of fibres in Ethiopia

4.3.2 Chemical composition of Injibara bamboo using ANOVA

<u>The cellulose content</u>

As presented in Table 4.21, the linear regression of the cellulose of Injibara bamboo culm at the model and residual of $F(2,42)=14.80$, $P= 0.0000$), and R- squared of 60% is statistically significant on the mean of cellulose content. Moreover, the age is statistically significant, but the culm height is not statistically significant in the mean cellulose content. The linear equation of cellulose content is calculated as follows:

Cellulose content = 1.22Year + 0.06Height + 47.77.

Table 4. 21: Cellulose content of bamboo culm for Injibara bamboo

Cellulose	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	1.22	0.22	5.43	0.001	0.76	1.67
Height	0.06	0.22	0.27	0.792	- 0.39	0.51
cons.	47.77	0.66	72.57	0.001	46.44	49.09

Hemicelluloses content

As presented in Table 4.22, the linear regression of the hemicellulose of Injibara bamboo culm at the model and residual of *F*(2,42)=1.99, *P*= 0.0867), and R- squared of 12% is not statistically significant on the mean of hemicellulose content. Moreover, the ages and culm height are not statistically significant on the mean of hemicellulose content. The linear equation of hemicellulose content is calculated as follows:

hemicellulose content = -0.16Year + 0.41Height + 18.49.

Table 4. 22: Hemicelluloses content of bamboo culm for Injibara bamboo

Hemicellulose	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-0.16	0.22	-0.73	0.471	-0.59	0.28
Height	0.41	0.22	1.86	0.07	-0.03	0.84
cons.	18.49	0.64	28.85	0.001	17.21	19.79

The lignin content

As presented in Table 4.23, the linear regression of the lignin of Injibara bamboo culm at the model and residual of *F*(2,42)=7.47, *P*= 0.0017), and R- squared of 36% is statistically significant on the mean of hemicellulose content. Moreover, the age is statistically significant, however, the culm height is not statistically significant on the mean of lignin content. The linear equation of lignin content is calculated as follows:

Lignin content = 0.87Year – 0.25Height + 22.27.

Table 4. 23: Lignin content of bamboo culm for Injibara bamboo

Lignin	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	0.87	0.23	3.72	0.001	0.39	1.34
Height	-0.25	0.23	-1.6	0.295	-0.72	0.22
cons.	22.27	0.69	32.33	0.000	20.88	23.66

Extractives content

As presented in Table 4.24, the linear regression of the extractive content of Injibara bamboo culm at the model and residual of *F*(2,42)=68.15, *P*= 0.0000), and R- squared of 76% is statistically significant on the mean of extractive content. Moreover, the ages and culm height are statistically significant on the mean of extractive content. The linear equation of extractive content is calculated as follows:

Extractive content = -0.63Year – 0.98Height + 8.51

Table 4. 24: Extractives content of bamboo culm for Injibara bamboo

Extractives	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-0.63	0.09	-6.32	0.000	-0.83	-0.43
Height	-0.98	0.09	-9.81	0.000	-1.18	-0.78
cons.	8.51	0.29	29.01	0.000	7.92	9.11

Ash content

As presented in Table 4.25, the linear regression of the extractive content of Injibara bamboo culm at the model and residual of *F*(2,42)=24.92, *P*= 0.0000), and R- squared of 54% is statistically significant on the mean of ash content. Moreover, the ages and culm height are statistically significant on the mean of ash content. The linear equation of ash content is calculated as follows:

Ash content = -0.15Year – 0.38Height + 2.94

Table 4. 25: Ash content of bamboo culm for Injibara bamboo

Ash	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-0.15	0.06	-2.52	0.015	-0.26	-0.03
Height	-0.38	0.06	-6.59	0.000	-0.49	-0.27
cons.	2.94	0.17	17.23	0.000	2.59	3.29

4.3.3 Chemical composition of Kombolcha bamboo using ANOVA

The cellulose content

As presented in Table 4.26, the linear regression of the cellulose of Kombolcha bamboo culm at the model and residual of *F*(2,42)=88.57, *P*= 0.0000), and R- squared of 81% is statistically significant on the mean of cellulose content. Moreover, the age is statistically significant, but the culm height is not statistically significant in the mean cellulose content. The linear equation of cellulose content is calculated as follows:

Cellulose content = 2.72Year – 0.16Height + 40.48.

Table 4. 26: Cellulose content of bamboo culm for Kombolcha bamboo

Cellulose	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	2.72	0.21	13.28	0.000	2.31	3.14
Height	-0.16	0.21	-0.8	0.427	-0.58	0.25
cons.	40.48	0.6	67.11	0.000	39.27	41.71

Hemicelluloses content

As presented in Table 4.27, the linear regression of the hemicellulose of Kombolcha bamboo culm at the model and residual of *F*(2,42)=250.76, *P*= 0.0000), and R- squared of 92% is statistically significant on the mean of hemicellulose content. Moreover, the ages are statistically significant, but the culm height is not statistically significant on the mean of hemicellulose content. The linear equation of hemicellulose content is calculated as follows:

Hemicellulose content = -1.95Year + 0.04Height + 25.6.

Table 4. 27: Hemicellulose content of bamboo culm for Kombolcha bamboo

Hemicellulose	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-1.95	0.09	-22.39	0.000	-2.13	-1.77
Height	0.04	0.09	0.44	0.659	-0.14	0.21
cons.	25.6	0.26	99.87	0.000	25.08	26.12

The lignin content

As presented in Table 4.28, the linear regression of the lignin of Kombolcha bamboo culm at the model and residual of *F*(2,42)=464.23, *P*= 0.0000), and R- squared of 96% is statistically significant on the mean of lignin content.

Moreover, the ages and height are statistically significant on the mean of the lignin content. The linear equation of lignin content is calculated as follows:

lignin content = 1.48Year + 0.3Height + 17.39.

Table 4. 28: Lignin content of bamboo culm for Kombolcha bamboo

Lignin	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	1.48	0.05	29.87	0.000	1.38	1.58
Height	0.29	0.05	6.01	0.000	0.19	0.39
cons.	17.39	0.15	119.36	0.000	17.09	17.69

Extractives content

As presented in Table 4.29, the linear regression of the extractive content of Kombolcha bamboo culm at the model and residual of $F(2,42)=464.23$, $P= 0.0000$), and R- squared of 96% is statistically significant on the mean of extractive content. Moreover, the ages and height are statistically significant on the mean of the extractives content. The linear equation of extractives content is calculated as follows:

Extractives content = -1.74Year - 0.5Height + 13.99.

Table 4. 29: Extractives content of bamboo culm for Kombolcha bamboo

Extractive	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-1.74	0.12	-14.99	0.000	-1.97	-1.5
Height	-0.5	0.12	-4.31	0.000	-0.73	-0.27
cons.	13.99	0.34	41.03	0.000	13.29	14.67

Ash content

As presented in Table 4.30, the linear regression of the ash content of Kombolcha bamboo culm at the model and residual of $F(2,42)=200.09$, $P= 0.0000$), and R- squared of 91% is statistically significant on the mean of ash content. Moreover, the ages and height are statistically significant in the mean of the ash content. The linear equation of ash content is calculated as follows:

Ash content = -0.38Year + 0.25Height + 2.4.

Table 4. 30: Ash content of bamboo culm for Kombolcha bamboo

Ash	Coef.	Std.Err.	t	p>/t/	[95% Conf. Interval]	
Year	-0.38	0.02	-16.82	0.000	0.43	-0.34
Height	0.25	0.02	10.83	0.000	0.2	0.29
cons.	2.4	0.07	35.78	0.000	2.27	2.54

4.3.4 Chemical composition of Mekaneselam bamboo using ANOVA

The cellulose content

As presented in Table 4.31, the linear regression of the cellulose of Mekaneselam bamboo culm at the model and residual of $F(2,42)=9.39$, $\alpha = 0.0000$), and R- squared of 31% is statistically significant on the mean of cellulose content. Moreover, the ages and culm height are statistically significant on the mean of cellulose content. The linear equation of cellulose content is calculated as follows:

Cellulose content = 0.18Year – 0.15Height + 53.54.

Table 4. 31: Cellulose content of bamboo culm for Mekaneselam bamboo

CC	Coef.	Std.Err.	t	α >/t/	[95% Conf. Interval]	
Year	0.18	0.06	3.32	0.002	0.07	0.29
Height	-0.15	0.06	-2.79	0.008	-0.26	-0.04
cons.	53.54	0.16	330.51	0.000	53.21	53.86

Hemicelluloses content

As presented in Table 4.32, the linear regression of the hemicellulose of Mekaneselam bamboo culm at the model and residual of $F(2,42)=79.42$, α = 0.0000), and R- squared of 79% is statistically significant on the mean of hemicellulose content. Moreover, the ages and culm height are statistically significant on the mean of hemicellulose content. The linear equation of hemicellulose content is calculated as follows:

Hemicellulose content = -0.84Year – 0.37Height + 19.91.

Table 4. 32: Hemicelluloses content of bamboo culm for Mekaneselam bamboo

Hemicellulose	Coef.	Std.Err.	t	α >/t/	[95% Conf. Interval]	
Year	-0.84	0.07	-11.54	0.000	-0.99	-0.69
Height	-0.37	0.07	-5.07	0.000	-0.52	-0.22
cons.	19.91	0.21	92.95	0.000	19.47	20.34

The lignin content

As presented in Table 4.33, the linear regression of the lignin content of Mekaneselam bamboo culm at the model and residual of $F(2,42)=22.45$, α = 0.0000), and R- squared of 52% is statistically significant on the mean of lignin content.

Moreover, the age is statistically significant, However, culm height is statistically insignificant on the mean of lignin content. The linear equation of lignin content is calculated as follows:

Lignin content = 0.29Year + 0.05Height + 22.00.

Table 4. 33: Lignin content of bamboo culm for Mekaneselam bamboo

LC	Coef.	Std.Err.	t	α>/t/	[95% Conf. Interval]	
Year	0.29	0.04	6.61	0.000	0.2	0.38
Height	0.05	0.04	1.13	0.27	-0.04	0.14
cons.	22.01	0.13	167.55	0.000	21.74	22.27

Extractives content

As presented in Table 4.34, the linear regression of the extractives content of Mekaneselam bamboo culm at the model and residual of $F(2,42)=164.6$, $\alpha = 0.0000$), and R- squared of 87% is statistically significant on the mean of extractives content. Moreover, the ages and culm height are statistically significant on the mean of extractives content. The linear equation of extractives content is calculated as follows:

extractives content = 0.96Year + 0.29Height + 1.88.

Table 4. 34: Extractives content of bamboo culm for Mekaneselam bamboo

EC	Coef.	Std.Err.	t	α >/t/	[95% Conf. Interval]	
Year	0.96	0.06	17.38	0.000	0.85	1.07
Height	0.29	0.06	5.23	0.000	0.18	0.4
cons.	1.88	0.16	11.51	0.000	1.55	2.2

Ash content

As presented in Table 4.35, the linear regression of the ash content of Mekaneselam bamboo culm at the model and residual of $F(2,42)=65.96$, $\alpha = 0.0000$), and R- squared of 76% is statistically significant on the mean of ash content. Moreover, the age is statistically significant, Moreover culm height is not statistically significant in the mean of ash content. The linear equation of ash content is calculated as follows:

Ash content = -0.36Year - 0.06Height + 2.69.

Table 4. 35: Ash content of bamboo fibres for Mekaneselam

AC	Coef.	Std.Err.	t	α >/t/	[95% Conf. Interval]	
Year	-0.36	0.03	-11.33	0.000	-0.43	-0.29
Height	-0.06	0.03	-1.9	0.065	-0.13	0.004
cons.	2.69	0.09	28.62	0.000	2.51	2.89

4.3.5 Summary results of chemical properties of bamboo fibres

The purpose of this study was to investigate the effect of age and height on the chemical composition of bamboo species in Ethiopia. As a result of this research, we observed small but significant increases in cellulose, hemicellulose, and lignin content from the base to the top of the culm in all three ages. The highest and lowest cellulose, hemicellulose, and lignin content are found at the ages of 2 and 1 year, respectively.

The cellulose content of Injibara bamboo at the ages of 1, 2, and 3 years have 11%, 9%, and 12% higher than Kombolcha, and 6%, 4%, and 6% higher than Mekaneselam, respectively.

Whereas Mekaneselam bamboo has 6%, 7%, and 6% higher than Kombolcha, respectively. The hemicellulose content of Injibara bamboo fibres at the ages of 1, 2, and 3 years have 15%, 17%, and 18% higher than Kombolcha, and 10%, 13%, and 14% higher than Mekaneselam, respectively. Whereas Mekaneselam bamboo has 6%, 5%, and 6% higher than Kombolcha, respectively. The lignin content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years have 30%, 28%, and 29% higher than Injibara, and 22%, 17%, and 18% higher than Mekaneselam, respectively. Whereas Mekaneselam bamboo has 10%, 12%, and 13% higher than Injibara, respectively. The extractive content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years have 42%, 40%, and 41% higher than Injibara, and 33%, 30%, and 29% higher than Mekaneselam, respectively. Whereas Mekaneselam bamboo has 13%, 14%, and 17% higher than Injibara, respectively. The ash content of Kombolcha bamboo fibres at the ages of 1, 2, and 3 years have 40%, 39%, and 43% higher than Injibara and 29%, 35%, and 32% higher than Mekaneselam, respectively. Whereas Mekaneselam bamboo has 16%, 5%, and 17% higher than Injibara, respectively.

The highest value of cellulose, hemicellulose and lignin content of Kombolcha bamboo at the age of 2 years has 6%, 11%, and 7% higher than the lowest value at the age of 1 year, respectively. Whereas the highest value of extractive and ash contents of Kombolcha at the age of 1 year has 15% and 20% higher than the lowest value at the age of 3 years, respectively. The highest value of cellulose, hemicellulose and lignin content of Mekaneselam bamboo at the age of 2 years has 6%, 10%, and 13% higher than the lowest value at the age of 1 year, respectively. Whereas the highest value of extractive and ash contents of Mekanselam at the age of 1 year has 10% and 24% higher than the lowest value at the age of 3 years, respectively. The highest value of cellulose, hemicellulose, and lignin content of Injibara bamboo at the age of 2 years has 4%, 13%, and 10% higher than the lowest value at the age of 1 year, respectively. Whereas The highest value of extractive and ash contents of Injibara at the age of 1 year has 13% and 24% higher than the lowest value at the age of 3 years, respectively.

The extractives content of bamboo fibres decreased when the age of culm was older, and its move from the bottom to the top position. The ash content of bamboo fibres increased from the bottom to the top position, but it decreases when the age of the culm is older. This result demonstrated that bamboo species in Ethiopia can be a potential feedstock for lignocellulose ethanol and bamboo fibres composite production since it has a higher cellulose content. Based on the analysis results of the chemical composition of bamboo species in Ethiopia, it may be declared that it has good potential as raw materials for fibre composite production which substitute for glass fibres.

Therefore, extractive content in the chemical composition is removed and soluble from the bamboo fibres during alcohol treatment as waste. The bamboo culm develops a more vascular bundle during growth and matures which is substituted by celluloses, hemicelluloses and lignin. The alcohol soluble materials like wax and fat are more when the bamboo culm a younger stage due to the low content of vascular bundles which the extractive contents are the highest at a younger age compared to an older age.

4.4 Result and discussion on the tensile strength of single bamboo fibres

4.4.1 Distribution of fibres diameter

The fibres diameter was determined using the weight of individual fibres and the apparent average fibres density. For practical reasons, only the area weight method was used to determine the area of all tested fibres (400 specimens). The fibre diameter distribution of all tested fibres is presented in Figure 4.30 (diameter calculated from the area by assuming a circular shape), also distinguishing between a thick and a thin fraction. The range of fibre diameter of Injibara, Kombolcha, and Mekaneselam bamboo is 100–500 µm, 50–500 µm, and 100–450 µm, respectively. The highest distribution of fibre diameter range of Injibara, Kombolcha, and Mekaneselam bamboo is 250–300 µm, 200–250 µm, and 350–400 µm, respectively. Kombolcha bamboo fibres have the lowest measured fibre diameter compared to Injibara and Mekaneselam bamboo.

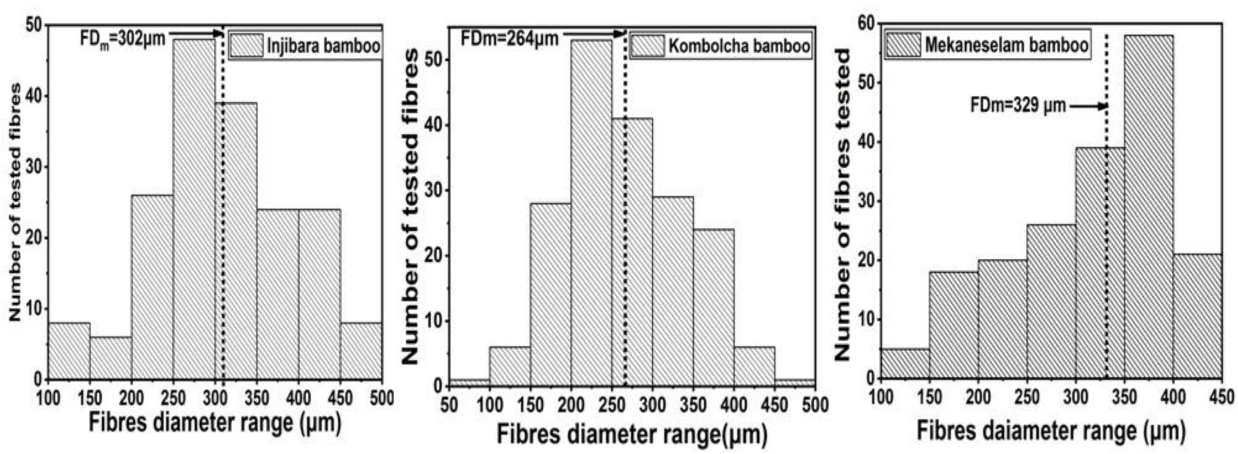


FIGURE 4.30: Two halves of the fibre population (Nt=400) (a) Injibara, (b) Kombolcha, and (c) Mekaneselam

4.4.2 Measurement of tensile strength of single bamboo fibres

The single bamboo fibres tensile strength of Ethiopian bamboo species based on the gauge length is presented in Table 4.36. The tensile strength and Young's modulus are decreased when the gauge length is increased. The maximum Young's modulus is lower than the corrected Young's modulus due to slippage of fibres during tensile testing, then increased strain to failure. The corrected strain to failure is calculated based on the constant value of the properties of fibres and gauge length. From the highest to the lowest single fibres tensile strength and Young's modulus are Injibara, Mekaneselam, and Kombolcha.

Table 4. 36 measurements of tensile strength of single bamboo fibres

Bamboo species	GL (mm)	Emax. GPa)	Ecor. (GPa)	UTS (MPa)	ε max. (%)	εcor. (%)
Injibara	15	50±5	52±5	600±80	1.31±0.11	1.24±0.11
	25	43±4	45±3	580±70	1.45±0.13	1.54±0.13
	30	35±4	37±3	553±60	1.69±0.14	1.45±0.12
	40	29±3	31±3	542±55	1.6±0.13	1.53±0.13
	50	26±3	29±3	432±45	2.09±0.18	1.56±0.12
Kombolcha	15	41±5	43±5	508±50	1.09±0.09	1.05±0.08
	25	34±3	36±4	470±45	1.18±0.08	1.1±0.06
	30	29±3	31±3	385±40	1.16±0.09	1.12±0.09
	40	27±3	28±3	378±35	1.52±0.13	1.45±0.12
	50	20±2	22±2	370±35	2.18±0.19	1.57±0.13
M/selam	15	46±5	48±6	566±60	1.15±0.11	1.07±0.09
	25	41±4	43±5	528±55	1.43±0.12	1.34±0.11
	30	40±4	42±4	515±50	1.57±0.13	1.45±0.12
	40	26±3	28±3	452±45	1.71±0.13	1.59±0.13
	50	24±2	26±2	448±40	2.08±0.17	1.78±0.15

Note: GL is Gauge length, Emax. is maximum Young`s modulus, Ecor. is corrected by Young`s modulus, εmax. is the maximum strain to failure, εcor. is corrected strain to failure.

4.4.3 Correlation within-fiber diameter variations

As reported by Zhang, the sensitivity parameter (γ) is measured using the slope value of the logarithm value of CVFD versus the logarithm value of the testing gauge length (Zhang et al., 2002). Figure 4.31 describes the relation between CVFD and testing gauge length. The coefficient value R^2 of Injibara, Kombolcha, and Mekaneselam bamboo is 96.8%, 95.7%, and

93.4%, respectively, which indicates that it is a good linear fit between the logarithm value of CVFD and gauge length. The sensitivity parameter (γ) of Injibara, Kombolcha, and Mekaneselam bamboo is 0.63, 0.33, and 0.327, respectively. The equation formula of the sensitivity parameter (γ) for Injibara, Kombolcha, and Mekaneselam bamboo is ln (CVFD) = 0.63 x ln (L) + 0.707 +, ln (CVFD) = 0.33 x ln (L) + 1.638 +, and ln (CVFD) = 0.327 * ln (L) + 1.78 +, respectively.

Variations in the cross-sectional area within the length of a fibre induce variations in stress that may direct to a different overall fibre strength compared to a constant fibre cross-section with the same average area. As a measure of the within-fiber diameter variation with gauge length, the parameter was presented in Figure 4.31. This diameter is graphically determined as the slope of the logarithm of the fibre diameter coefficient variation (CVFD), versus the logarithm of the gauge length. The CVFD increased with the length of the fiber, and the exponent was 0.47 (R^2 = 90%) (E. Trujillo, 2014). According to literature reported that wool (Zhang et al., 2002) and jute (Xia et al., 2009), the sensitivity parameter (γ) was described to be 0.18 and 0.33, respectively. According to our studies, when the variation in fiber diameter is considered, the original Weibull model's strength prediction improves.

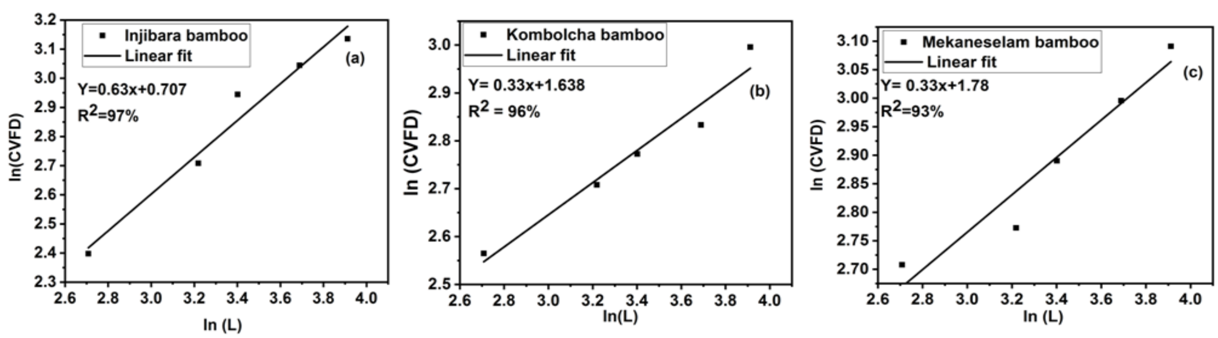


FIGURE 4.31: Change of within-fiber diameter variation with the gauge length:

(a) Injibara, (b) Kombolcha, c) Mekaneselam bamboo

Weibull plots based on Eqn. (9) for bamboo fibre of strength at 15 mm, 25 mm, 30 mm, 40 mm, and 50 mm gauge lengths are shown in Figures (4.32–4.34). In all cases, the R^2 coefficient is from 0.934 to 0.968, which shows a good linear fit. In other words, the linear regression of the fiber strength at 15 mm, 25 mm, 30 mm, 40 mm, and 50 mm gauge lengths shows a good approximation of the experimental data. The ranges of shape parameters (β) for Injibara, Kombolcha, and Mekaneselam bamboo are 6.02–7.83, 5.87–10.21, and 5.86–9.63, respectively. The shape parameters show the failure strength variability, which affects the fiber's characteristic strength.

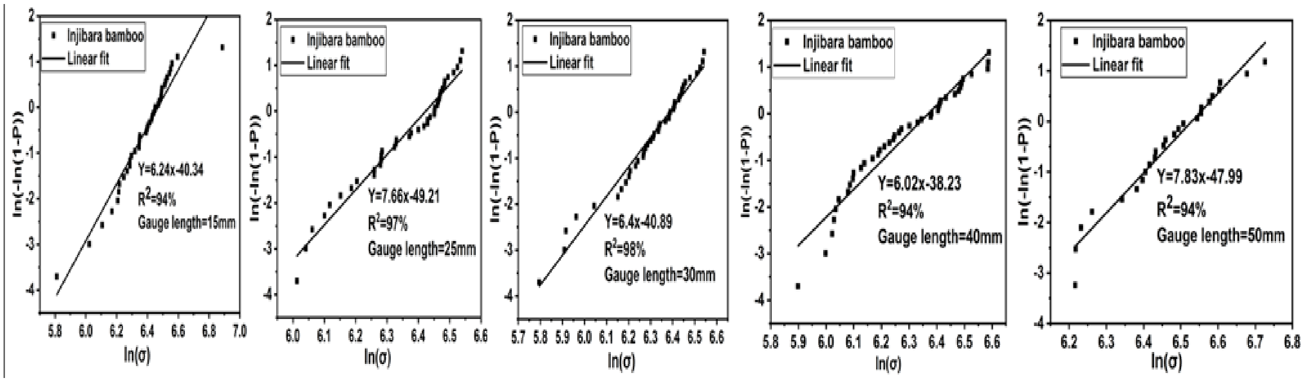


FIGURE 4. 32: Weibull plots of Injibara bamboo fiber in various testing lengths

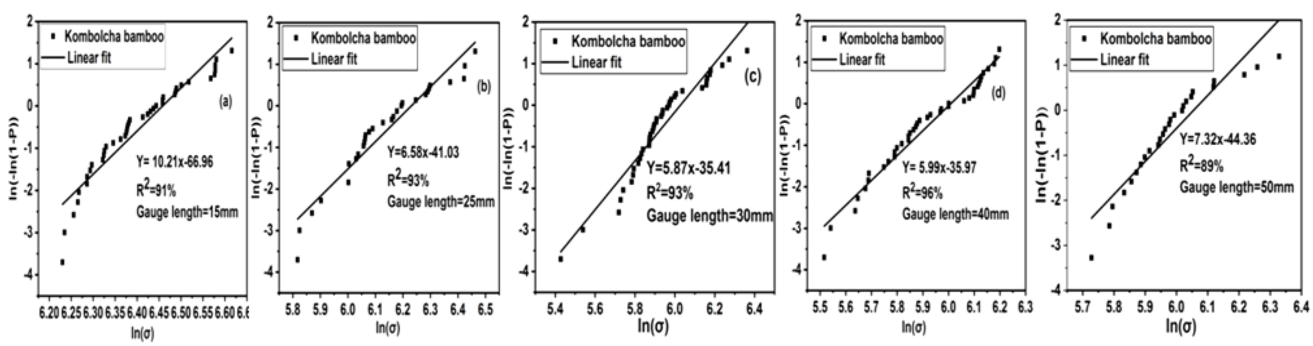


FIGURE 4.33: The Weibull plots of Kombolcha bamboo fibre in various testing lengths.

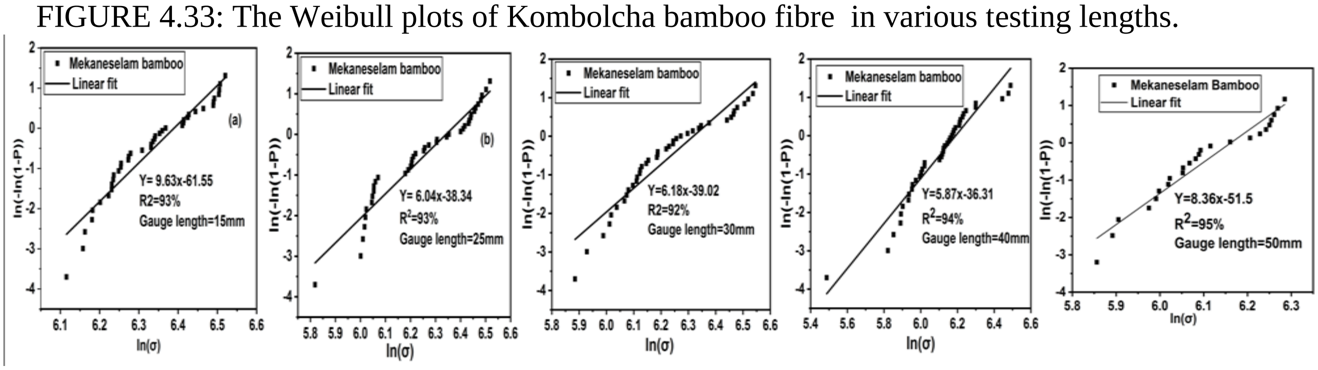


FIGURE 4. 34: The Weibull plots of Mekaneselam bamboo fibre in various testing lengths.

The sensitivity parameter, shape parameter, and characteristic strength are provided in Table 4.37. Because of the increased likelihood of a flaw in a longer testing gauge length, the characteristic strength of bamboo fiber decreases as the gauge length increases. The inherent flaw distribution along with a fiber, as well as the fiber-to-fiber strength variability within a batch of fibers, cause strength variability. Figure (4.32–4.34) depicts the distribution of tensile strength for five different test lengths of 15, 25, 30, 40, and 50 mm in Weibull coordinates to analyze the statistical distribution of fiber strength.

The sensitivity parameters of Injibara, Kombolcha, and Mekaneselam bamboo fibres are 0.23, 0.33, and 0.327, respectively. Injibara bamboo has a higher coefficient of variation of fibre diameter than Kombolcha and Mekaneselam bamboo, although Kombolcha and Mekaneselam have a similar shape parameters. The shape parameter (β) was used to calculate the Weibull strength, and the sensitivity parameter (γ) was used to calculate the modified Weibull strength. The Weibull and modified Weibull strengths of Injibara bamboo are high compared to Kombolcha and Mekaneselam. However, the Weibull and modified Weibull strengths of Mekaneselam bamboo are the lowest values recorded.

The current results of the shape parameter of Injibara bamboo have similar results to the previous research reported (Zhang et al., 2002; Trujillo et al., 2014), higher than those (Xia et al., 2009; F. Wang et al., 2014; Edy Pramono et al., 2015), and lower than (Defoirdt et al., 2010), whereas Kombolcha bamboo has similar with (Defoirdt et al., 2010), and higher than (Zhang et al., 2002; Xia et al., 2009; F. Wang et al., 2014; Trujillo et al., 2014; Edy Pramono et al., 2015). The current results of Injibara, Kombolcha, and Mekaneselam bamboo have higher sensitivity parameters than the previous research reported (Trujillo et al., 2014). Furthermore, the current results of Injibara, Kombolcha, and Mekaneselam bamboo have high characteristic strength compared to previous research reported (Zhang et al., 2002; Xia et al., 2009; F. Wang et al., 2014), lower than those (Trujillo et al., 2014), and similar with (Edy Pramono et al., 2015).

Table 4. 37: Strength of bamboo fibres using Weibull parameter

Bamboo species	Gauge length (mm)	sensitivity parameter (γ)	shape parameter (β)	characteristic strength (MPa)	Refe.
Injibara	15	0.23	6.24	642	study
	25	0.23	7.66	617	
	30	0.23	6.4	595	
	40	0.23	6.02	582	
	50	0.23	7.83	459	
Kombolcha	15	0.33	10.21	638	study
	25	0.33	6.58	470	
	30	0.33	5.87	438	
	40	0.33	7.32	425	
	50	0.33	7.33	408	
M/ Selam	15	0.327	9.63	597	study
	25	0.327	6.045	568	
	30	0.327	6.18	552	
	40	0.327	5.866	488	
	50	0.327	8.36	474	
Literature	10-100	-	6.3-7.9	197-201	(Zaremba et al., 2000)
	5-20	-	1.19-2.18	377-436	(Xia et al., 2009)
	20-50	-	3.22-4.77	402-566	(F. Wang et al., 2014)
	20	-	4.02	612	(Shao et al., 2013)
	5-35	-	3.5-9.3	683-855	(Defoirdt et al., 2010)
	1-40	0.48	7.6	982	(Trujillo et al., 2014)

4.4.4 Effect of diameter and gauge length on tensile strength

The mean fibre strength results are presented in Table 4.38. This data shows a decrease in fibre strength when testing length increase. ANOVA revealed statistically significant strength differences between the groups of "thin" and "thick" fibres with gauge lengths of 15 mm, 25 mm, 30 mm, 40 mm, and 50 mm. The fibres with a gauge length of 15 mm have not only a higher strength but also a lower variance. Because of a greater possibility of the elementary fibres being clamped between the top and bottom ends. ANOVA (>0.05) revealed no statistically significant differences in strength as a function of fibre diameter, even when evaluated at different testing lengths.

Moreover, the fibres were divided into a group of "thin" fibres and a group of "thick" fibres, based on whether the fiber diameter was lower or higher than the median fibre diameter. If the fibre diameter would influence the strength, then a systematic difference in strength should be found for each testing length. Table 4.38 shows only a statistically significant difference, according to the Student's t-test, for Injibara bamboo species with the group of gauge lengths of 25 and 30 mm and Mekaneselam bamboo species with the group of testing lengths of 15 and 30 mm. The technical bamboo fibres are made up of hundreds of elementary fibres. Consequently, even at short testing lengths, the typical discontinuities of the elementary fibres at certain points will be bridged by many other elementary fibres placed around, as observed in Figure 4.6.

Table 4. 38: Effect of various testing lengths on the tensile strength. Each testing length is divided into "thin" and "thick" fibres, which have a diameter below and above the median.

Bamboo Species	Gauge length (mm)	Average fibre diameter (μm)	Average strength all fibres (MPa)	Average strength "thin" fibres (MPa)	Average strength "thick" fibres (MPa)	P- value "thin"&"thick" fibre (α=0.05)	R-Square (linear regression)
Injibara	15	296±31	600±80	602±70	597±58	0.876	0.0007
	25	339±32	580±70	512±55	648±62	0.000	0.7101
	30	327±33	553±60	560±58	545±55	0.000	0.6174
	40	275±26	542±55	522±53	563±53	0.207	0.0416
	50	340±35	432±45	431±45	433±45	0.916	0.0006
Kombolcha	15	253±24	508±50	614±62	602±59	0.57	0.0086
	25	248±25	470±45	414±45	432±42	0.479	0.0133
	30	256±25	385±40	512±52	374±37	0.372	0.021
	40	276±26	378±35	376±38	380±39	0.868	0.0007
	50	322±33	370±35	390±40	386±37	0.908	0.0005
M/selam	15	299±31	566±60	590±60	543±55	0.022	0.1314
	25	309±32	528±55	531±55	524±53	0.817	0.0014
	30	317±33	515±50	527±54	504±51	0.442	0.0157
	40	339±34	452±45	454±46	451±44	0.925	0.0002
	50	320±31	448±40	438±45	433±42	0.903	0.0006

The strength of a technical fibre versus its corresponding fibre diameter is presented in Figure 4.35, whereas all samples of data are indicated in Figure 4.30. As presented in Figure 4.35, all "thin" and "thick" fibres of Injibara and Kombolcha bamboo almost similar in strength are found. However, the 'thick' fibres of Injibara bamboo have a higher variance than the thin fibres. The diameter of the thin fibres of Mekaneselam bamboo has a lower variance and higher strength compared to the thick fibres' diameter.

The median of tensile strength for Injibara, Kombolcha, and Mekaneselam bamboo are 559 MPa, 405 MPa, and 487 MPa, Whereas the median diameters, are 301.65 μm, 263.6 μm, and 329.18 μm respectively. As presented in Figure 4.35, Injibara bamboo has a lower standard deviation of strength above the median, whereas Kombolcha and Mekaneselam bamboo has a lower standard deviation of strength below the median of all fibre strength.

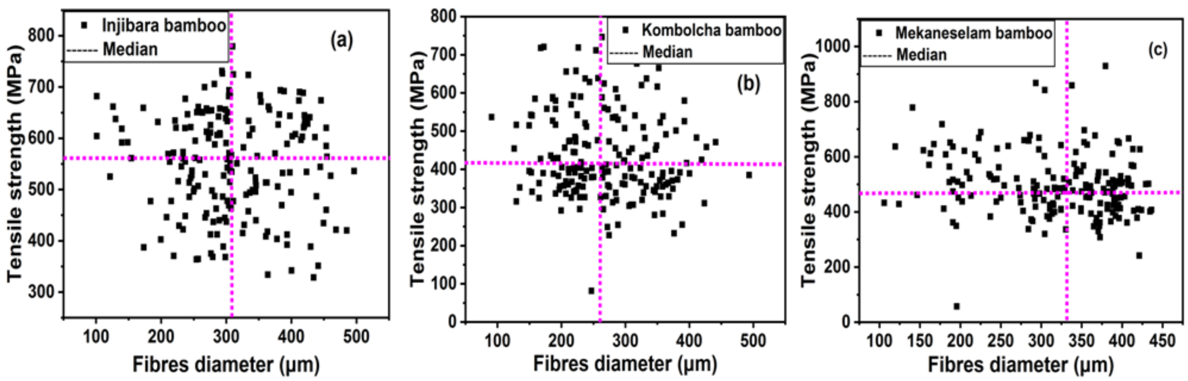


FIGURE 4. 35: Single technical fibre strength versus fibre diameter where the median for fibre strength and fibre diameter is drawn (a) Injibara, (b) Kombolcha, and (c) Mekaneselam.

4.4.5 Determine prediction strength based on gauge length

The influences of testing length on the Weibull modulus and the sensitivity parameter are seen in Table 4.39. The estimations of the testing length influence on the modified Weibull model (equation (3.15)) are presented in Table 4.39, along with those from the conventional Weibull model (equation (3.11)) and the experimental values. Experimentally measured strength and predictive Weibull strength have close data values on Injibara and Kombolcha bamboo because they have good values for the shape parameter (β) and sensitivity parameter (γ), which determine the predictive modified Weibull strength. The sensitivity parameter measured the fibre diameter coefficient variation.

However, the experimentally measured strength and the predictive Weibull strength have close data values on Mekaneselam bamboo, hence the shape parameter (β) has a high coefficient of value, which determines the variability of failure strength.

The fibre diameter coefficient variation does not measure the predicted Weibull strength, but the predicted modified Weibull strength. The sample size affects the coefficient variation of fibre diameter at various testing gauges. If large sample sizes are used, the average diameters may be close to each other. Table 4.39 clearly shows that the modified model incorporates the within-fiber diameter variation that can predict the gauge length effect more accurately than the conventional Weibull distribution. Therefore, if the average fiber strength at one testing length is determined, then its average strength at another testing length can be predicted. The predictive modified Weibull strength is significant at a very short testing length, which is difficult to achieve experimentally.

Table 4. 39: Summary results of the measured and the predicted values on the mean fiber strength (predictions are based on the results at 15 mm testing length)

Bamboo Species	Gauge Length (mm)	Measured Strength (Mpa)	Weibull Strength (Mpa)	modified Weibull strength (Mpa)
Injibara	15	600±105	600	600
	25	580±81	552	570
	30	553±90	537	559
	40	542±100	512	543
	50	432±59	494	531
Kombolcha	15	508±66	508	508
	25	470±83	578	500
	30	385±73	568	497
	40	378±69	552	492
	50	370±60	540	489
M/selam	15	566±65	566	566
	25	528±94	537	556
	30	515±93	527	553
	40	452±84	511	547
	50	448±57	499	543

4.4.6 Summary results of tensile strength of single bamboo fibres

The quality of bamboo fibres and their composites is influenced by the extraction methods of the fibres. Nowadays, the extraction of bamboo fibres is a challenging task. The authors developed a simple and easy extraction of bamboo fibres in the workshop. At the tested length of 15 mm–50 mm, the measured tensile strength of Injibara, Kombolcha, and Mekaneselam are 432±59–600±105 MPa, 370±60–508±66 MPa, and 448±57–566±65 MPa, whereas the characteristic tensile is 459-642 MPa, 408-638 MPa, and 474-597 MPa, and modified Weibull strengths at the predictive tested length of 15 mm are 531–600 MPa, 489–508 MPa, and 543–566 MPa, respectively. The characteristics strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres are 7%, 20%, and 5% higher than experimentally measured.

Injibara and Mekaneselam have a lower probability of failure strength compared to Kombolcha bamboo. Hence, Weibull-modified strength is more closely related to strength value with experimental strength data compared to conventional Weibull strength predictive test length at 15 mm. The sensitivity parameter (γ) of Injibara, Kombolcha, and Mekaneselam bamboo fibres was 0.23, 0.33, and 0.33, whereas the shape parameter (β) was 6.24–7.83, 5.87–10.21, and 5.86–9.63, respectively. The quality of the existing extraction machine is acceptable for the current research work, which has comparable sensitivity parameters to jute fibres as reported in the literature review. Moreover, the higher value of the shape parameter indicates that the variation of strength data is low. Further research work should be required based on defect distribution in the area, volume, and diameter of the fibres.

4.5 Result and discussion on Mechanical strength of bamboo fibres and epoxy composite

4.5.1 Tensile strength of bamboo fibres and epoxy composite

Tensile strength of bamboo fibres

The back-calculated tensile strength of bamboo species in Ethiopia from IFBT in terms of the effect of age and harvesting season is shown in Figure 4.36. The highest and lowest back-calculated tensile strengths of Injibara bamboo fibres at the ages of 2 and 1 year has 539±44 MPa and 422±45 MPa in February, whereas in November, it has 548±40 MPa and 431±42 MPa, respectively.

The highest and the lowest back-calculated tensile strength of Kombolcha bamboo fibres at the ages of 2 and 1 year have 449±26 MPa and 339±40 MPa in February, whereas in November, it has 496±46 MPa and 422±40 MPa, respectively. The highest and lowest back-calculated tensile strengths of Mekaneselam bamboo fibres at the ages of 2 and 1 year have 507±48 MPa and 421±38 MPa in February, whereas in November, it has 541±21 MPa and 399±55 MPa, respectively.

The back-calculated tensile strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November has been 2%, 10%, and 6% higher than in February, respectively. The highest measured values of Injibara, Kombolcha, and Mekaneselam bamboo fibres at the age of 2 years have 22%, 15%, and 17% higher back-calculated tensile strength than the lowest measured values at the age of 1 year in February, whereas in November, they have 21%, 38 %, and 26 % higher tensile strength than the lowest measured values, respectively.

Injibara bamboo fibres have 17% and 6% higher in February, whereas in November, it is 9% and 1% higher back-calculated tensile strength than Kombolcha and Mekaneselam, respectively. The back-calculated tensile strength of Mekaneselam bamboo fibres has 11% and 8% higher than Kombolcha bamboo fibres in February and November, respectively.

From the highest to the lowest cellulose contents are Injibara, Mekaneselam, and Kombolcha bamboo fibres. The highest and the lowest percentage of cellulose content and percentage of degree of crystallinity are recorded at the age of 2 and 1 years old.

Therefore, the tensile strength of bamboo fibres is correlated with the amount of cellulose content and percentage of crystallinity. The tensile strength of bamboo fibres increases with cellulose content and the percentage degree of crystallinity. The effect of cellulose content on tensile strength was studied by previous researchers. The percentage of cellulose content improved the tensile strength of bamboo fibres (Martijanti et al., 2021). The effect of chemical composition and crystallinity on tensile strength was studied by previous researchers. The tensile strength of fibres was directly influenced by the percentage of cellulose and hemicellulose content (Wang et al., 2016; Diyana et al., 2021). The extraction of bamboo fibres was influenced by the amount of moisture content during harvesting. The higher the moisture content of bamboo fibres during harvesting, the easier bamboo fibres can be extracted without damage to bamboo fibres (Ovat, 2018).

In Ethiopia, November is a cold season with low room temperatures and high relative humidity compared to February. The month of November makes the bamboo culm higher in moisture content and makes it easier to extract fibres from it. The ranges of standard deviation on the back-calculated tensile strength in February and November are 5 to 10% and 8 to 15%, respectively. The back-calculated tensile strengths of Injibara bamboo fibres are 12%, 20%, and 40% higher than the previous studies of GAK (481 MPa), DMM (436 MPa), and PNB (329 MPa), whereas Kombolcha bamboo is 3%, 12%, and 34% higher than the previous studies of GAK (481 MPa), DMM (436 MPa), and PNB (329 MPa). Furthermore, Mekaneselam bamboo is 11%, 19%, and 39% higher than the previous studies of GAK (481 MPa, DMM (436 MPa), and PNB (329 MPa), respectively (Delphine E C Depuydt, Sweygers, Appels, et al., 2019).

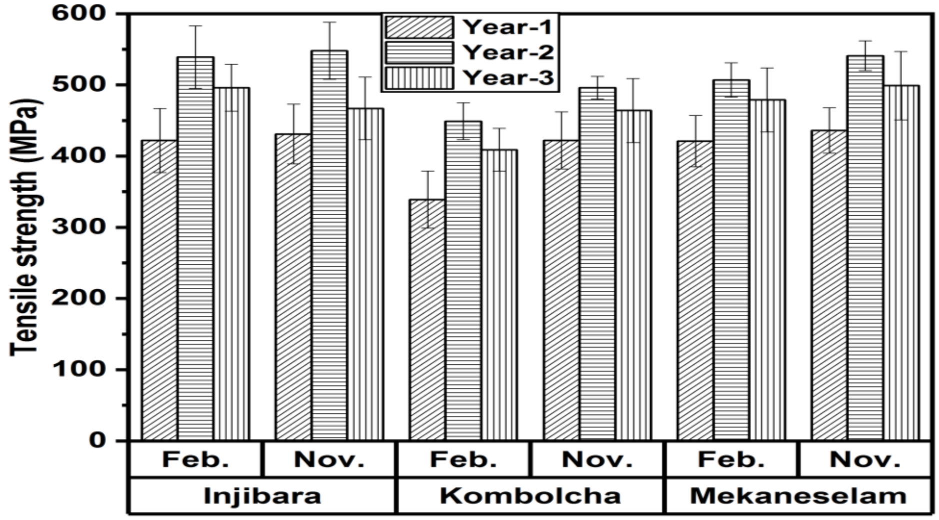


FIGURE 4. 36: Back calculated tensile strength of Ethiopian bamboo fibre from BFEPCs.

Young's modulus of bamboo fibres

As shown in Figure 4.37, the highest and lowest Young's modulus of Injibara bamboo fibres at the ages of 2 and 1 year in February has 44±4 GPa and 37±2 GPa, whereas, in November, it has 48±5 GPa and 39±4 GPa, respectively. The highest and the lowest Young's modulus of Kombolcha bamboo fibres at the ages of 2 and 1 year in February has 33±3 GPa and 25±2 GPa, whereas, in November, it has 36±3 GPa and 29±3 GPa, respectively. The highest and lowest Young's modulus of Mekaneselam bamboo fibres at the ages of 2 and 1 year old in February has 42±4 GPa and 38±3 GPa, whereas, in November, it has 45±5 GPa and 40±4 GPa, respectively.

The back-calculated Young's modulus of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 8%, 9%, and 7% higher than in February, respectively.

The highest measured values at the age of 2 years in February of Injibara, Kombolcha, and Mekaneselam bamboo fibres have 16%, 24%, and 10% higher Young's modulus than the lowest recorded values at the age of 1 year old, whereas, in November, they have 19%, 20%, and 11%, respectively. The range of the standard deviation of Young's modulus of bamboo fibres was 5 to 11%. Injibara bamboo fibres have 25% and 5% higher in February, whereas in November are 24% and 6% higher back-calculated Young's modulus than Kombolcha and Mekaneselam bamboo, respectively. Moreover, Mekaneselam bamboo fibres have 21% and 20% higher than Kombolcha in February and November, respectively.

The back-calculated Young's modulus of Injibara bamboo fibres is 8%, 15%, and 23% higher than the previous studies of GAK (44 GPa), DMM (41 GPa), and PNB (37 GPa), whereas Kombolcha bamboo is 18% and 12% higher than the previous studies of GAK (44 GPa), and DMM (41 GPa), but it is a similar value to previous studies of PNB (37 GPa). Furthermore, Mekaneselam bamboo is comparable with the previous studies of GAK (44 GPa), but it is 9% and 18% higher than the previous studies of DMM (41 GPa), and PNB (37 GPa), respectively (Delphine E C Depuydt, Sweygers, Appels, et al., 2019).

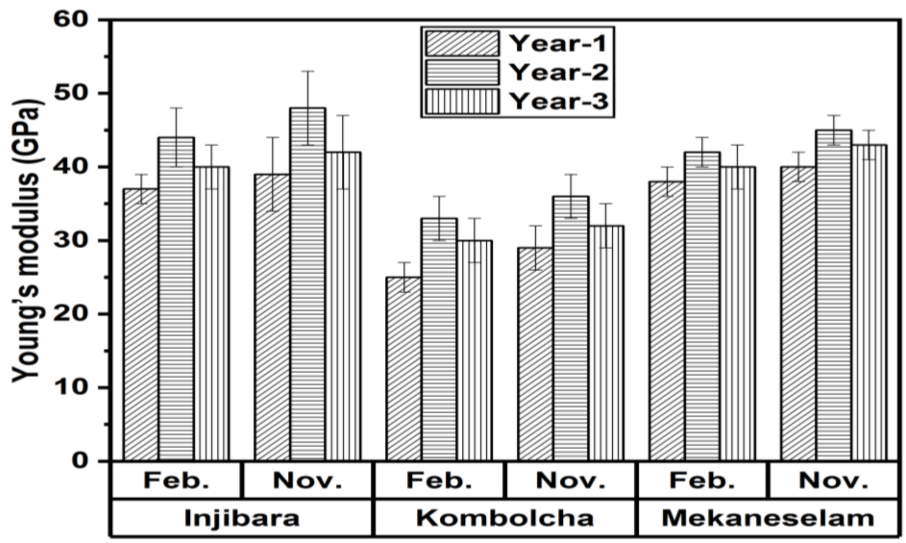


FIGURE 4.37: Back calculated Young's modulus of IFBT

Stress-strain curve of ultimate tensile strength

As shown in Figure 4.38, the tensile stress, and strain to failure in the ages of 1-3 years of BFEPCs are measured at 200-250 MPa and 1.4-1.6% in February, whereas in November, they are measured at 250-300 MPa and 1.0-1.2%, respectively. The age of 2 years measured the highest tensile stress and the lowest strain to failure of BFEPCs compared to 1 and 3 years old, whereas November has the highest stress and the lowest strain to failure compared to February. From the highest to the lowest tensile stress of BFEPCs are Injibara, Mekaneselam, and Kombolcha, respectively. As indicated in Figure 4.38, the type of failure of the composites is a brittle failure, which breaks the composite without the movement of the transition from ductile to brittle. The failure of the composite indicated that it is a hard material that resists ductility failure.

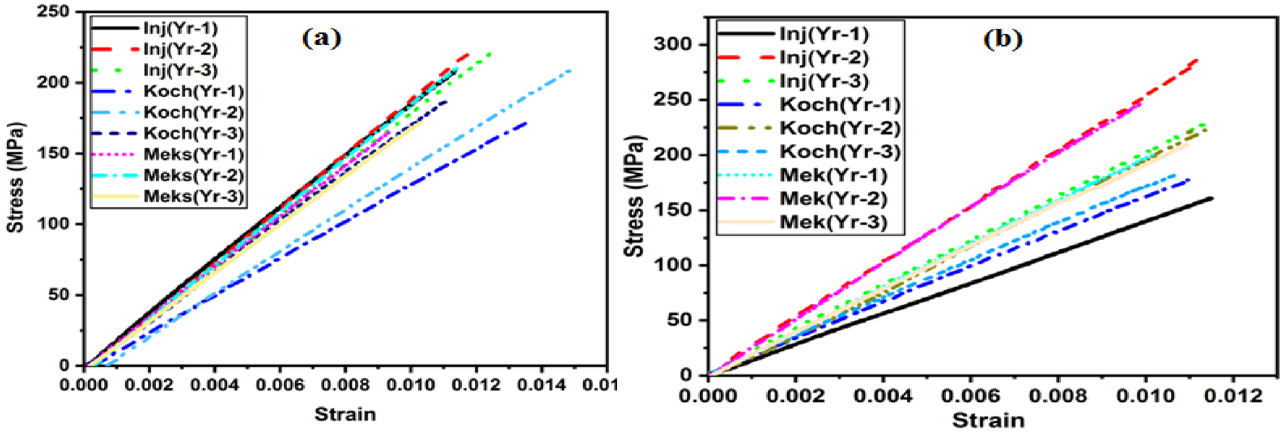


FIGURE 4.38: Stress-strain of BFEPCs: (a) February, and (b) November

Strain to failure of BFEPCs

The effect of age and harvesting month on the tensile strain to failure of BFEPCs is shown in Figure 4.39. The highest and the lowest tensile strain to failure of Injibara BFEPCs at the ages of 2 and 1 year in February has 1.13±0.06% and 1.07±0.08%, whereas, in November, it has 1.08±0.05% and 1.01±0.05%, respectively. The highest and lowest tensile strains to failure of Kombolcha BFEPCs at the ages of 2 and 1 year in February has 1.35±0.07% and 1.16±0.08%, whereas, in November, it has 1.17±0.03% and 1.14±0.03%, respectively.

The highest and lowest strains of failure of Mekaneselam BFEPCs at the ages of 2 and 1 year in February has 1.07±0.07% and 0.98±0.07%, whereas, in November, it has 1.13±0.075% and 0.92±0.06%, respectively.

The strain to failure of Injibara, Kombolcha, and Mekaneselam BFEPCs in February has 4%, 13%, and 5% higher in tensile strain to failure than in November. February is the most susceptible to failure compared to November for all Ethiopian bamboo species. The highest measured values at the age of 1 year in February for Injibara, Kombolcha, and Mekaneselam bamboo are 5%, 14%, and 8% higher tensile strains to failure than the lowest at the age of 2 years old, whereas in November, they have 7%, 3%, and 19%, respectively. The tensile strain to failure of Injibara BFEPCs is 8%, and 24% higher than the previous studies of DMM (0.93%), and PNB (0.77%), but it is 5% lower than GAK (1.06%), whereas Kombolcha bamboo is 7%, 18%, and 32% higher than the previous studies of GAK (1.06%), DMM (0.93%), and PNB (0.77%). Furthermore, Mekaneselam bamboo is 16% higher than the previous studies of PNB (0.77%), but it is 13% and 2% lower than the previous studies of

GAK (1.06%), and DMM (0.93%), respectively (Delphine E C Depuydt, Sweygers, Appels, et al., 2019).

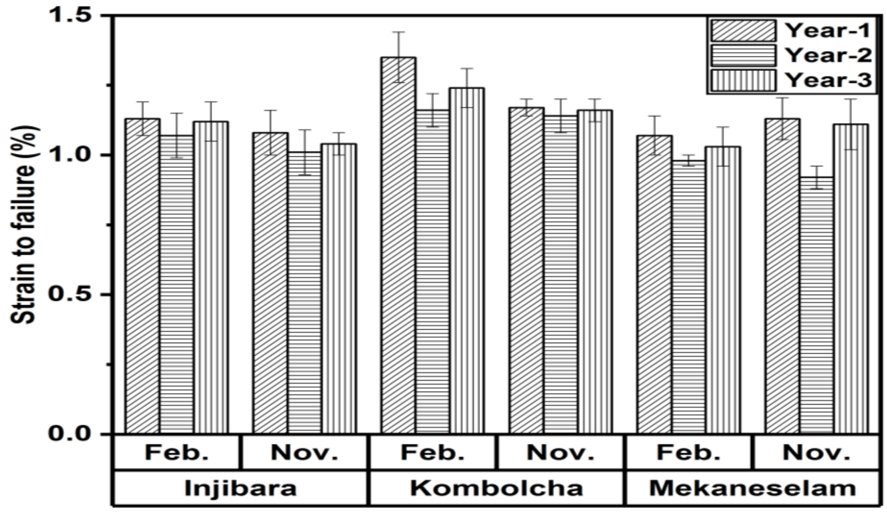


FIGURE 4.39: Tensile strain to failure of BFEPCs

Young's modulus of BFEPCs.

The effect of age and harvesting month on Young's modulus of Injibara, Kombolcha, and Mekaneselam BFEPCs are shown in Figure 4.40. The highest and the lowest experimental Young's modulus of Injibara BFEPCs at the ages of 2 and 1 year in February has 19±1.06 GPa and 17±1.05 GPa, whereas the theoretical is 19±1.07 GPa and 18±1.06 GPa in February, respectively. Moreover, the experimental Young's modulus in November has 21±2.05 GPa and 16±1.04 GPa, whereas the theoretical has 21±2.04 GPa and 17±1.05 GPa, respectively. An efficiency factor of 95% was reached after comparing the experimental value with the theoretical value both in February and November for Injibara.

The highest and the lowest experimental Young's modulus of Kombolcha BFEPCs at the ages of 2 and 1 year in February has 17±1.06 GPa and 11±1.02 GPa, whereas the theoretical has 21±2.06 GPa and 13±1.05 GPa, respectively. Moreover, the experimental Young's modulus in November has 18±2.05 GPa and 11±1.03 GPa, whereas the theoretical has 20±2.02 GPa and 12±1.04 GPa, respectively. An efficiency factor of 81% and 90% was reached after comparing the experimental value with the theoretical value in February and November for Kombolcha, respectively.

The highest and the lowest experimental Young's modulus of Mekaneselam BFEPCs at the ages of 2 and 1 years in February has 18±1.06 GPa and 16±1.02 GPa, whereas the theoretical has 19±1.07 GPa and 18±1.06 GPa, respectively. Moreover, the experimental Young's modulus in November has 19±1.07 GPa and 17±1.03 GPa, whereas the theoretical has 20±2.04 GPa and 18±1.07 GPa, respectively. An efficiency factor of 95% was reached after comparing the experimental value with the theoretical value both in February and November for Mekaneselam.

In general, Young's modulus of BFEPCs of the theoretical value is comparable to the experimental value. This indicates good fibre/matrix adhesion, possibly improved due to good fibre extraction and fiber special properties that promote mechanical interlocking. From the highest to the lowest Young's modulus of BFEPCs is Injibara, Mekaneselam, and Kombolcha bamboo, respectively.

Injibara BFEPCs have 11% and 5% higher in February, whereas in November, it has 14% and 10% higher Young's modulus BFEPCs than Kombolcha and Mekaneselam, respectively. Mekaneselam bamboo has 6%, and 5% higher Young's modulus of BFEPCs than Kombolcha in February and November, respectively. The Young's modulus of Injibara, Kombolcha, and Mekaneselam BFEPCs have 9%, 22%, and 17% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (23±2 GPa), respectively (Delphine E.C. Depuydt, Soete, et al., 2019). Moreover, they are 38%, 47%, and 44% lower than the previous studies of glass fibre epoxy composite (34 GPa), respectively (Megahed et al., 2021).

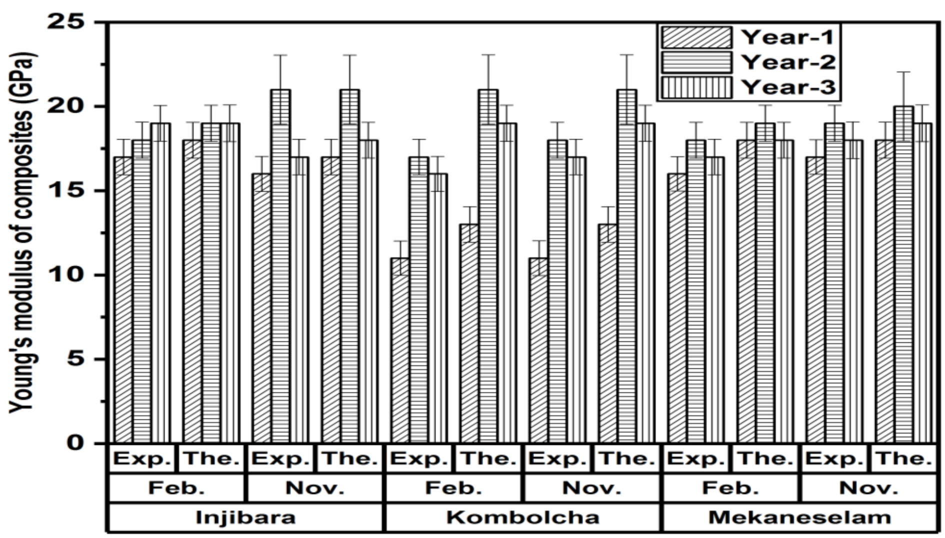


FIGURE 4.40: Young's modulus of BFEPCs

Tensile strength of BFEPCs

The effect of age and harvesting month on the tensile strength of BFEPCs for Injibara, Kombolcha, and Mekaneselam bamboo is measured in Figure 4.41. The highest and lowest tensile strengths of Injibara BFEPCs at the ages of 2 and 1 years in February has 206±23 MPa and 191±20 MPa, whereas, in November, it has 227±20 MPa and 171±17 MPa, respectively.

The highest and the lowest tensile strengths of Kombolcha BFEPCs in February has 198±18 MPa and 139±15 MPa, whereas, in November, it has 205±18 MPa and 129±11 MPa, respectively.

The highest and lowest tensile strengths of Mekaneselam BFEPCs at the ages of 2 and 1 years in February has 199±18 MPa and 151±13 MPa, whereas, in November, it has 216±19 MPa and 166±17 MPa, respectively. The tensile strength of Injibara, Kombolcha, and Mekanesealm BFEPCs in November has 9%, 10%, and 3% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFEPCs are 8%, 30%, and 24% higher tensile strength than the lowest recorded values in February, whereas in November 25%, 37 %, and 23 % higher tensile strength than the lowest recorded values, respectively.

Injibara BFEPCs has 4% and 3% higher in February, whereas, in November, it is 10% and 5% higher tensile strength than Kombolcha and Mekaneselam BFEPCs, respectively. The tensile strength of Mekaneselam BFEPCs has 1% and 5% higher than Kombolcha BFEPCs in February and November, respectively. The tensile strength of Injibara, and Mekaneselam BFEPCs are 8%, and 4% higher than the previous studies of *Guadua angustifolia Kunth* (GAK) (208±19 MPa), respectively. Kombolcha BFEPCs is a similar tensile strength to GAK (Delphine E.C. Depuydt, Soete, et al., 2019). However, they are 31%, 24%, and 28% higher than the previous studies of glass fibre epoxy composite (156 MPa), respectively (Megahed et al., 2021).

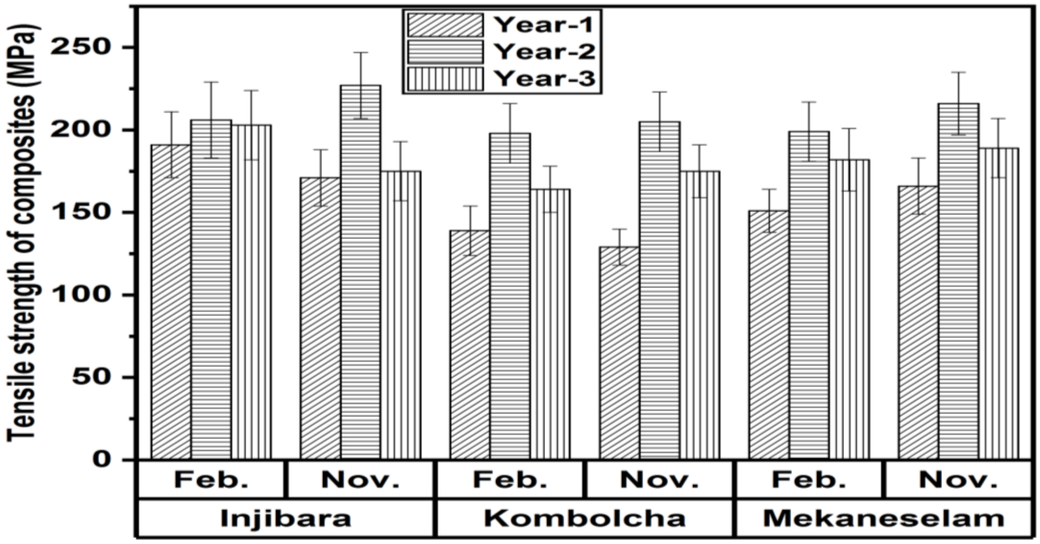


FIGURE 4.41: Tensile strength of BFEPCs

4.5.2 Three-point bending test of BFEPCs

Flexural strength

The effect of age and harvesting month on the flexural strength of BFEPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.42. The highest and the lowest flexural strengths of Injibara BFEPCs at the ages of 2 and 1 years in February has 211±21 MPa and 156±17 MPa, whereas, in November, it has 234±21 MPa and 166±14 MPa, respectively. The highest and the lowest flexural strengths of Kombolcha BFEPCs at the ages of 2 and 1 years in February has 129±10 MPa and 81±7 MPa, whereas, in November, it has 190±18 MPa and 124±13 MPa, respectively. The highest and lowest flexural strengths of Mekaneselam BFEPCs at the ages of 2 and 1 years in February has 189±17 MPa and 139±12 MPa, whereas, in November, it has 198±21 MPa and 116±12 MPa, respectively. The flexural strength of Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 10%, 32%, and 5% higher than in February, respectively.

The highest measured values for Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 2 years have 26%, 37%, and 26% higher flexural strength than the lowest recorded values at the age of 1 year in February, whereas, in November, they have 29%, 35%, and 41% higher flexural strength than the lowest recorded values, respectively.

Injibara bamboo fibres epoxy composite has 39% and 10% higher in February, whereas in November, it has 19% and 15% higher flexural strength than Kombolcha and Mekaneselam, respectively. The flexural strength of Mekaneselam BFEPCs has 32% and 4% higher than Kombolcha in February and November, respectively. The range of standard deviation in the harvesting month of February and November are 5–11% and 8–13%, respectively. The flexural strength of Injibara, Kombolcha, and Mekaneselam BFEPCs are 12%, 28, and 25% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (265±12 MPa), respectively (Delphine E.C. Depuydt, Soete, et al., 2019). Moreover, they are 44%, 31%, and 34% higher than the previous studies of glass fibre epoxy composite (131 MPa), respectively (Megahed et al., 2021).

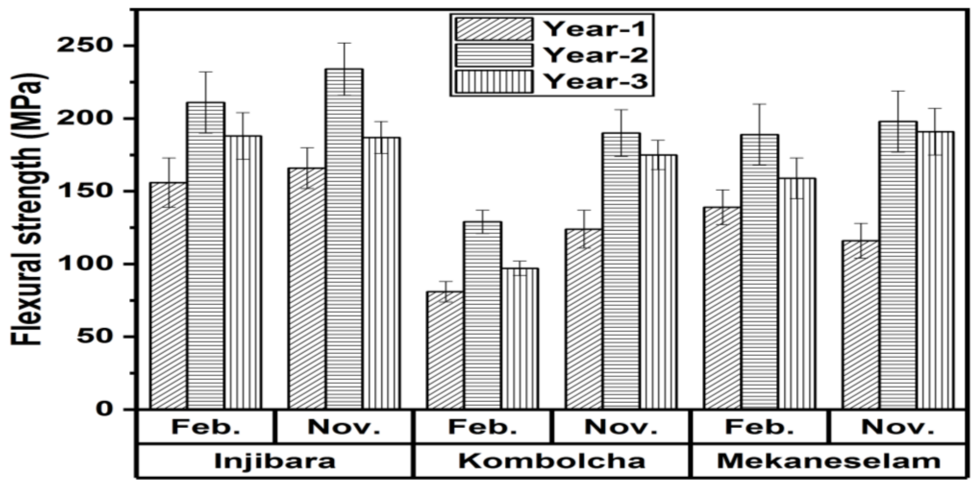


FIGURE 4.42: Flexural strength of 3pt bending test in the longitudinal direction

Modulus of elasticity

The effect of age and harvesting month on the modulus of elasticity of BFEPCs for Injibara, Kombolcha, and Mekaneselam bamboo are shown in Figure 4.43. The highest and the lowest modulus of elasticity of Injibara BFEPCs at the ages of 2 and 1 years in February has 19±1.76 GPa and 14±1.59 GPa, whereas, in November, it has 17±1.49 GPa and 13±1.19 GPa, respectively. The highest and the lowest modulus of elasticity of Kombolcha BFEPCs at the ages of 2 and 1 year in February has 12±0.87 GPa and 8±0.26 GPa, whereas, in November, it has 13±1.21 GPa and 10±1.34 GPa, respectively. The highest and lowest modulus of elasticity of Mekaneselam BFEPCs at the ages of 2 and 1 years in February has 13±1.11 GPa and 10±0.87 GPa, whereas, in November, it has 15±1.19 GPa and 11±0.73 GPa, respectively.

Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 11%, 8%. and 13% higher modulus of elasticity than in February. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFEPCs have 18%, 33%, and 23% higher modulus of elasticity than the lowest recorded values in February, whereas in November, they have 32%, 23%, and 27% higher modulus of elasticity than the lowest recorded values, respectively.

Injibara BFEPCs has 29% and 24% higher in February, whereas in November is 32% and 21% higher modulus of elasticity than Kombolcha and Mekaneselam, respectively. The modulus of elasticity of Mekaneselam BFEPCs has 8% and 13% higher than Kombolcha in February and November, respectively. The range of standard deviation in the harvesting month of February and November are 5–11%, and 8–13% respectively.

The modulus of elasticity of Kombolcha and Mekaneselam BFEPCs is 33% and 22% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (19.3±0.8 GPa), respectively. However, the Injibara BFEPCs has a similar modulus of elasticity with *Guadua angustifolia Kunth* (E. Trujillo, 2014). The modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFEPCs are 60%, 41%, and 49% higher than the previous studies of glass fibre epoxy composite (7.64 GPa), respectively (Megahed et al., 2021).

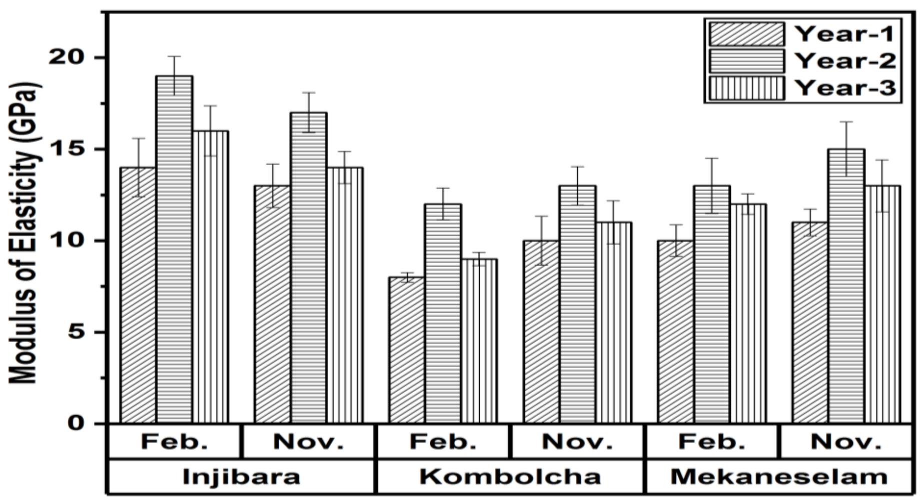


FIGURE 4.43: Comparison of modulus of Elasticity in 3pt bending test.

Flexural strain to failure

The effect of age and harvesting month on the flexural strain to failure of BFEPCs for Injibara, Kombolcha, and Mekaneselam bamboo are shown in Figure 4.44. The highest and the lowest flexural strain to failure of Injibara BFEPCs at the ages of 2 and 1 years in February has 2.22±0.21% and 2.11±0.18%, whereas, in November, it has 2.31±0.22% and 2.01±0.19%, respectively.

The highest and the lowest flexural strain to failure of Kombolcha BFEPCs at the ages of 2 and 1 years in February has 2.64±0.22% and 2.08±0.21%, whereas, in November, it has 2.04±0.39% and 1.96±0.21%, respectively.

The highest and lowest flexural strain to failure of Mekaneselam BFEPCs at the ages of 2 and 1 years in February has 2.11±0.18% and 1.75±0.13%, whereas, in November, it has 2.05±0.17% and 1.96±0. 12%, respectively. Kombolcha and Mekaneselam BFEPCs in February have 22%, and 3% higher than in November, respectively. Whereas Injibara BFEPCs in November has a 4% higher flexural strain to failure than in February. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFEPCs are 5%, 21%, and 17% higher flexural strain to failure than the lowest recorded values in February, whereas in November 11%, 4%, and 5% higher flexural strain to failure than the lowest recorded values, respectively.

Kombolcha BFEPCs have 13% and 20% higher flexural strain to failure than Injibara and Mekaneselam, respectively. The flexural strain to failure of Injibara BFEPCs has 9% higher than Mekaneselam. The range of standard deviation in the harvesting month of February and November are 5–11%, and 8–13% respectively. The flexural strain to failure of Injibara and Mekaneselam BFEPCs is 4% and 12% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (2.4%), respectively. However, the Kombolcha bamboo fibres epoxy composite has a 9% higher tensile strain to failure than *Guadua angustifolia Kunth* (E.trujillo, 2014). The tensile strain to failure of Injibara, Kombolcha, and Mekaneselam BFEPCs are 50%, 25%, and 40% higher than the previous studies of glass fibre epoxy composite (7.64 GPa), respectively (Megahed et al., 2021).

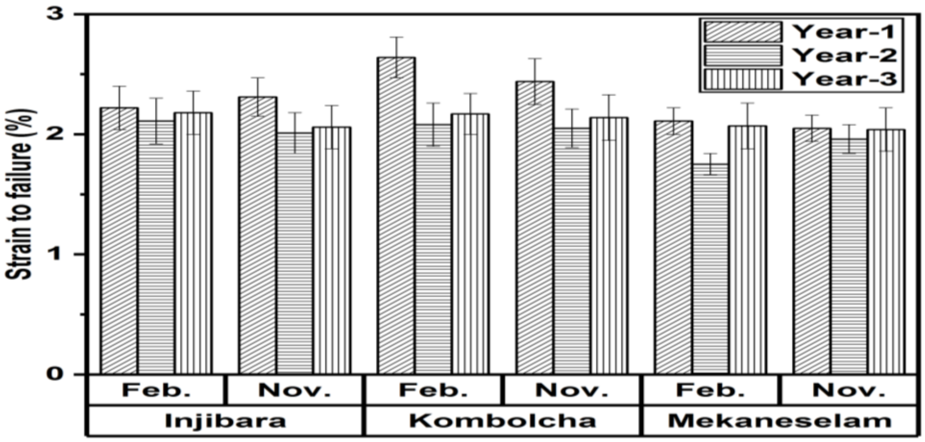


FIGURE 4.44: Comparison of flexural strain to failure BFEPCs.

Stress-strain of three-point bending test

The flexural stress-strain curve based on the ages of 1-3 years and harvesting months of BFEPCs are indicated in Figure 4.45. The flexural stress 200-250MPa is measured in February, whereas in November 250-300 MPa is measured, respectively. The flexural stress and strain are influenced by the ages and harvesting months of the bamboo fibres. These curves showed that the different ages, harvesting months, and bamboo species led to different tensile behaviors. From the highest to the lowest tensile stress of BFEPCs are Injibara, Mekaneselam, and Kombolcha, respectively.

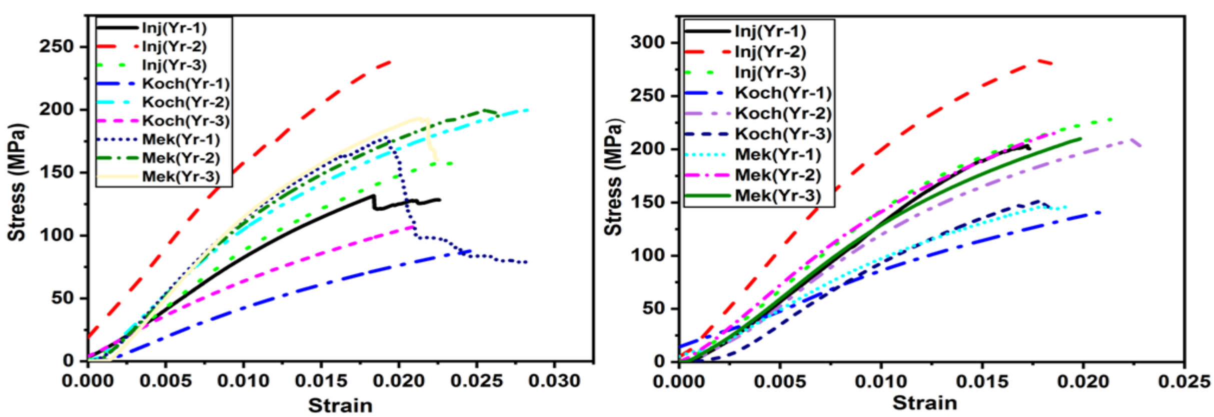


FIGURE 4.45: Flexural stress-strain curve of BFEPCs

4.5.3 Impact strength of BFEPCs.

The effect of age and harvesting month on the impact strength of BFEPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.46. The highest and the lowest impact strength of Injibara BFEPCs at the ages of 2 and 1 year in February has 55±4.9 KJ/m^2 and 31±3.4 KJ/m^2, whereas, in November, it has 70±5.8 KJ/m^2 and 43±4.2 KJ/m^2, respectively.

The highest and the lowest impact strength of Kombolcha BFEPCs at the ages of 2 and 1 year in February has 55±4.5 KJ/m^2 and 43±3.8 KJ/m^2, whereas, in November, it has 63±6.4 KJ/m^2 and 48±4.2 KJ/m^2, respectively.

The highest and lowest impact strength of Mekaneselam BFEPCs at the ages of 2 and 1 year in February has 53±4.9 KJ/m^2 and 42±3.6 KJ/m^2, whereas, in November, it has 66±5.8 KJ/m^2 and 51±4.6 KJ/m^2, respectively. Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 21%, 13%. and 20% higher impact strength than in February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFEPCs are 44%, 22%, and 21% higher impact strength than the lowest recorded values in February, whereas in November 39%, 24%, and 23% higher impact strength than the lowest recorded values, respectively.

The impact strength of Injibara BFEPCs has 1% and 4% higher in February, whereas in November, it has 10% and 6% higher than Kombolcha and Mekaneselam, respectively. The impact strength of Mekaneselam BFEPCs in February has 4% lower than Kombolcha, but in November, it has 5% higher than Kombolcha. The range of standard deviation in the harvesting month of February and November are 5–11%, and 8–13% respectively.

The impact strength of Injibara, Kombolcha, and Mekaneselam BFEPCs have 37% and 43% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (111KJ/m^2), respectively (Rua et al., 2021). The impact strength of Injibara, Kombolcha, and Mekaneselam BFEPCs are 60%, 60%, and 62% higher than the previous studies of glass fibre epoxy composite (25KJ/m^2 GPa), respectively(Megahed et al., 2021). The current studies of Injibara, Kombolcha, and Mekaneselam BFEPCs are73%, 70%, and 71% higher impact strength compared to the previous studies(18.86 KJ/m^2) (Banga et al., 2015).

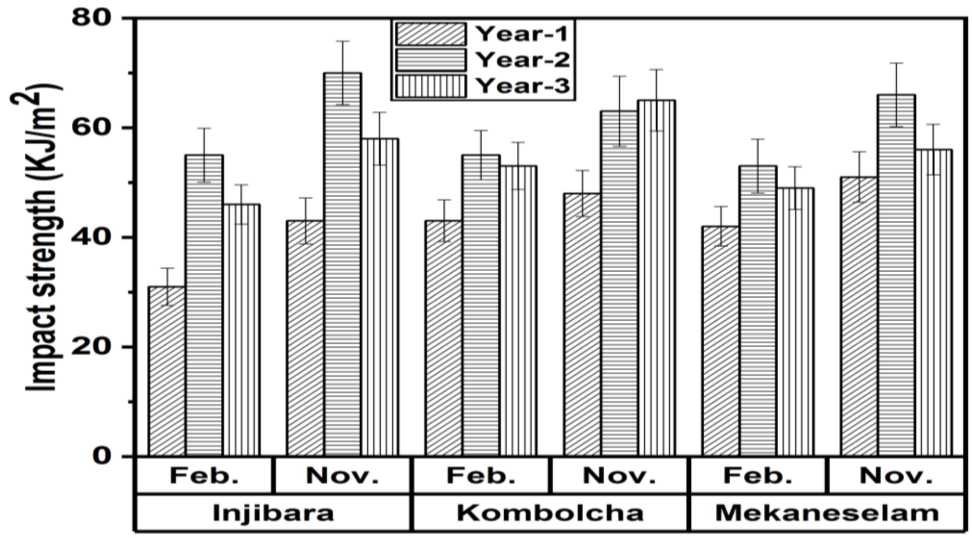


FIGURE 4.46: Comparison of Izod impact strength

4.5.4 Tensile strength of Injibara bamboo using ANOVA

Tensile strength

As presented in Table 4.40, the ages are statistically significant, however, the harvesting months are not statistically significant differences between groups on the tensile strength at α= 0.05 as evaluated by one-way ANOVA. Whereas pairwise comparison tests reveal that 2 compared to 1years, and 3 compared to 2 years are statistically significant, however, the ages of 3 compared to 1 year and harvesting months are statistically insignificant at α= 0.05 for the tensile strength of Injibara fibre.

Table 4. 40: Pairwise comparisons of the mean Tensile Strength for Injibara bamboo

Factors	UTS	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
Year	2 and 1	79.6	29.3649	2.71	0.03	6.79216	152.408
	3 and 1	-19.1	29.3649	-0.65	0.794	-91.908	53.7078
	3 and 2	-98.7	29.3649	-3.36	0.006	-171.51	-25.892
Month	2 and 11	-3.4	28.5467	-0.12	0.906	-61.875	55.0753

Young's modulus

As presented in Table 4.41, the ages are statistically significant, however, the harvesting months are statistically insignificant differences between groups on Young's modulus at α= 0.05 as evaluated by one-way ANOVA. Moreover, pairwise comparison tests reveal that 2 compared to 1 year, and 3 compared to 2 years are statistically significant, however, 3 compared to 1 year, and harvesting months are statistically insignificant at α = 0.05 for Young's modulus of Injibara fibre.

Table 4. 41: Pairwise comparisons of the mean of Young's modulus for Injibara bamboo.

				Tukey's method			
Factors	E	Coefti.	Std.Error	t	α>/t/	[95% confid. Interval]	
	2 and1	7.1	2.19106	3.24	0.009	1.66745	12.5326
	3 and 1	0.6	2.191059	0.27	0.96	-4.83255	6.032551
Years	3 and 2	-6.5	2.191059	-2.97	0.017	-11.9326	-1.06745
Months	2 vs 11	2.06667	2.10004	0.98	0.333	-2.2351	6.3684

4.5.5 Tensile strength of Kombolcha bamboo using ANOVA

Tensile strength

As presented in Table 4.42, the ages are statistically significant, however, the harvesting months are statistically insignificant differences between groups on the tensile strength at α= 0.05 as evaluated by one-way ANOVA. Moreover, pairwise comparison tests reveal that 2 compared to 1 year, as well as, 3 compared to 1 year are statistically significant, however, 3 compared to 2 years, and harvesting months are statistically insignificant at α= 0.05 for the tensile strength of Kombolcha bamboo fibre.

Table 4. 42: Pairwise comparisons of the mean tensile strength for Kombolch fibres.

				Tukey's method			
Factors	UTS	Coffie.	Std.Error	t	α>/t/	[95% confid. Interval]	
	2 and 1	144	30.46	4.73	0.000	68.45	219.55
	3 and 1	129	30.46	4.23	0.001	53.45	204.55
Ages (Yrs)	3 and 2	-15	30.46	-0.49	0.876	-90.55	60.55
months	2 and 11	23.13	34.27	0.67	0.505	-47.069	93.34

Young's Modulus

As presented in Table 4.43, the ages and harvesting months are statistically significant differences between groups on Young's modulus at α= 0.05 as evaluated by one-way ANOVA. Moreover, the pairwise comparison test reveals that 2 compared to 1 year old, and 3 compared to 2 years old are statistically significant, however, 3 compared to 1 year old, and harvesting months are statistically insignificant at α = 0.05 for Young's modulus of Kombolcha bamboo fibre.

Table 4. 43: Pairwise comparisons of the mean of Young's modulus for Kombolcha fibres.

				Tukey's method			
Factors	Compar.	Coeffi.	Std.Error	t	α>/t/	[95% confid. Interval]	
	2 and 1	11.3	2.93	3.86	0.002	4.033	18.57
	3 and 1	12.6	2.93	4.3	0.001	5.33	19.87
Ages (Yrs)	3 and 2	1.3	2.93	0.44	0.898	-5.97	8.57
Months	2 and 11	6.47	2.93	2.2	0.036	0.459	12.475

4.5.6 Tensile strength of Mekaneselam bamboo fibres using ANOVA

Tensile strength

As presented in Table 4.44, the ages are statistically significant, however, the harvesting months are statistically insignificant differences between groups on the tensile strength at P= 0.05 as evaluated by one-way ANOVA. Moreover, pairwise comparison tests reveal that 3 compared to 1 year, and 3 compared to 2 years are statistically significant, however, 2 compared to 1 year, and harvesting months are statistically insignificant at α = 0.05 for the tensile strength of Mekaneselam bamboo fibre.

Table 4. 44: Pairwise comparisons of the mean tensile strength for Mekaneselam fibres

				Tukey's method			
Factors	Comparasion	Coeffi.	Std.Error	t	α>/t/	[95% confid. Interval]	
	2 and 1	16.4	19.37	0.85	0.678	-31.63	64.43
	3 and 1	-97.7	19.37	-5.04	0.000	-145.73	-49.67
Ages(Yrs)	3 and 2	-114.1	19.37	-5.89	0.000	-162.13	-66.07
Months	2 and 11	23.2	24.17	0.96	0.345	-26.32	72.72

Young's modulus of bamboo fibres

As presented in Table 4.45, the ages are statistically significant, whereas the harvesting months are a statistically insignificant difference between groups on Young's modulus at α= 0.05 as evaluated by one-way ANOVA. Moreover, pairwise comparison tests reveal that 3 compared to 1 year, and 3 compared to 2 years are statistically significant, however, 2 compared to 1 year, and harvesting months are statistically insignificant at α = 0.05 for Young's modulus of Mekaneselam bamboo fibre.

Table 4. 45: Pairwise comparisons of the mean of Young's modulus for Mekaneselam bamboo

Factors	Compar.	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
	2 and 1	1.1	0.918	1.2	0.464	-1.18	3.38
	3 and1	-3	0.918	-3.27	0.008	-5.28	-0.72
Ages(Yrs)	3 and 2	-4.1	0.918	-4.47	0.000	-6.38	-1.82
Month	2 and 11	0.667	0.977	0.68	0.501	-1.335	2.668

4.5.7 Three points bending test of Injibara BFEPCs using ANOVA

Flexural strength

As presented in Table 4.46, the ages of the bamboo culm are statistically significant, however, the harvesting month is not a statistically significant difference between groups on the flexural strength at *P*= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison tests reveal that 2 compared to 1 year, and 3 compared to 2 years are statistically significant, but 3 compared to 1 year, and harvesting months are not statistically significant at $\alpha = 0.05$ for the flexural strength of Injibara BFEPCs.

Table 4. 46: Pairwise comparisons of the mean flexural strength for Injibara BFEPCs

Factors	Flexural strength	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
	2 and 1	55.67	11.58	4.8	0.000	27.228	84.105
	3 and 1	26.92	11.58	2.32	0.067	-1.52	55.36
Ages (Yrs)	3 and 2	-28.75	11.58	-2.48	0.047	-57.19	-0.3115
Month	2 and 11	0.1111	12.15	0.01	0.993	-24.59	24.81

*2=February, and *11 = November.

Modulus of elasticity

As presented in Table 4.47, the ages and harvesting months of the bamboo culm are a statistically significant difference between groups on the modulus of elasticity at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 2 compared to 1 year, 3 compared to 2 years, and harvesting months are statistically significant, but at the ages of 3 compared to 1 year are not statistically significant at $\alpha = 0.05$ for the modulus of elasticity of Injibara BFEPCs.

Table 4. 47: Pairwise comparisons of the mean modulus of elasticity for Injibara BFEPCs.

Factors	MOE	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
Ages (Yrs)	2 and 1	3.42	0.78	4.37	0.000	1.499	5.335
	3 and 1	1.08	0.78	1.39	0.359	-0.8335	3.002
	3 and 2	-2.33	0.78	-2.99	0.014	-4.25	-0.4164
Month	2 and 11	-2	0.718	-2.78	0.009	-3.46	-0.5396

*2=February, and *11 = November

4.5.8 Three-point bending test of Kombolcha BFEPCs using ANOVA

Flexural strength

As presented in Table 4.48, the ages of the bamboo culm are statistically significant, but harvesting months are not a statistically significant difference between groups on the modulus of elasticity at α = 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 2 compared to 1 year are statistically significant, but 3 compared to 1 year, 3 compared to 2 years, and harvesting months are statistically insignificant at α = 0.05 for the flexural strength of Kombolcha BFEPCs.

Table 4. 48: Pairwise comparisons of the mean flexural strength for Kombolcha BFEPCs.

Factors	F. strength	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
Year	2 and 1	56.25	7.45	3.89	0.001	20.79	91.71
	3 and 1	33.25	7.45	2.3	0.7	-2.21	68.71
	3 and 2	-23	7.45	-1.59	0.263	-58.46	12.46
Month	2 and 11	19.83	5.65	1.45	0.155	-7.903	47.57

*2=February, and *11 = November.

Modulus of elasticity

As presented in Table 4.49, the ages and harvesting months of the bamboo culm are a statistically significant difference between groups on the modulus of elasticity at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison tests reveal that 2 compared to 1 year, 3 compared to 1 year, and harvesting months are statistically significant, but 3 compared to 2 years and 3 compared to 1 year are statistically insignificant at α = 0.05 for the modulus of elasticity of Kombolcha BFEPCs.

Table 4. 49: Pairwise comparisons of the mean of MOE for Kombolcha BFEPCs.

Factors	Flexural strength	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
Ages (Yrs)	2 and 1	2.75	0.91	3.02	0.013	0.51	4.98
	3 and 1	2.17	0.91	2.38	0.051	-0.0705	4.4
	3 and 2	-0.58	0.91	-0.64	0.799	-2.82	1.65
Months	2 and 11	1.72	0.78	2.2	0.035	0.128	3.316

*2=February, and *11 = November.

4.5.9 Three-point bending test of Mekaneselam BFEPCs using ANOVA

Flexural strength

As presented in Table 4.50, the ages and harvesting months of the bamboo culm are a statistically significant difference between groups on the flexural strength at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 2 compared to 1 year old, 3 compared to 2 years, and 3 compared to 1 year are statistically insignificant, whereas the harvesting months are statistically significant at α = 0.05 for the flexural strength of Mekaneselam BFEPCs.

Table 4. 50: Pairwise comparisons of the mean flexural strength for Mekaneselam BFEPCs

Factors	Flexural strength	Coeffi.	Std.Error	Tukey's method t	α>/t/	[95% confid. Interval]	
Year	2 and 1	6.25	13.73	0.46	0.892	-27.45	39.95
	3 and 1	-1.08	13.73	-0.08	0.997	-34.779	32.61
	3 and2	-7.33	13.73	-0.53	0.855	-41.029	26.36
Month	2 and 11	-41.89	8.46	-4.95	0.000	-59.09	-24.69

*2=February, and *11 = November.

Modulus of elasticity

As presented in Table 4.51, the ages of the bamboo culm are not statistically significant, whereas the harvesting months are statistically significant differences between groups on the modulus of elasticity at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 2 compared to 1 year, 3 compared to 2 years, and 3 compared to 1 year are statistically insignificant, whereas harvesting months are statistically significant at α = 0.05 for the modulus of elasticity of Mekaneselam BFEPCs.

Table 4. 51: Pairwise comparisons of the mean of modulus of elasticity Mekaneselam BFEPCs

Factors	F.strength	Coeffi.	Std.Error	Tukey's method			
				t	α>/t/	[95% confid. Interval]	
	2 and 1	0.833	0.85	0.98	0.595	-1.25	2.92
	3 and 1	1.58	0.85	1.86	0.166	-0.504	3.67
Ages (Yrs)	3 and 2	0.75	0.85	0.88	0.655	-1.34	2.84
Month	2 and 11	-2.17	0.62	-3.52	0.001	-3.418	-0.915

*2=February, and *11 = November.

4.5.10 Impact strength of Injibara BFREPC using ANOVA

As presented in Table 4.52, the ages and harvesting months of the bamboo culm are statistically significant differences between groups on the impact strength at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 3 compared to 1 year, and harvesting months are statistically significant. However, 2 compared to 1 year, as well as, 3 compared to 2 years are not statistically significant at α = 0.05 for the impact strength of Injibara BFEPCs.

Table 4. 52: Pairwise comparisons of the mean impact strength for Injibara BFEPCs

Factors	Impact strength	Coeffi.	Std.Error	Tukey's method			
				t	α>/t/	[95% confid. Interval]	
	2 and 1	10.33	6.93	1.49	0.309	-6.69	27.36
	3 and 1	22.83	6.93	3.29	0.007	5.81	39.86
Ages (Yrs)	3 and 2	12.5	6.93	1.8	0.185	-4.53	29.83
Month	2 and 11	-24.89	4.82	-5.17	0.000	-34.68	-15.11

*2=February, and *11 = November.

4.5.11 Impact strength of Kombolcha BFREPC using ANOVA

As presented in Table 4.53, the ages, and the harvesting months of the bamboo culm are statistically significant differences between groups on the impact strength at α = 0.05 as determined by one-way ANOVA. Whereas pairwise comparison test reveals that 2 compared to 1 year, 3 compared to 1 year, and the harvesting months are statistically significant. However, 3 compared to 2 years are not statistically significant at α= 0.05 for the impact strength of Kombolcha BFEPCs.

Table 4. 53: Pairwise comparisons of the mean impact strength for Kombolcha BFEPCs.

Factors	Comparasion	Coeffi.	Std.Error	Tukey's method			
				t	α>/t/	[95% confid. Interval]	
	2 and 1	11.42	3.71	3.07	0.012	2.29	20.53
	3 and 1	13.92	3.71	3.74	0.002	4.79	23.035
Year	3 and 2	2.5	3.71	0.67	0.781	-6.62	11.62
	2 and 11	-8.39	3.34	-2.51	0.017	-15.19	-1.59

*2=February, and *11 = November.

4.5.11 Impact strength of Mekaneselam BFEPCs using ANOVA

As presented in Table 4.54, the ages are statistically significant, however, the harvesting months of the bamboo culm are not a statistically significant difference between groups on the impact strength at α= 0.05 as determined by one-way ANOVA. Whereas pairwise comparison tests reveal that 3 compared to 1 year are statistically significant. However, 2 compared to 1 year, and 3 compared to 2 years and harvesting months are statistically insignificant at α = 0.05 for the impact strength of Mekaneselam BFEPCs.

Table 4. 54: Pairwise comparisons of mean impact strength for Mekaneselam BFEPCs

Factors	Impact strength	Coeffi.	Std.Error	Tukey's method			
				t	α>/t/	[95% confid. Interval]	
	2 and 1	9.22	4.73	1.19	0.218	-5.49	26.32
	3 and 1	21.38	4.73	3.29	0.007	6.71	29.18
Ages (Yrs)	3 and 2	13.5	4.73	1.33	0.145	-3.35	19.45
Month	2 and 11	-5.44	4.26	-1.28	0.211	-14.12	3.23

*2=February, and *11 = November.

4.5.12 Summary results of bamboo fibres and their epoxy composites

The highest value of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 2 years has 22%, 15%, and 17% higher back-calculated tensile strength compared to the lowest value at the age of 1 year in February, whereas, in November, they have 21%, 38%, and 26% higher back-calculated tensile strength compared to the lowest value at the age of 1 year, respectively. The back-calculated tensile strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November has 2%, 10%, and 6% higher than in February, respectively.

The highest value of Injibara, Kombolcha, and Mekaneselam bamboo fibres has 16%, 24%, and 10% higher back-calculated Young's modulus compared to the lowest value in February, whereas, in November, they are 19%, 20%, and 11% higher back-calculated Young's modulus compared to the lowest value, respectively. Hence, the back-calculated Young's modulus of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 8%, 9%, and 7% higher back-calculated Young's modulus than in February.

The highest recorded values for Injibara, Kombolcha, and Mekaneselam bamboo fibres epoxy composite are 26%, 37%, and 26% higher flexural strength than the lowest recorded values in February, whereas in November 29%, 35%, and 41% higher flexural strength than the lowest recorded values, respectively. The flexural strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres epoxy composite in November has 10%, 32%, and 5% higher flexural strength than in February.

Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 11%, 8%. and 13% higher modulus of elasticity than in February. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFEPCs are 18%, 33%, and 23% higher modulus of elasticity than the lowest recorded values in February, whereas, in November 32%, 23%, and 27% higher modulus of elasticity than the lowest recorded values, respectively. The highest and lowest impact strength of 53±4.9 KJ/m^2 and 42±3.6 KJ/m^2 is recorded in February, whereas in November 66±5.8 KJ/m^2 and 51±4.6 KJ/m^2 are recorded for Mekaneselam bamboo fibres, respectively. Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 21%, 13%. and 20% higher impact strength than in February, respectively.

Hence, the highest and the lowest values of tensile strength, Young's modulus, flexural strength, modulus of elasticity, and impact strength are recorded at 2 and 1 years old, respectively. Therefore, bamboo species, age, and harvesting month have a significant influence on the tensile strength, Young's modulus, flexural strength, modulus of elasticity, and impact strength of the BFEPCs. According to the previous study in Ethiopia, bamboo had been only utilized for domestic use. This study reported that Ethiopian bamboo fibres and their epoxy composites are more superior properties when compared to other bamboo species so they can be successfully used to utilize for composites application in the Automobile industry. The mechanical properties of fibres composites have been investigated to be greatly influenced by ages, harvesting season, and the type of bamboo species.

4.6 Result and discussion on the strength of bamboo fibres polymer composites.

4.6.1 Tensile strength of bamboo fibres and BFPPCs

The back-calculated tensile strength of bamboo species in Ethiopia from IFBT in terms of the effect of age and harvesting season is shown in Figure 4.47. The highest and lowest back-calculated tensile strengths of Injibara bamboo fibres at the ages of 2 and 1 year in February has 334±23 MPa and 245±30 MPa, whereas, in November, it has 386±36 MPa and 326±30 MPa, respectively. The highest and lowest back-calculated tensile strengths of Kombolcha bamboo fibres at the ages of 2 and 1 year in February has 328±31 MPa and 270±26 MPa, whereas, in November, it has 337±32 MPa and 276±25 MPa, respectively. The highest and lowest back-calculated tensile strengths of Mekaneselam bamboo fibres at the ages of 2 and 1 year in February has 330±32 MPa and 271±25 MPa, whereas, in November, it has 379±31 MPa and 293±30 MPa, respectively.

The back-calculated tensile strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 16%, 18%, and 23% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam bamboo fibres are 27%, 18%, and 17% higher tensile strength than the lowest recorded values in February, whereas in November, they have 21%, 38%, and 26% higher tensile strength than the lowest recorded values, respectively. The back-calculated tensile strength of Injibara bamboo fibres has 2% and 1% higher in February, whereas in November is 13% and 2% higher than Kombolcha and Mekaneselam, respectively. The back-calculated tensile strength of Mekaneselam bamboo fibres has 1% and 11% higher than Kombolcha in February, and November, respectively.

BFEPCs have higher back-calculated tensile strength than BFPPCs due to a weak interface between the fibres and the matrix. The current research results show that epoxy has good interfacial bonding with bamboo fibres compared to PP. The current studies of back-calculated tensile strength of Injibara, Kombolcha, and Mekaneselam bamboo fibre are 34%, 42%, and 35% lower than the previously reported by (584 MPa) (C. Wang et al., 2015).

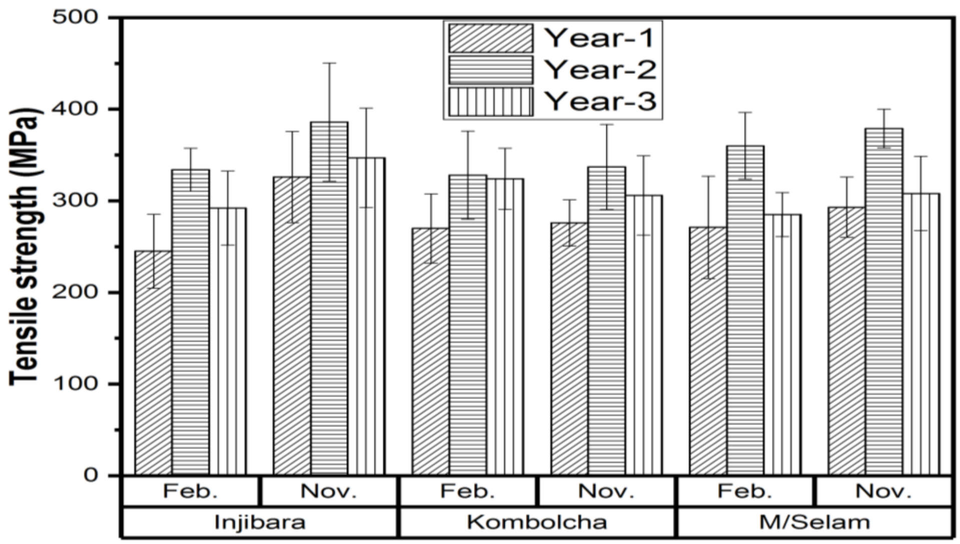


FIGURE 4.47: Back-calculated tensile strength of the bamboo fibre from BFPPCs

Young's modulus

The back-calculated Young's modulus of bamboo species in Ethiopia from IFBT in terms of the effect of age and harvesting season is shown in Figure 4.48. The highest and lowest back-calculated Young's modulus ofInjibara bamboo fibres at the ages of 2 and 1 year in February has 37±4 GPa and 25±3 GPa, whereas, in November, it has 43±4 GPa and 28±3 GPa, respectively. The highest and lowest back-calculated Young's modulus of Kombolcha bamboo fibres at the ages of 2 and 1 year in February has 25±3 GPa and 18±2 GPa, whereas, in November, it has 35±4 GPa and 29±3 GPa, respectively. The highest and lowest back-calculated Young's modulus of Mekaneselam bamboo fibres at the ages of 2 and 1 year in February has 32±3 GPa and 25±2 GPa, whereas, in November, it has 41±4 GPa and 33±2 GPa, respectively.

The back-calculated Young's modulus of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 14%, 29%, and 22% higher than in February, respectively.

The highest recorded values for Injibara, Kombolcha, and Mekaneselam bamboo fibres are 32%, 28%, and 22% higher Young's modulus than the lowest recorded values in February, whereas in November, they have 35%, 17%, and 20% higher Young's modulus than the lowest recorded values, respectively. The back-calculated Young's modulus of Injibara bamboo fibres has 32% and 14% higher in February, whereas in November is 19% and 5% higher than Kombolcha and Mekaneselam bamboo fibres, respectively. The back-calculated

Young’s modulus of Mekaneselam bamboo fibres has 22% and 15% higher than Kombolcha bamboo fibres in February, and November, respectively. The current studies of back-calculated Young’s modulus of Injibara, Kombolcha, and Mekaneselam bamboo fibre are 37%, 23%, and 34% higher than the previous reports (27±3.2 GPa) (Cui. Wang et al., 2015)

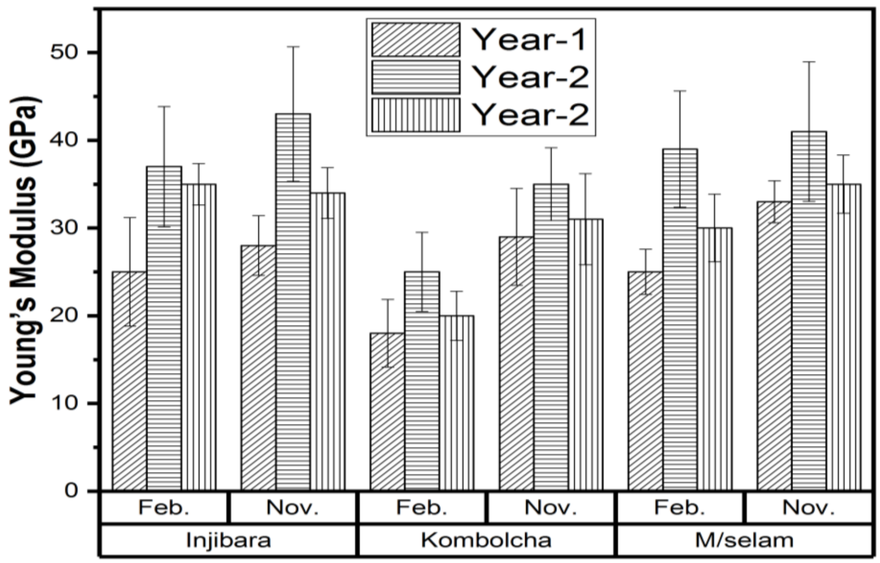


FIGURE 4.48: Back-calculated Young’s modulus of bamboo fibres from BFPPCs

Strain to failure

The effect of age and harvesting month on the tensile strain to failure of BFPPCs for Injibara, Kombolcha, and Mekaneselam bamboo are shown in Figure 4.49. The highest and the lowest tensile strain to failure of Injibara BFPPCs at the ages of 2 and 1 year in February has 0.95±0.06% and 0.46±0.03%, whereas, in November, it has 0.89±0.06% and 0.41±0.04%, respectively.

The highest and the lowest tensile strain to failure of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 1.21±0.92% and 0.83±0.06%, whereas, in November, it has 1.32±0.96% and 0.63±0.05%, respectively.

The highest and lowest tensile strain to failure of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 0.98±0.08% and 0.76±0.06%, whereas, in November, it has 0.87±0.06% and 0.71±0.06%, respectively. Injibara and Mekaneselam BFPPCs in February have 6% and 11% higher than in November, whereas Kombolcha BFPPCs in November has 8% higher tensile strain to failure than in February. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 52%, 31%, and 22% higher tensile strain to failure than the lowest recorded values in February, whereas in November, they have 54%, 53%, and 18% higher tensile strain to failure than the lowest recorded values, respectively. Kombolcha BFPPCs have 28% and 26% higher tensile strain to failure than Injibara and Mekaneselam, respectively. The tensile strain to failure of Mekaneselam BFPPCs has 3% higher than Injibara BFPPCs. The current studies of tensile strain to failure of Injibara, Kombolcha, and Mekaneselam BFPPCs are 67%, 54%, and 66% lower than the previous reports (2.88±0.18%) (Cui. Wang et al., 2015)

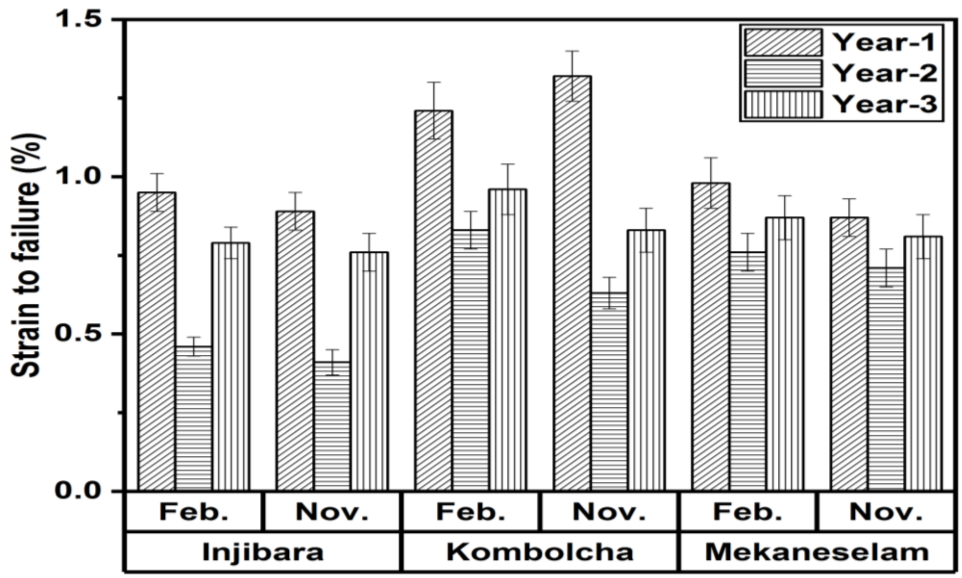


FIGURE 4.49: Tensile strain to failure of BFPPCs.

<u>Stress-strain of BFPPCs</u>

The stress-strain plot of BFPPCs is shown in Figure 4.50. The stress-strain curve is influenced by ages, harvesting seasons, and the type of bamboo species. The ultimate tensile stress of Injibara, Kombolch, and Mekaneselam BFPPCs in February increased by 21%, 42%, and 16%, whereas in November, they increase by 21%, 16%, and 4%, respectively. The highest and the lowest tensile stresses are at the age of 2 and 1 year, respectively. This increase in tensile strength and a decrease in maximum allowable strain can be attributed to improving crystallinity and cellulose content of bamboo fibres when become matured at one growth season of age, as well as, to improved interface bonding between the fiber and PP resin.

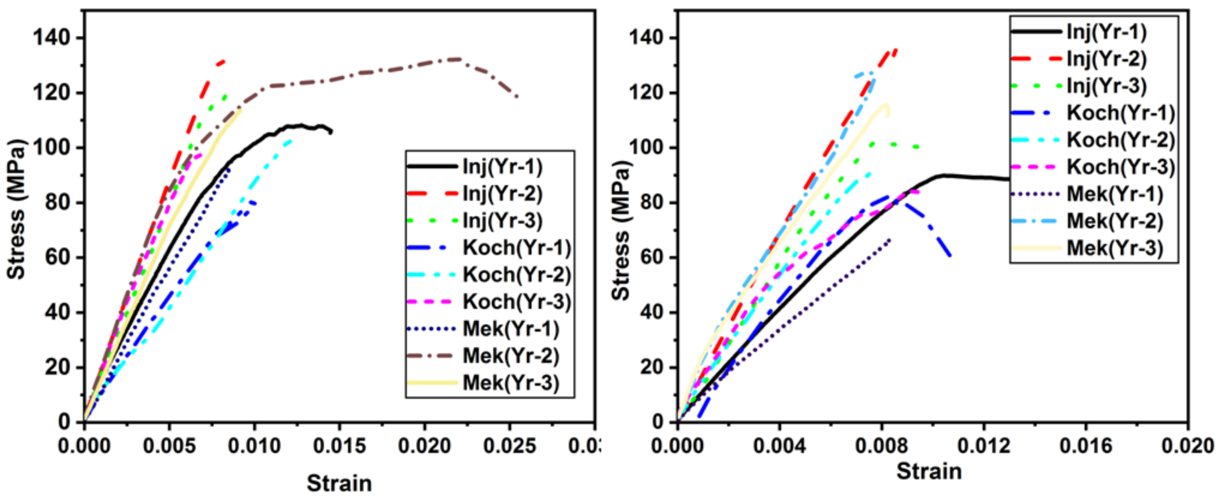


FIGURE 4.50: the tensile stress-strain curve of BFPPCs

Tensile strength of BFPPCs

The effect of age and harvesting month on the tensile strength of BFPPCs for Injibara, Kombolcha, and Mekaneselam bamboo is presented in Figure 4.51. The highest and lowest tensile strengths of Injibara BFPPCs at the ages of 2 and 1 year in February has 116±11 MPa and 91±8 MPa, whereas, in November, it has, 125±12 MPa and 99±8 MPa, respectively. The highest and the lowest tensile strengths of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 104±11 MPa and 60±7 MPa, whereas, in November, it has 111±12 MPa and 93±8 MPa, respectively. The highest and lowest tensile strengths of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 101±10 MPa and 85±7 MPa, whereas, in November, it has 116±10 MPa and 111±5 MPa, respectively.

The tensile strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 7%, 6%, and 13% higher than in February, respectively.

The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 22%, 42%, and 16% higher tensile strength than the lowest recorded values in February, whereas in November 21%, 16%, and 4% higher tensile strength than the lowest recorded values, respectively. The tensile strength of Injibara BFPPCs has 10% and 13% higher in February, whereas in November, it is 11% and 7% higher than Kombolcha and Mekaneselam, respectively. The tensile strength of Mekaneselam BFPPCs has 1% and 4% higher than Kombolcha BFPPCs in February and November, respectively. The current studies of tensile strength of Injibara, Kombolcha, and Mekaneselam BFPPCs are 68%, 64%, and 65% higher than *Neosinocalamus affinis* bamboo in the previous reports (40±0.58 MPa) (Cui. Wang et al., 2015).

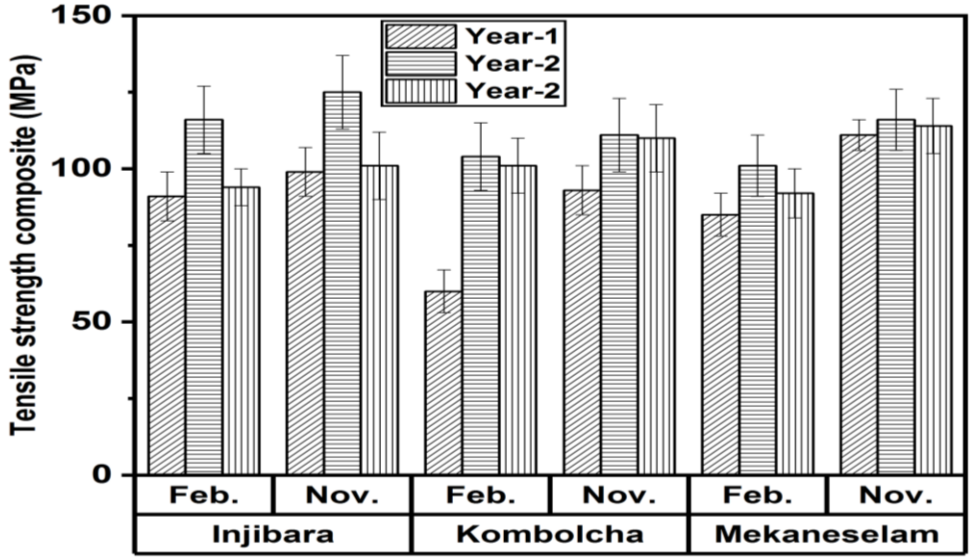


FIGURE 4.51: Tensile strength of BFPPCs

<u>Young's modulus of BFPPCs</u>

The Young's modulus BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.52. The highest Young's modulus in theoretical and experimental of Injibara BFPPCs in February has 16±1.19 GPa and 14±1.13 GPa, whereas, in November, it has 19±1.21 GPa and 18±1.18 GPa, respectively. The efficiency factor of 88% and 95% are reached in February and November, respectively.

Moreover, the highest theoretical and experimental values of Young's modulus of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 16±1.15 GPa and 14±0.92 GPa, whereas, in November, it has 17±1.12 GPa and 15±1.07 GPa, respectively. An efficiency factor of 87% and 88% are recorded in February and November, respectively.

Furthermore, the highest theoretical and experimental values of Young's modulus of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 15±1.07 GPa and 14±1.04 GPa, whereas, in November, it has 17±1.09 GPa and 16±1.08 GPa, respectively. An efficiency factor of 93% and 94% are recorded in the harvesting months of February and November, respectively.

In general, Young's modulus of BFPPCs of the theoretical value is comparable to the experimental value. This efficiency value indicates a good fibre/matrix interfacial which improves mechanical properties and fiber special properties that promote mechanical interlocking. The current studies of Young’s modulus of Injibara, Kombolcha, and Mekaneselam BFPPCs are higher than those previously reported by Cabrera et al (1.3 GPa) (Cabrera De Lima et al., 2021), Shah et al (3.75 GPa) (A. U. M. Shah et al., 2016), Ibrahim et al (1.14 GPa) (Ibrahim et al., 2015), Liu et al (2.29 GPa) (Liu et al., 2012), Keya et al (4.96 GPa) (Nahar Keya et al., 2019), Cuicui Wang et al., 2015 (2.07±0.22 GPa)

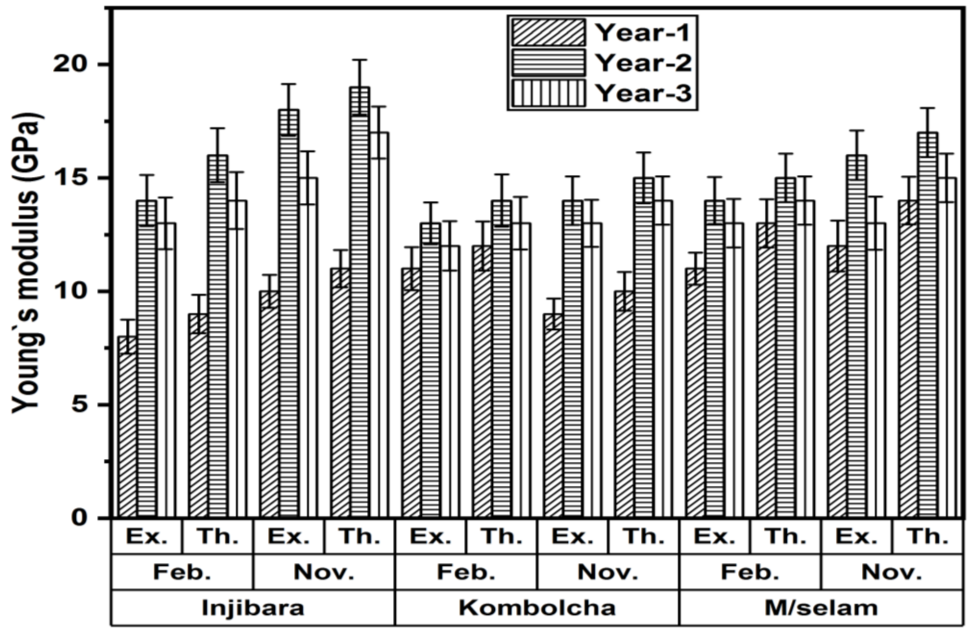


FIGURE 4.52: Young`s modulus of BFPPCs

4.6.2 Three-point bending test of BFPPCs

Longitudinal flexural strength

The effect of age and harvesting month on the longitudinal flexural strength of bamboo fibres reinforced PP composite for Injibara, Kombolcha, and Mekaneselam bamboo are shown in Figure 4.53. The highest and the lowest longitudinal flexural strengths of Injibara BFPPCs at the ages of 2 and 1 year in February has 138±4 MPa and 92±10 MPa, whereas, in November, it has 159±8 MPa and 113±12 MPa, respectively. The highest and the lowest longitudinal flexural strengths of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 96±10 MPa and 72±13 MPa, whereas, in November, ti has 99±7 MPa and 66±12 MPa, respectively. The highest and lowest longitudinal flexural strengths ofMekaneselam BFPPCs at the ages of 2 and 1 year in February has 127±13 MPa and 89±6 MPa, whereas, in November, it has 152±15 MPa and 105±16 MPa, respectively.

The longitudinal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 13%, 3%, and 16% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 33%, 25%, and 30% higher flexural strength than the lowest recorded values in February, whereas in November 29%, 33%, and 31% higher flexural strength than the lowest recorded values, respectively. The longitudinal Flexural strength of Injibara BFPPCs has 30% and 8% higher in February, whereas in November is 38% and 4% higher flexural strength than Kombolcha and Mekaneselam, respectively. The flexural strength of Mekaneselam BFPPCs has 24% and 35% higher than Kombolcha in February and November, respectively.

The current studies of longitudinal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs are 75%, 60%, and 74% higher than previously reported by Shubra et al (Shubhra et al., 2013), as well as, 69%, 49%, and 67% higher than the previously reported by Wang et al (Yunfei Wang et al., 2020), moreover, 51%, 21%, 49% higher than the previously reported by Keya et al (Nahar Keya et al., 2019), respectively. However, they are 40%, 63%, and 43% lower than previously reported by E. Trujillo (E. Trujillo, 2014) respectively.

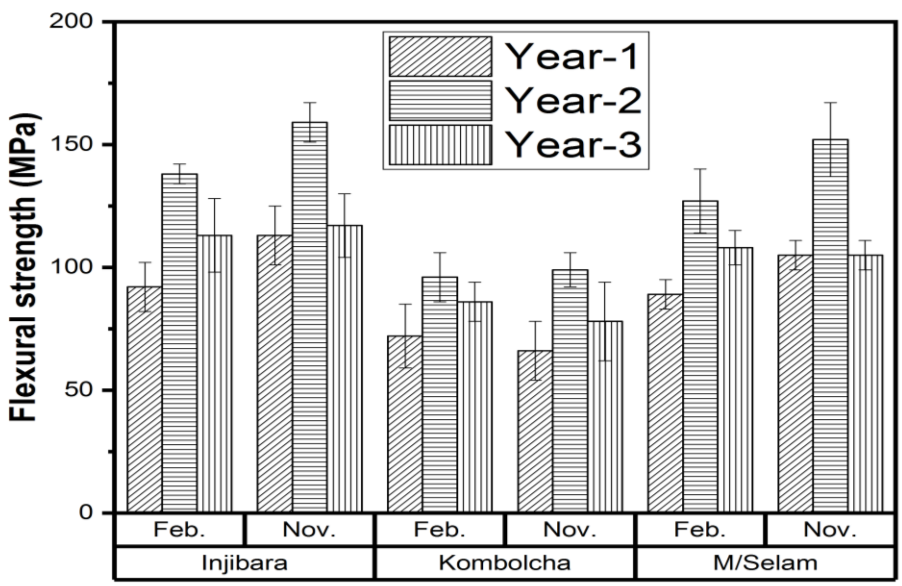


FIGURE 4. 53: Longitudinal flexural strength of BFPPCs.

Longitudinal modulus of elasticity

The effect of age and harvesting month on the longitudinal modulus of elasticity of BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.54. The highest and the lowest longitudinal modulus of elasticity of BFPPCs at the ages of 2 and 1 year in February has 8±0.22 GPa and 6±0.55 GPa, whereas, in November, it has 11±0.76 GPa and 7±0.29 GPa, respectively. The highest and the lowest longitudinal modulus of elasticity of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 6±0.35 GPa and 4±0.26 GPa, whereas, in November, it has 7±0.41 GPa and 4±0.28 GPa, respectively.

The highest and lowest longitudinal modulus of elasticity of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 8±0.29 GPa and 5±0.24 GPa, whereas, in November, it has 9±0.22 GPa and 6±0.28 GPa, respectively. Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 27%, 14%. and 11% higher longitudinal modulus of elasticity than in February. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 25%, 33%, and 38% higher longitudinal modulus of elasticity than the lowest recorded values in February, whereas in November 36%, 43%, and 33% higher longitudinal modulus of elasticity than the lowest recorded values, respectively.

The longitudinal modulus of elasticity of Injibara BFPPCs has 25% higher than Kombolcha, but Mekaneselam has a similar longitudinal modulus of elasticity with Injibara in February, whereas in November, it is 36% and 18% higher than Kombolcha and Mekaneselam, respectively. The longitudinal modulus of elasticity of Mekaneselam BFPPCs has 25% and 22% higher than Kombolcha in February and November, respectively.

The current studies of longitudinal modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFPPCs are 87%, 80%, and 84% higher than the previously reported by Cabrera et al (Cabrera De Lima et al., 2021), 81%, 71%, and 78% higher than the previously reported by wang et al (Yunfei Wang et al., 2020), 48%, 18%, and 36% higher than the previously reported by Keya et al (Nahar Keya et al., 2019), and 42%, 63%, and 53% higher than the previously reported by E. trujillo (E. tujiloo, 2014) respectively.

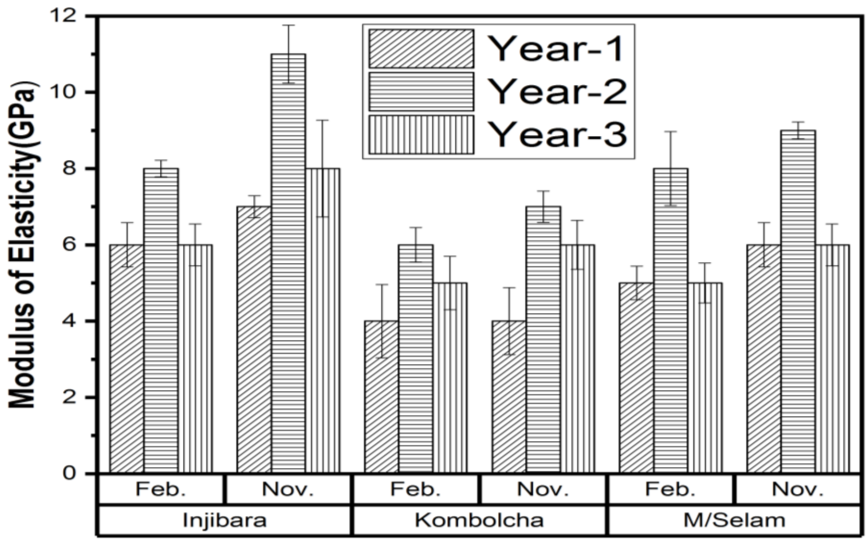


FIGURE 4.54: Longitudinal modulus of elasticity of BFPPCs

Longitudinal strain To failure

The effect of age and harvesting month on the longitudinal strain to failure of BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.55. The highest and the lowest longitudinal strain to failure of Injibara BFPPCs at the ages of 2 and 1 year in February has 2.11±0.11% and 1.75±0.09%, whereas, in November, it has 2.05±0.11% and 1.96±0.12%, respectively.

The highest and the lowest longitudinal strain to failure of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 2.64±0.17% and 2.08±0.18%, whereas, in November, it has 2.44±0.19% and 2.05±0.16%, respectively. The highest and lowest longitudinal strain to failure of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 2.31±0.18% and 2.11±0.19%, whereas, in November, it has 2.22±0.16% and 2.01±0. 17%, respectively.

Injibara, Kombolcha, and Mekaneselam BFPPCs in February have 3%, 8%, and 4% higher than in November. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 17%, 21%, and 9% higher longitudinal strain to failure than the lowest recorded values in February, whereas in November, they are 4%, 16%, and 9% higher longitudinal strain to failure than the lowest recorded values, respectively.

Kombolcha BFPPCs has 20% and 13% higher in February, whereas in November, it is 16% and 9% higher longitudinal strain to failure than Injibara and Mekaneselam, respectively. The longitudinal strain to failure of Mekaneselam BFPPCs has 9% and 8% higher than Injibara in February and November, respectively.

The current studies of strain to failure of Injibara, Kombolcha, and Mekaneselam BFPPCs are 27%, 15%, and 16% lower than GAK previously reported by E. trujillo (E. trujillo, 2014), respectively.

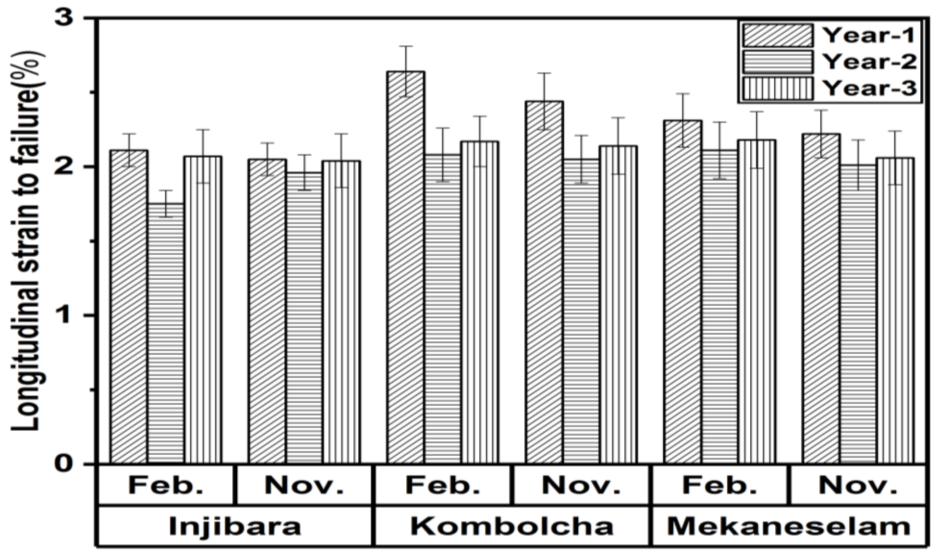


FIGURE 4.55: Longitudinal flexural strain to failure of BFPPCs

Flexural stress-strain of three-point bending test

The longitudinal flexural stress-strain curve based on the ages of 1-3 years, bamboo species, and harvesting month of BFPPCs are shown in Figure 4.56. The flexural stress of 65-120 MPa is measured in February, whereas in November 70-120 MPa are measured, respectively. The longitudinal flexural stress and strain are influenced by the ages and harvesting months of the bamboo fibres. These curves showed that the different ages, harvesting months, and bamboo species led to different tensile behaviors. From the highest to the lowest flexural stress of BFPPCs are Injibara, Mekaneselam, and Kombolcha, respectively. Age 2 and 1 years have the highest and the lowest longitudinal flexural stress of bamboo fibres PP composites, respectively. February has lower tensile stress, but higher longitudinal flexural strain to failure of BFPPCs.

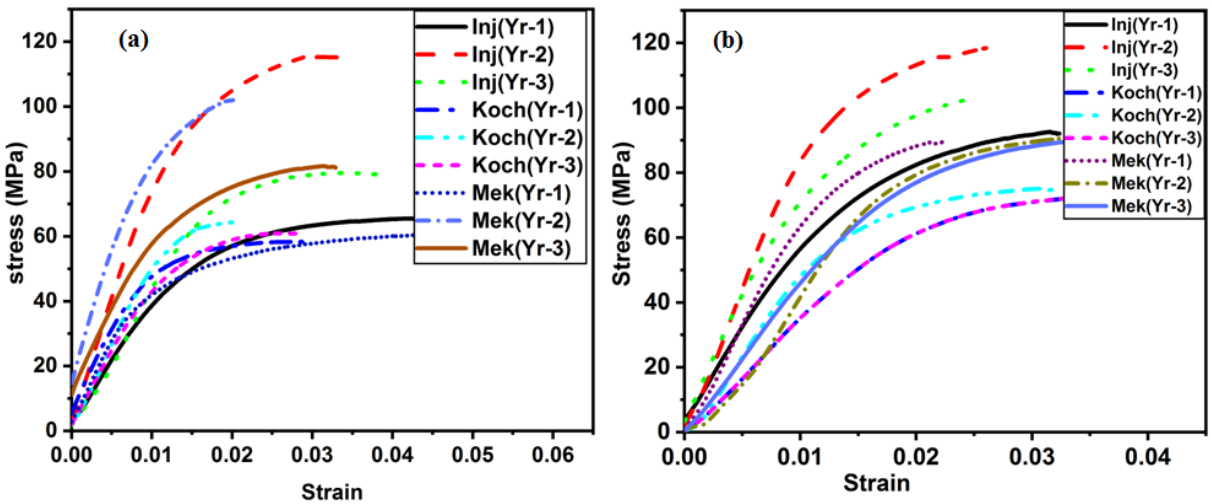


FIGURE 4. 56: Flexural stress-strain curve of BFPPCs (a) February, (b) November

4.6.3 Transversal three-point bending test of BFPPCs

Transversal flexural strength

The effect of age and harvesting month on the transversal flexural strength of BFPPCs for Injibara, Kombolcha, and Mekaneselam bamboo are in Figure 4.57. The highest and the lowest transversal flexural strengths of Injibara BFPPCs at the ages of 2 and 1 year in February had 12±0.12 MPa and 6±0.4 MPa, whereas, in November, it has 18±1.4 MPa and 12±1.02 MPa, respectively. The highest and the lowest transversal flexural strengths of Kombolcha BFPPCs at the ages of 2 and 1 year in February had 9±0.5 MPa and 7±0.39 MPa, whereas, in November, it has 11±1.09 MPa and 6±0.45 MPa, respectively.

The highest and lowest transversal flexural strengths of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 12±1.03 MPa and 6±0.02 MPa, whereas, in November, it has 15±1.05 MPa and 6±0.03 MPa, respectively. The transversal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 33%, 18%, and 20% higher than in February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 50%, 22%, and 52% higher transversal flexural strength than the lowest measured values in February, whereas, in November, they have 33%, 45%, and 60% higher transversal flexural strength than the lowest recorded values, respectively.

The transversal flexural strength of Injibara BFPPCs has 25% and 2% higher in February, whereas, in November, it has 39% and 17% higher transversal flexural strength than Kombolcha and Mekaneselam, respectively. The transversal flexural strength of Mekaneselam BFPPCs has 25% and 27% higher than Kombolcha in February and November, respectively.

The current studies of transversal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs are 60%, 76%, and 67% higher than previously reported by Chattopadhyay et al (Chattopadhyay et al., 2010), 53%, 71%, and 61% higher than the previously reported by Divya et al (Divya et al., 2016), and 45%, 67%, and 55% higher than the previously reported by E. Trujillo (E. Trujillo, 2014), respectively.

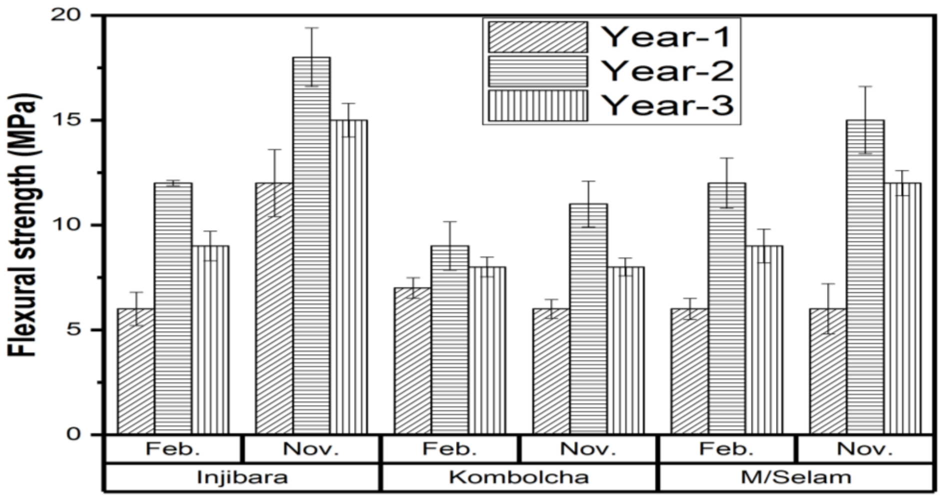


FIGURE 4.57: Transverse flexural strength of BFPPCs.

Transversal modulus of elasticity

The effect of age and harvesting month on the transversal modulus of elasticity of BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.58. The highest and the lowest transversal modulus of elasticity of Injibara BFPPCs at the ages of 2 and 1 year in February has 1.6±0.08 GPa and 1±0.05 GPa, whereas, in November, it has 1.8±0.08 GPa and 1.36±0.09 GPa, respectively. The highest and the lowest transversal modulus of elasticity of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 0.74±0.05 GPa and 0.58±0.06 GPa, whereas, in November, it has 0.78±0.03 GPa and 0.49±0.02 GPa, respectively. The highest and lowest transversal modulus of elasticity of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 0.79±0.02 GPa and 0.49±0.01 GPa, whereas, in November, it has 1.4±0.02 GPa and 0.71±0.04 GPa, respectively.

Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 11%, 5%. and 44% higher transversal modulus of elasticity than in February. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 38%, 34%, and 37% higher transversal modulus of elasticity than the lowest recorded values in February, whereas, in November, they have 24%, 25%, and 50% higher transversal modulus of elasticity than the lowest recorded values, respectively. The transversal modulus of elasticity of Injibara BFPPCs has 54%, and 51% higher in February, whereas, in November, it has 57% and 22% higher than Kombolcha and Mekaneselam, respectively. The transversal modulus of elasticity of Mekaneselam BFPPCs has 6% and 44% higher than Kombolcha in February and November, respectively.

The current studies of the transversal modulus of elasticity of Injibara, Kombolch, and Mekaneselam BFPPCs are 33%, 71%, and 48% lower than GAK E. Trujillo (E. Trujillo, 2014), 13%, 62%, and 33% lower than Chattopadhyay et al (Chattopadhyay et al., 2010), and Kombolcha and Mekaneselam BFPPCs are 53%, and 15% lower, but Injibara BFPPCs is 8% higher than Divya et al (Divya et al., 2016), respectively.

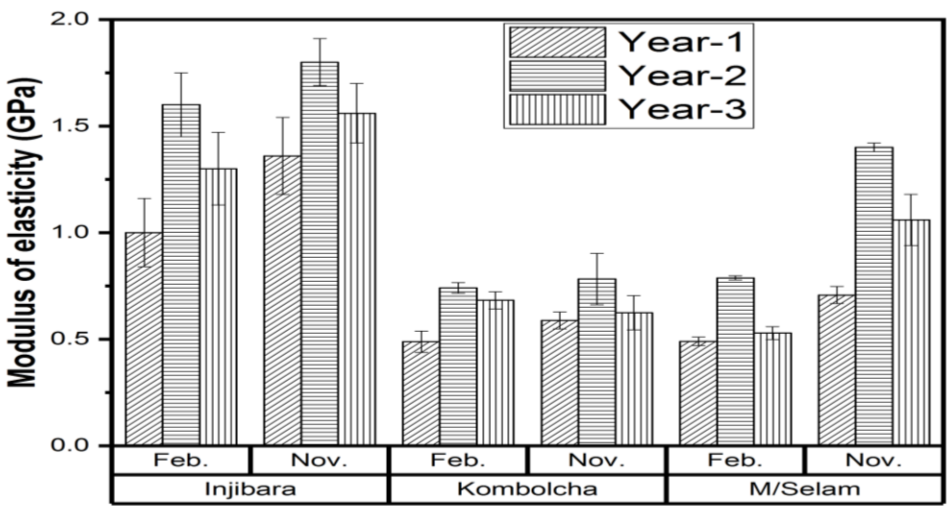


FIGURE 4.58: Transverse modulus of elasticity of BFPPCs

Transverse flexural strain to failure

The effect of age and harvesting month on the transversal strain to failure of BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.59. The highest and the lowest transversal strain to failure of Injibara BFPPCs at the ages of 2 and 1 year in February has 3.31±0.28% and 2.43±0.13%, whereas, in November, it has 3.04±0.23% and 2.23±0.22%, respectively. The highest and the lowest transversal strain to failure of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 3.41±0.28% and 2.84±0.26%, whereas, in November, it has 3.49±0.27% and 2.03±0.19%, respectively.

The highest and lowest transversal strain to failure of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 3.53±0.31% and 2.48±0.26%, whereas, in November, it has 2.41±0.23% and 1.73±0. 13%, respectively. Injibara, and Mekaneselam BFPPCs in February have 8%, and 32% higher than in November, whereas Kombolcha in November has a 2% higher transversal strain to failure than in February.

The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 27%, 17%, and 30% higher transversal strain to failure than the lowest measured values in February, whereas, in November, they have 27%, 42%, and 28% higher transversal strain to failure than the lowest measured values, respectively.

Kombolcha BFPPCs has 11% and 29% higher transversal strain to failure than Injibara and Mekaneselam, respectively. The transversal strain to failure of Mekaneselam BFPPCs has 6% higher than Injibara. The current studies of transversal strain to failure of Injibara, Kombolcha, and Mekaneselam BFPPCs are 21%, 30%, and 2% higher than the previously reported by E. Trujillo (E. Trujillo, 2014), respectively.

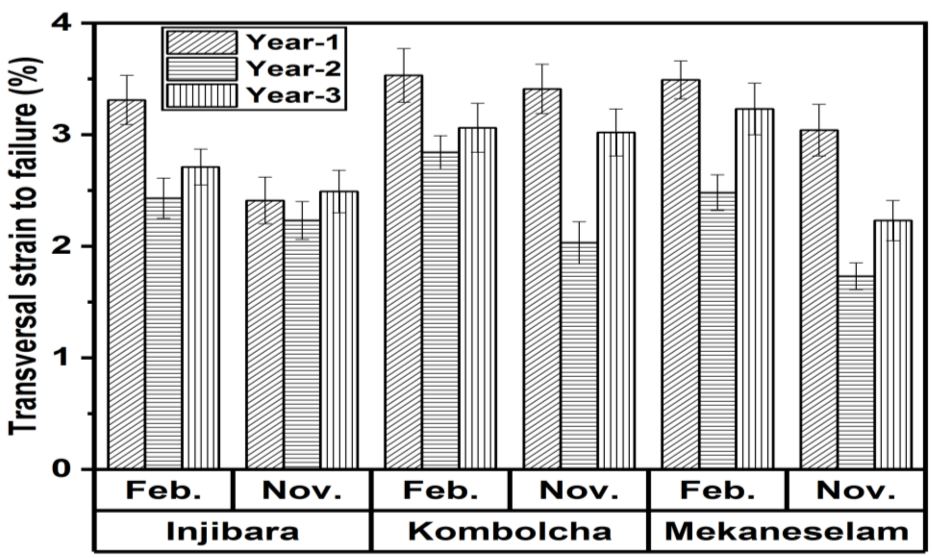


FIGURE 4.59: Transverse strain to failure of BFPPCs.

4.6.4 Impact strength of BFPPCs

The effect of age and harvesting month on the impact strength of BFPPCs for Injibara, Kombolcha, and Mekaneselam are shown in Figure 4.60. The highest and the lowest impact strength of Injibara BFPPCs at the ages of 2 and 1 year in February has 52±6.4 KJ/m^2 and 34±3.8 KJ/m^2, whereas, in November, it has 57±6.96 KJ/m^2 and 47±5.45 KJ/m^2, respectively.

The highest and the lowest impact strength of Kombolcha BFPPCs at the ages of 2 and 1 year in February has 38±3.86 KJ/m^2 and 26±3.34 KJ/m^2 in February, respectively. Whereas in November, it has 44±5.68 KJ/m^2 and 39±4.15 KJ/m^2, respectively.

The highest and lowest impact strength of Mekaneselam BFPPCs at the ages of 2 and 1 year in February has 40±4.62 KJ/m^2 and 34±3.38 KJ/m^2, whereas, in November, it has 46±5.51 KJ/m^2 and 37±4.35 KJ/m^2, respectively. Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 9%, 14%. and 13% higher impact strength than in February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 35%, 32%, and 15% higher impact strength than the lowest values in February, whereas, in November, they have 18%, 11%, and 20% higher impact strength than the lowest values, respectively. The range of standard deviation in the harvesting month of February and November are 5–11%, and 8–13% respectively.

The impact strength of Injibara, Kombolcha, and Mekaneselam BFPPCs are 56%, 43%, and 46% higher than GFREPCs (25 KJ/m^2)(Megahed et al., 2021), and 67%, 57%, and 59% higher than the previous studies of bamboo fibres (18.86 KJ/m^2) (Banga et al., 2015), 82%, 77%, and 78% higher than the previously reported by Cabrera et al (10 KJ/m^2) (Cabrera De Lima et al., 2021), 65%, 55%, and 57% higher than Keya et al (20 KJ/m^2) (Nahar Keya et al., 2019), respectively. However, the impact strength of Injibara, Kombolcha, and Mekaneselam BFPPCs are 49%, 60%, and 58% lower than the previous studies of *Guadua angustifolia Kunth* (GAK) (Rua et al., 2021) (111KJ/m^2), respectively.

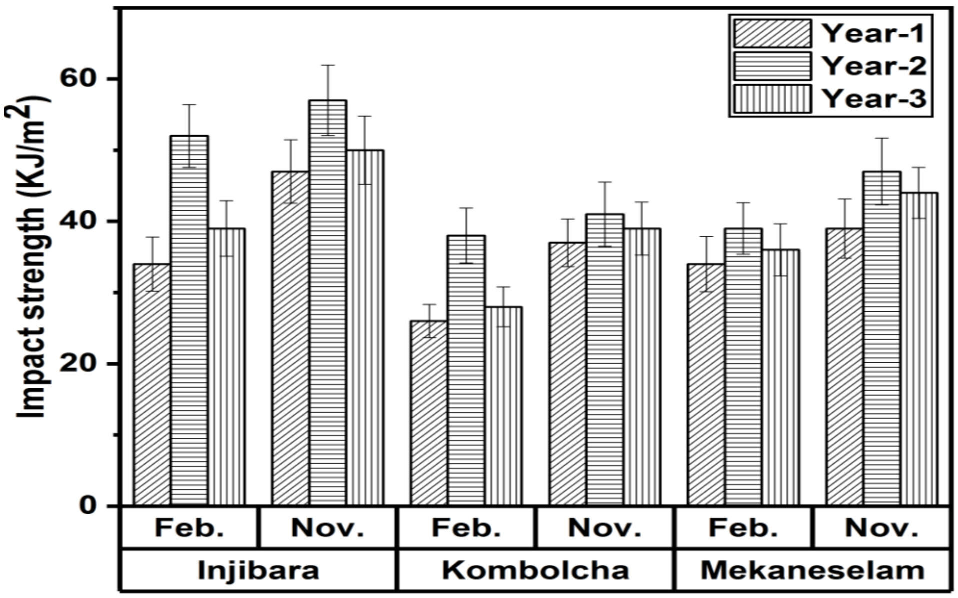


FIGURE 4.60: Impact strength of BFPPCs.

4.6.5 Ultimate tensile strength of BFPPCs ANOVA

As presented in Table 4.55, the ages of Injibara bamboo fibres are not statistically significant on the tensile strength, Young's modulus, and strain to failure, whereas harvesting month is statistically insignificant on Young's modulus, and strain to failure, but it is statistically significant on tensile strength difference between groups at P= 0.05 as determined by one-way ANOVA.

The age of Kombolcha bamboo fibres is statistically significant on the tensile strength and Young's modulus, but it does not strain to failure, whereas harvesting month is not statistically significant on the tensile strength, Young's modulus, and strain to failure difference between groups at P= 0.05 as determined by one-way ANOVA. The age of Mekaneselam bamboo fibres is statistically significant, whereas harvesting month is statistically insignificant on the tensile strength, Young's modulus, and strain-to-failure difference between groups at P= 0.05 as determined by one-way ANOVA.

Table 4. 55: ANOVA-test results of tensile test on the effect of ages and harvesting seasons

	Injibara			Kombolcha			Mekaneselam		
Effect of Ages	TS	E	ε	TS	E	ε	TS	E	ε
P-value	0.7858	0.2961	0.2653	0.0372	0.0264	0.2237	0.0109	0.0000	0.0000
f-ratio	0.24	1.27	1.39	3.73	4.17	1.58	5.36	27.2	17.22
Signif.(P<0.05)	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Effect of season	TS	E	ε	TS	E	ε	TS	E	ε
P-value	0.0303	0.8136	0.1467	0.0632	0.8509	0.1309	0.1734	0.2135	0.1914
f-ratio	5.21	0.06	2.23	3.74	0.04	2.42	1.59	1.62	1.79
Signif.(P<0.05)?	Yes	No	No	No	No	No	No	No	No

Note:- TS- Tensile strength, E-Young`s modulus, and ε - strain to failure

4.6.6 Longitudinal three-point–bending test using ANOVA

As presented in Table 4.56, the ages of the Injibara and Mekaneselam bamboo fibres are statistically significant, whereas, harvesting months of Injibara bamboo are not statistically significant on the longitudinal flexural strength, modulus of elasticity, and strain to failure difference between groups at P= 0.05 as determined by one-way ANOVA. Moreover, the ages of Kombolchaa bamboo fibres are statistically insignificant on the longitudinal flexural strength, modulus of elasticity, and strain-to-failure difference between groups at P= 0.05 as determined by one-way ANOVA. Harvesting seasons of Mekaneselam and Kombolcha bamboo fibres are statistically significant on the longitudinal flexural strength and modulus of elasticity difference between groups at P= 0.05 as determined by one-way ANOVA respectively.

Table 4. 56: ANOVA-test results of longitudinal 3pt bending test

	Injibara			Kombolcha			Mekaneselam		
Effect of Ages	FS	MOE	ε	FS	MOE	ε	FS	MOE	ε
P-value	0.0023	0.0003	0.0114	0.5288	0.1109	0.1510	0.0008	0.0120	0.0015
f-ratio	7.33	10.41	5.14	0.65	2.35	2.00	8.91	5.07	7..97
Signif.(P<0.05)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Effect of season	FS	MOE	ε	FS	MOE	ε	FS	MOE	ε
P-value	0.6701	0.8051	0.2421	0.0691	0.0089	0.0880	0.0502	0.0715	0.1390
f-ratio	0.18	0.06	1.42	3.52	7.69	3.09	4.05	3.46	2.30
Signif.(P<0.05)?	No	No	No	No	Yes	No	Yes	No	No

Note:- FS- Flexural strength, MOE-Modulus of elasticity, and ε - strain to failure

As presented in Table 4.57, bamboo species (Injibara, Kombolcha, and Mekaneselam) are statistically significant differences between groups on the longitudinal flexural strength, modulus of elasticity, impact strength, and strain to failure at *P*= 0.05 as determined by one-way ANOVA.

Table 4. 57: ANOVA- test of longitudinal 3pt bending test on the effect of bamboo species

Properties of Bamboo species	Statistical difference between bamboo species		
	f- ratio	P-value	Significant at P<0.05?
FS	31.48	0.0000	Yes
MOE	13.44	0.0000	Yes
Strain to failure	25.45	0.0000	Yes
Impact strength	107.04	0.0000	Yes

4.6.7 Transversal three-point bending test using ANOVA

As presented in Table 4.58, the ages of Injibara bamboo fibres are statistically significant on the transversal flexural strength and modulus of elasticity, but they are statistically insignificant on the strain of failure, whereas, ages of Kombolcha bamboo fibres are statistically significant on the transversal flexural strength, but they are not statistically significant on the transversal modulus of elasticity and strain of failure, however, ages of Mekaneselam bamboo fibres are statistically significant on the transversal flexural strength, modulus of elasticity, and strain to failure between groups at *P*= 0.05 as determined by one-way ANOVA.

As presented in Table 4.58, harvesting seasons of Injibara bamboo fibres are statistically significant on the transversal modulus of elasticity, but they are statistically insignificant on the flexural strength and strain of failure, whereas, harvesting seasons of Kombolcha bamboo fibres are statistically significant on the transversal flexural strength, modulus of elasticity and strain of failure. Ages of Mekaneselam BFPPCs are statistically significant on the transversal flexural strength, but they are statistically insignificant on the modulus of elasticity and strain of failure between groups at *P*= 0.05 as determined by one-way ANOVA.

Table 4. 58: ANOVA-test results of transversal 3pt bending test

	Injibara			Kombolcha			Mekaneselam		
Effect of Ages	FS	MOE	ε	FS	MOE	ε	FS	MOE	ε
P-value	0.0000	0.0009	0.2102	0.0044	0.1913	0.4029	0.0009	0.0006	0.0000
f-ratio	14.26	8.66	1.64	6.42	1.74	0.93	8.80	9.32	16.94
Signif.(P<0.05)?	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes
Effect of season	FS	MOE	ε	FS	MOE	ε	FS	MOE	ε
P-value	0.0880	0.0063	0.3402	0.0000	0.0344	0.0048	0.0477	0.3397	0.3632
f-ratio	3.08	8.49	0.94	42.67	4.86	9.08	4.22	0.94	0.85
Signif.(P<0.05)?	No	Yes	No	Yes	Yes	Yes	Yes	No	No

As presented in Table 4.59, bamboo species (Injibara, Kombolcha, and Mekaneselam) are statistically significant differences between groups on the transversal flexural strength, modulus of elasticity, and strain to failure at P= 0.05 as determined by one-way ANOVA.

Table 4. 59: ANOVA- test of transversal 3pt bending test on the effect of bamboo species

Properties of Bamboo species	Statistical difference between bamboo species		
	f- ratio	P-value	Significant at P<0.05 ?
FS	9.90	0.0001	Yes
MOE	52.51	0.0000	Yes
Strain to failure	4.05	0.0201	Yes

4.6.8 Analysis of impact strength of BFRPPCs using ANOVA

As presented in Table 4.60, the age of Injibara, Kombolcha, and Mekaneselam BFPPCs are statistically significant on the impact strength, moreover, the harvesting months of Injibara, and Kombolcha BFPPCs is statistically significant, but harvesting months Mekaneselam BFPPCs is statistically insignificant on the impact strength difference between groups at P= 0.05 as determined by one-way ANOVA.

Table 4. 60: ANOVA-test of impact strength on the effect of ages and harvesting seasons.

	Injibara			Kombolcha			Mekaneselam		
Impact strength	p-value	f-ratio	Sign.	p-value	f-ratio	Sign.	p-value	f-ratio	Sign.
Effect of Age	0.0407	5.71	Yes	0.0248	8.91	Yes	0. 0345	5.25	Yes
Effect of season	0.0159	6.45	Yes	0.0004	15.71	Yes	0.3887	0.76	No

4.6..9 Summary results of BFPPCs.

The tensile strength, Young`s modulus, flexural strength, modulus of elasticity, and impact strength of bamboo fibres and their reinforced PP composites in Ethiopia are studied based on the effect of ages and harvesting months. The highest and the lowest tensile strength, Young`s, flexural strength, modulus of elasticity, and impact strength of BFPPCs at the age of 2 and 1 years old, respectively. The harvesting month of November has higher mechanical properties compared to February. The highest to the lowest mechanical properties of bamboo fibres and their PP composites are Injibara, Kombolcha, and Mekaneselam, respectively.

The highest recorded values for Injibara, Kombolcha, and Mekaneselam bamboo fibres are 27%, 18%, and 17% higher back calculated tensile strength than the lowest measured values in February, whereas, in November, it has 21%, 38 %, and 26 % higher than the lowest measured values, respectively. The back-calculated tensile strength of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 16%, 18%, and 23% higher than in February, respectively. The back-calculated tensile strength of Injibara bamboo fibres in February has 2% and 1% higher, whereas, in November, it is 13% and 2% higher than Kombolcha and Mekaneselam bamboo fibres. whereas Mekaneselam bamboo fibres have 1% and 11% higher than Kombolcha bamboo fibres in February and November, respectively.

The back-calculated Young’s modulus of Injibara, Kombolcha, and Mekaneselam bamboo fibres in November have 14%, 29%, and 22% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam bamboo fibres are 32%, 28%, and 22% higher back-calculated Young’s modulus than the lowest recorded values in February, whereas, in November, they have 35%, 17%, and 20% higher than the lowest recorded values, respectively. The back-calculated Young’s modulus of Injibara bamboo fibres in February has 32% and 14%, whereas in November, it is 19% and 5% higher than Kombolcha and Mekaneselam bamboo fibres and Mekaneselam bamboo fibres has 22% and 15% higher than Kombolcha bamboo fibres in February and November, respectively.

The tensile strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November has 7%, 6%, and 13% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs are 22%, 42%, and 16% higher tensile strength than the lowest recorded values in February, whereas in November 21%, 16%, and 4% higher than the lowest measured values, respectively. The tensile strength of Injibara BFPPCs has 10%

and 13% higher in February, whereas in November, it is 11% and 7% higher than Kombolcha and Mekaneselam and Mekaneselam BFPPCs have 1% and 4% higher than Kombolcha bamboo in February and November, respectively.

The longitudinal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 13%, 3%, and 16% higher than in February, respectively. The highest recorded values for Injibara, Kombolcha, and Mekaneselam BFPPCs have 33%, 25%, and 30% higher longitudinal flexural strength than the lowest recorded values in February, whereas, in November, they have 29%, 33%, and 31% higher than the lowest recorded values, respectively. Longitudinal Flexural strength of Injibara BFPPCs in February have 30% and 8%, whereas, in November, it has 38% and 4% higher than Kombolcha and Mekaneselam bamboo, as well as, Mekaneselam BFPPCs has 24% and 35% higher than Kombolcha bamboo in February and November, respectively.

The longitudinal modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFPPCs in November has 27% and 14%. and 11% higher than February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs have 25%, 33%, and 38% higher longitudinal modulus of elasticity than the lowest measured values in February, whereas in November, they have 36%, 43%, and 33% higher than the lowest measured values, respectively. The longitudinal modulus of elasticity of Injibara BFPPCs in November has 36% and 18% higher than Kombolcha and Mekaneselam, moreover, Mekaneselam BFPPCs has 25% and 22% higher than Kombolcha bamboo in February and November, respectively.

The transversal flexural strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 33%, 18%, and 20% higher than in February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs have 50%, 22%, and 52% higher transversal flexural strength than the lowest measured values in February, whereas, in November, they have 33%, 45%, and 60% higher than the lowest measured values, respectively. Transversal flexural strength of Injibara BFPPCs has 25% and 2% higher in February, whereas in November, it has 39% and 17% higher than Kombolcha and Mekaneselam, moreover, Mekaneselam BFPPCs has 25% and 27% higher than Kombolcha bamboo in February and November, respectively.

The transversal modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFPPCs in November have 11% and 5%. and 44% higher than in February. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs have 38%, 34%, and 37% higher transversal modulus of elasticity than the lowest values in February, whereas in November, they have 24%, 25%, and 50% higher than the lowest values, respectively. The transversal modulus of elasticity of Injibara BFPPCs in February has 54% and 51%, whereas, in November, it has 57% and 22% higher than Kombolcha and Mekaneselam, moreover, Mekaneselam BFPPCs has 6% and 44% higher than Kombolcha bamboo in February and November, respectively.

The impact strength of Injibara, Kombolcha, and Mekaneselam BFPPCs in November has 9%, 14%. and 13% higher than February, respectively. The highest measured values for Injibara, Kombolcha, and Mekaneselam BFPPCs have 35%, 32%, and 15% higher impact strength than the lowest measured values in February, whereas, in November, they have 18%, 11%, and 20% higher than the lowest measured values, respectively.

The modulus of elasticity is the slope of the stress-strain diagram which indicates the toughness of the material that absorbs energy during a collision. Strain to failure is the ability of the material to stretch in length due to collusion or applied energy. Two-year-old bamboo fibres have good mechanical properties because they have a high modulus of elasticity and a low strain to failure. Moreover, 2 years old of bamboo fibres have the best material properties which are absorbing energy and less strain to failure during collusion.

4.7 Result and discussion on the properties of bamboo fibres polymer composites for headliners in the automotive industry

4.7.1 Tensile strength of bamboo fibres polymer composites

As presented in Table 4.61, the tensile strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 1–3 years in February are 191– 206 MPa, 139–198 MPa, and 151–199 MPa, whereas, in November, they have 171–227 MPa, 129–205 and 166–216 MPa, respectively. Moreover, the tensile strengths of Injibara, Kombolcha, and Mekaneselam BFPPCs at the age of 1–3 years in February have 91–111 MPa, 60–104 MPa, and 85–101 MPa, whereas, in November, they have 99–125 MPa, 93–111 MPa, and 111–116 MPa, respectively. As presented in Table 4.60, the tensile strengths of the BFEPCs of Injibara, Kombolcha, and Mekaneselam have higher measured values compared to Jute felt PU, CFPU, GFPU, BFPP, BFEP, PP foam, and TPU (Husić, 2003; Samal et al., 2009; Kushwaha et al., 2010; Yang et al., 2010; Abdul Khalil et al., 2012; Liu et al., 2012; Yeh et al., 2017; Vaidya, 2017; Ababu et al., 2021; Cabrera De Lima et al., 2021; Dou et al., 2021), and are comparable with BFEP, GFPU, GF laminated with PE (Abdul Khalil et al., 2012; Suresh et al., 2015; Karnoub et al., 2020). However, they have lower measured values compared to GFEP, GFPU840871, GFPU 90IK01, and Glass laminated (Husić, 2003; Araki et al., 2004; Mohamed et al., 2015; Batabyal et al., 2018).

Young's modulus of bamboo fibres polymer composites

As presented in Table 4.61, Young's modulus of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 1–3 years in February have 17– 19 GPa, 11–17 GPa, and 16–18 GPa, whereas, in November, they have 16–21 GPa, 11–18 and 17–19 GPa respectively. Moreover, Young's modulus of Injibara, Kombolcha, and Mekaneselam BFPPCs at the age of 1–3 years in February have 8–14 GPa, 12–14 GPa, and 11–14 GPa, whereas, in November, they have 11–18 GPa, 9–15 GPa, and 13–16 MPa, respectively. Moreover, Young's modulus of BFEPCs of Injibara, Kombolcha, and Mekaneselam have higher measured values compared to GFEP, Jute felt PU, CFPU, GFMPU, BFPP, BFEP, GFEP, pp foam, GFPU, Glass laminated (Ababu et al., 2021; Abdul Khalil et al., 2012; Araki et al., 2004; Batabyal et al., 2018; Cabrera De Lima et al., 2021; Dou & Rodrigue, 2021; Husić, 2003; Kushwaha & Kumar, 2010; Liu et al., 2012; Samal et al., 2009; Suresh & Jayakumari, 2015; Vaidya, 2017; Chattopadhyay et al., 2010; Yeh et al., 2017), and are comparable with GFPU840871, and GF laminated PE (Mohamed et al., 2015; Karnoub et al., 2020). However, they have lower measured values compared to GFPU 90IK01, and TPU (Mohamed et al., 2015; Yeh et al., 2017).

Table 4. 61: Tensile properties of composite materials for Automobile headliners

Composite materials	Tensile strength (MPa)	Young`s modulus (GPa)	strain to failure (%)	refere
GF epoxy	330	3.29	0.1	(Husić, 2003)
10% jute felt PU	4.15	0.104	-	(Mohamed et al., 2015)
10% CFPU	14.86	0.156	-	(Mohamed et al., 2015)
10% Glass fibres mat PU	4.51	0.066	-	(Mohamed et al., 2015)
GFPU840871	351.77	19.53	0.024	(Vaidya, 2017)
GFPU 90IK01	309.06	21.43	0.023	(Vaidya, 2017)
20%BFRPP	21.92	2.31	-	(Abdul Khalil et al., 2012)
BFEPCs, Vf 65%	87-165	3-15	-	(Chattopadhyay et al., 2010)
GFEPCs, Vf 65%	180-220	5-10	-	(Chattopadhyay et al., 2010)
BFPPCs, 40%	26.27	1.776	-	(Kushwaha et al., 2010)
BFEPCs	86	6.736	-	(Ababu et al., 2021)
BFEPCs	138.88	4.96	2.7	(Liu et al., 2012)
BFPPCs, 39%	16.9	2.9	-	(Samal et al., 2009)
BFPPCs, 50%	14.4	2.8	-	(Samal et al., 2009)
BFPPCs	40.25	1.29	-	(Cabrera De Lima et al., 2021)
BFPPCs	5.43	1.3	-	(Muñoz-Pascual et al., 2020)
PP foam	20	0.795	-	(Batabyal et al., 2018)
40% E galsss PU	225	1.5	-	(Karnoub et al., 2020)
Glass laminated	321	5.166	-	(Dou et al., 2021)
Glass laminated PE	178	16.328	0.856	(Yeh et al., 2017)
PP foam	23.83	1.528	4.29	(Dou et al., 2021)
TPU	26.27	20.84	-	(Yeh et al., 2017)
Injibara BFEPCs, Feb.	191– 206	17–19	1.07– 1.13	Study
Injibara BFEPCs, Nov.	171–227	16–21	1.01–1.08	Study
Injibara BFPPCs, Feb.	111–166	16.71–26.18	0.41–0.95	Study
Injibara BFPPCs, Nov.	85–101	11.07–25.9	0.46–0.89	Study
Kombolcha BFEPCs, Feb.	139–198	11.31–18.1	1.16–1.35	Study
Kombolcha BFEPCs,Nov.	129–255	11.51–18.8	1.14–1.17	Study
Kombolcha BFPPCs, Feb.	93–111	10.92–14.95	0.83–0.98	Study
Kombolcha BFPPCs, Nov.	60–104	7.51–19.56	0.63–0.96	Study
Mekaneselam BFEPCs, Feb.	151–199	16.82–18.92	0.98–1.07	Study
Mekaneselam BFEPCs, Nov.	166–206	17.75–18.86	0.92–1.13	Study
Mekaneselam BFPPCs, Feb.	99–125	9.82–17.85	0.76–1.32	Study
Mekaneselam BFPPCs, Nov.	91–116	8.75–15.86	0.71–1.21	Study

4.7.2 Flexural strength of bamboo fibres polymer composites

As presented in Table 4.62, the flexural strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 1–3 years in February have 156–211MPa, 81–129MPa, and 139–189MPa, whereas, in November, they have 166–234MPa, 124–190 and 116–198 MPa, respectively. Moreover, the tensile strengths of Injibara, Kombolcha, and Mekaneselamm BFPPCs at the age of 1–3 years in February have 92–138MPa, 72–96MPa, and 89–127MPa, whereas, in November, they have 113–159MPa, 66–99MPa, and 105–152MPa, respectively.

The flexural strengths of the BFEPCs, as well as, the BFPPCs of Injibara, Kombolcha, and Mekaneselam have higher measured values compared to Jute felt PU, CFPU, GFMPU, BFPP, BFEP, GFPE, GFPU, (Husić, 2003; Bledzki et al., 2006; Samal et al., 2009; Kushwaha et al., 2010; Yang et al., 2010; Suresh et al., 2015; Vaidya, 2017; Cabrera De Lima et al., 2021), and are comparable with UDMA, BFEP, (Araki et al., 2004; Kushwaha et al., 2010; Abdul Khalil et al., 2012). However, they have lower measured values compared to GFEP, GFPU840871, GFPU 90IK01, and Glass laminated PE (Araki et al., 2004; Abdul Khalil et al., 2012; Mohamed et al., 2015; Karnoub et al., 2020).

Modulus of elasticity of bamboo fibres polymer composites

As presented in Table 4.62, the modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 1–3 years in February have 13– 17 GPa, 8–12 GPa, and 10–13 GPa, whereas, in November, they have 14–19 GPa, 10–13 and 11–15 GPa, respectively. Moreover, the modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFPPCs at the age of 1–3 years in February have 6–8 GPa, 4–6 GPa, and 5–8 GPa, whereas, in November, they have 7–11 GPa, 4–7 GPa, and 6–9 MPa, respectively.

The modulus of elasticity of the BFEPCs and BFPPCs of Injibara, Kombolcha, and Mekaneselam have higher measured values compared to Jute felt PU, CFPU, GFMPU, UDMA, BFPP, GFPU (Husić, 2003; Araki et al., 2004; Samal et al., 2009; Yang et al., 2010; Suresh et al., 2015; Vaidya, 2017; Cabrera De Lima et al., 2021), and are comparable with GFEP, BFEP, GFEP, GFPE,(Araki et al., 2004; Kushwaha et al., 2010; Abdul Khalil et al., 2012; Karnoub et al., 2020). However, they have lower measured values compared to GFPU840871, GFPU 90IK01, and Glass laminated PE (Mohamed et al., 2015; Karnoub et al., 2020).

Table 4. 62: Flexural strength of composite materials for Automobile headliners

Composite materials	Flexural Strength (MPa)	MOE (GPa)	Strain to Failure(%)	refere
GF epoxy	255	8.47	0.0279	(Araki et al., 2004)
10% jute felt PU	6.99	0.214	-	(Husić, 2003)
10% carbon fibres PU	13.47	0.308	-	(Husić, 2003)
10% Glass fibres mat PU	7.86	0.358	-	(Husić, 2003)
GFPU840871 composite	642.34	14.56	4.96	(Mohamed et al., 2015)
GFPU 90IK01 composite	618.88	17.11	3.82	(Mohamed et al., 2015)
UDMA	133.8	1.8	-	(Araki et al., 2004)
20%BFPPCs	38.74	1.27	-	(Vaidya, 2017)
BFEPCs, Vf 65%	107-140	12--10	-	(Abdul Khalil et al., 2012)
GFEP, Vf 65%	195-250	7--12	-	(Abdul Khalil et al., 2012)
BFPPCs, 40%	46.6	2.432	-	(Yang et al., 2010)
BFEPCs	107	11.901	-	(Kushwaha et al., 2010)
BFEPCs	119	11.901	-	(Kushwaha et al., 2010)
GFPE, Vf 30%	80	6.01	2.22	(Bledzki et al., 2006)
BFPPCs	43.8	1.975	-	(Samal et al., 2009)
BFPPCs	26.1	1.43	-	(Cabrera De Lima et al., 2021)
40% E galsss PU	95	0.50	-	(Suresh et al., 2015)
Glass laminated PE	289	14.222	-	(Karnoub et al., 2020)
Injibara BFEPCs, Feb.	139–198	6.56–11.51	2.11–2.22	Study
Injibara BFEPCs, Nov.	116–191	4.73–10.49	2.01–2.31	Study
Injibara BFPPCs, Feb.	89–152	6.5–13.2	3.02–3.61	Study
Injibara BFPPCs, Nov.	105–127	6.8–13.4	3.31–4.25	Study
Kombolcha BFEPCs, Feb.	81–190	5.36–10.87	2.08–2.64	Study
Kombolcha BFEPCs,Nov.	124–175	8.05–12.18	1.96–2.05	Study
Kombolcha BFPPCs, Feb.	92–138	6.7–12.12	2.61–3.63	Study
Kombolcha BFPPCs, Nov.	113–159	13.6–19.4	2.61–3.02	Study
Mekaneselam BFEPCs, Feb.	188–234	14.37–19.06	1.75–2.07	Study
Mekaneselam BFEPCs, Nov.	156–187	11.09–13.88	1.96–2.05	Study
Mekaneselam BFPPCs, Feb.	72–96	8.45–10.15	2.43–3.31	Study
Mekaneselam BFPPCs, Nov.	66–99	6.42–12.42	2.23–3.04	Study

4.7.3 Impact strength of bamboo fibres polymer composites

As shown in Table 4.63, the impact strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs at the age of 1–3 years in February have 31–55 KJ/m^2, 843–55 KJ/m^2, and 42–53KJ/m^2, whereas, in November, they have 43–70 KJ/m^2, 48–63KJ/m^2 and 51–66 KJ.m^2, respectively. Moreover, the impact strengths of Injibara, Kombolcha, and Mekaneselam BFPPCs at the age of 1–3 years in February are 34–52KJ/m^2, 26–38KJ/m^2, and 34–40KJ/m^2, whereas, in November, they have 47–57KJ/m^2, 26–38KJ/m^2, and 37–46KJ/m^2, respectively. Moreover, the impact strengths of BFEPCs and BFPPCs of Injibara, Kombolcha, and Mekaneselam have higher measured values compared to Jute felt PU, CFPU, GFMPU, BFRPP, BFREP, Glass laminate, GFPE, GFPU (Cabrera De Lima et al., 2021; Husić, 2003; Kushwaha & Kumar, 2010; Liu et al., 2012; Marhoon, 2017; Suresh & Jayakumari, 2015; Vaidya, 2017; Chattopadhyay et al, 2010), and are comparable with BFPP, GFPE (Bledzki et al., 2006; Samal et al., 2009). However, they have lower measured values compared to Glass laminated PE (Karnoub et al., 2020).

Table 4. 63: impact strength of composite materials for Automobile headliners

Composite materials	Impact Strength (KJ/m^2)	Refer.
PU	3.39	(Marhoon, 2017)
jute felt PU, Vf 10%	3.31	(Husić, 2003)
carbon fibres PU,Vf 10%	8.21	(Husić, 2003)
Glass fibres mat PU,Vf 10%	6.73	(Husić, 2003)
BRPP, Vf 20%	1.42	(Chattopadhyay et al., 2010)
BFRPP, Vf 40%	27.54	(Kushwaha et al., 2010)
BFREP	15.56	(Bledzki et al., 2006)
GFPE, vf 30%	38	(Liu et al., 2012)
BFRPP, Vf 39%	3.4	(Samal et al., 2009)
BFRPP, Vf 50%	3.2	(Samal et al., 2009)
BFRPP	48.7	(Samal et al., 2009)
BFRPP	10.1	(Cabrera De Lima et al., 2021)
E-Glass laminate	17.82	(Samuel et al., 2012)
40% E galsss PU	18	(Suresh et al., 2015)
Glass laminated PE	99.71	(Karnoub et al., 2020)
Injibara BFEPCs, Feb.	43–66	Study
Injibara BFEPCs, Nov.	31–55	Study
Injibara BFPPCs, Feb.	50–57	Study
Injibara BFPPCs, Nov.	34–52	Study
Kombolcha BFEPCs, Feb.	48–70	Study
Kombolcha BFEPCs,Nov.	43–55	Study
Kombolcha BFPPCs, Feb.	39–47	Study
Kombolcha BFPPCs, Nov.	26–38	Study
Mekaneselam BFEPCs, Feb.	51–66	Study
Mekaneselam BFEPCs, Nov.	42–66	Study
Mekaneselam BFPPCs, Feb.	37–41	Study
Mekaneselam BFPPCs, Nov.	34–39	Study

4.7.4 Summary results of headliner materials for the automobile industry

The purpose of the study is to characterize the mechanical strength of bamboo fibres reinforced polymer composites for Automobile headliners. Three representatives of bamboo plants are harvested at the ages of 1–3 years old within two months (February and November). The harvesting month of November has higher mechanical properties of bamboo fibres polymer composites compared to February. The highest and the lowest mechanical properties of bamboo fibres polymer composites are Injibara, Mekanesealm, and Kombolcha bamboo, respectively. BFEPCs are higher mechanical properties compared to BFPPCs.

The tensile strength of Injibara, Kombolcha, and Mekaneselam BFEPCs in November has 9%, 3%, and 8% higher than in February, whereas BFPPCs in November have 11%, 6%, and 13% higher than in February, respectively. The tensile strength of Injibara, Kombolcha, and Mekaneselam BFEPCs in February, they have 46%, 47%, and 49% higher than BFPPCs, whereas, in November, they have 45%, 46%, and 46% higher than BFPPCs, respectively. The tensile strengths of Ethiopian bamboo fibres reinforced polymer composites are comparable with other bamboo species and are suitable for composite materials used in the automobile industry for the production of headliners.

The Young`s modulus of Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 10%, 6%, and 5% higher than in February, whereas BFPPCs in November have 22%, 7%, and 13% higher than in February, respectively. The Young`s modulus of Injibara, Kombolcha, and Mekaneselam BFEPCs in February, they have 46%, 18%, and 22% higher thanBFPPCs, whereas, in November, they have 14%, 17%, and 16% higher than BFPPCs, respectively. The flexural strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in November, they have 10%, 32%, and 5% higher than in February, whereas BFPPCs in November, they have 13%, 3%, and 16% higher than in February, respectively.

The flexural strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in February, they have 35%, 26%, and 33% higher than BFPPCs, whereas, in November, they have 32%, 48%, and 23% higher than BFPPCs, respectively. The modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 11%, 8%, and 13% higher than in February, whereas BFPPCs in November, they have 27%, 14%, and 11% higher than November, respectively.

The modulus of elasticity of Injibara, Kombolcha, and Mekaneselam BFEPCs in February, they have 53%, 50%, and 38% higher than BFPPCs, whereas, in November, they have 4%, 46%, and 40% higher than BFPPCs, respectively.

The impact strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in November have 21%, 13%, and 20% higher than in February, whereas BFPPCs in November, they have 9%, 14%, and 13% higher than in February, respectively. The impact strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in February have 5%, 31%, and 25% higher than BFPPCs, whereas, in November, they have has 23%, 30%, and 31% higher than BFPPCs, respectively. Headliners have evolved as the most dynamic, multifunctional interior component in a car. The automotive industry has focused on interior design, aesthetics, and comfort as consumer buying decisions have proven to be more influenced by interior features. Several design factors have evolved for the headliner material to meet the appearance, performance, and cost requirements in today’s competitive market. The tensile strength, Young`s modulus, flexural strength, modulus of elasticity, and impact strengths of Ethiopian bamboo fibres reinforced polymer composites are comparable with other bamboo species and are suitable for composite materials used in the automobile industry for the production of headliners. In situations involving head impact into the interior car roof area, the material of the headliner plays an important role in occupant protection. Accurate evaluation of its mechanical properties is indeed critical for predicting its behavior during a vehicle's interior impact analysis.

CONCLUSION AND RECOMMENDATION

Conclusion

Over 1 million hectares of bamboo plants are covered in Ethiopia. Bamboo plants in Ethiopia are used for structural applications like building houses, home furniture, and fences. Researchers have not investigated the properties of Ethiopian bamboo fibres and their polymer composites for headliners in the automobile industry so far. This Ph.D. research work has characterized the properties of bamboo fibres in Ethiopia, which are found in the three regions such as Injibara, Kombolcha, and Mechaneselam. The three regions are different climates and geographical conditions which are altitude, temperature, and humidity. The type of bamboo species in the Kombolcha region is *Bambusa oldhamii*, which has a higher outer diameter and wall thickness, but a lower internodal length compared to Injibara and Mekaneselam. Injibara and Mekaneselam bamboo are *Yushania alpina* bamboo species, which have higher Internodal culm lengths compared to Kombolcha. They have the same bamboo species, but they have different properties. An extraction machine for bamboo fibres was developed by the authors in the workshop, which is easily manipulated and extracted bamboo fibres using manual labor.

The mechanical properties of bamboo fibres and their polymer composites are influenced by the ages and harvesting seasons. This Ph.D. research work is to characterize the properties of bamboo fibres based on their ages, which are grouped into 1, 2, and 3 years old and harvesting seasons are November (cold seasons), and February (dry seasons). The outer diameter, culm wall thickness, and Internodal length are increased when the age of the bamboo culm matures. The highest and lowest properties of bamboo fibres polymer composites are at the age of 2 and 1 year old, respectively. Moreover, the mechanical properties of bamboo fibres are influenced by the moisture content of the culm during extraction. The low percentage of moisture content in the bamboo culm is difficult to extract and produced damaged bamboo fibres. The current research work is shown that November has higher mechanical properties of bamboo fibres than February. November has a higher moisture content which is suited for fiber extraction that extracts fibres without damage from the culm. The existence of water in the culm improves the easy extraction of the fibers from the culm.

The measured fibre densities (ρf) for Injibara, Kombolcha, and Mekaneselam bamboo fibres are 1.35–1.38 g/cm³, 1.35–1.36 g/cm³, and 1.34–1.36 g/cm³, respectively. The densities of Bamboo fibres in Ethiopia is low compared to other bamboo species which is the fittest for composite materials. The degree of crystallinity of Injibara, Kombolcha, and Mekaneselam bamboo fibres at the ages of 1-3 years old are 69-73%, 58-66%, and 66-68%, respectively. The degree of crystallinity of bamboo fibres indicates that it is good properties for composite application which is required high mechanical properties.

The cellulose content of Injibara bamboo fibres at the ages of 1, 2, and 3 years have 11%, 9%, and 12% higher than Kombolcha, and 6%, 4%, and 6% higher than Mekaneselam, respectively. Whereas Mekaneselam bamboo fibres have 6%, 7%, and 6% higher than Kombolcha. The mechanical properties of composites are influenced by the amount of cellulose and hemicellulose contents in the bamboo fibres that have a direct relationship with the performance of composite materials. Bamboo species in Ethiopia can be a source of feedstock for lignocellulose ethanol and composite production since it has higher cellulose content. The sensitivity parameter (γ) of Injibara, Kombolcha, and Mekaneselam bamboo fibres have 0.23, 0.33, and 0.327, whereas the Shape parameters (β), have 6.24–7.83, 5.87–10.21, and 5.86–9.63, respectively. The sensitivity parameter shows that Injibara bamboo fibres have a higher fibres diameter variation through length compared to Kombolcha and Mekaneselam, but it has higher tensile strength compared to Kombolcha and Mekanselam, whereas Kombolcha bamboo fibres have a lower shape parameter, which has a higher variation of bamboo fibres strength. The tensile strength of single bamboo fibres for Injbara, Kombolcha, and Mekaneselam at the gauge length of 50 mm have 7%, 34%, and 21% lower than the back-calculated tensile strength of bamboo fibres from epoxy composite, whereas the Young's modulus of single bamboo fibres have 66%, 64%, and 73% lower back-calculated Young's modulus from epoxy composites than at the age of 2 years old in November, respectively. The tensile strength and Young`s modulus of single bamboo fibres are decreased due to a chain-like joint structure of fibres throughout their length.

The tensile strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in February have 46%, 47%, and 49% higher than PP composites, whereas, in November, they have 45%, 47%, and 46% higher than PP composites, respectively. Moreover, they have 46%, 18%, and 22% higher Young`s modulus than PP composites in February, whereas, in November, they have 14%, 17%, and 16% higher Young`s modulus than PP composites, respectively. The tensile strengths of Ethiopian bamboo fibres polymer composites are comparable with other bamboo species and are suitable for composite materials used in the automobile industry for the production of headliners. Epoxy resins are more compatible with bamboo fibres compared to Polypropylene resins which are hydrophobic materials.

Injibara, Kombolcha, and Mekaneselam BFEPCs in February have 35%, 26%, and 33% higher flexural strength than PP composites, whereas, in November, they have 32%, 48%, and 23% higher than PP composites, respectively. Moreover, they have 53%, 50%, and 38% higher modulus of elasticity than PP composites in February, whereas, in November, they have 4%, 46%, and 40% higher than PP composites, respectively. The impact strengths of Injibara, Kombolcha, and Mekaneselam BFEPCs in February have 5%, 31%, and 25% higher than PP composites, whereas, in November, they have 23%, 30%, and 31% higher than PP composites, respectively.

The main objective of automotive producers reduced the mass of the vehicles to optimize the efficiency of fuel consumption and reduced green house gas emission which pollute the environment by emission of the CO_2. Three types of headliner material have been used in recent years: (1) stampable sheet made of GF and PP, such as KP Sheet, (2) GF laminated polyurethane foam, generally called polyurethane sandwich headliner (substrate), which consists of a GF mat laminated with polyurethane foam on both sides, and (3) thermoplastic foam. The features required for headliner materials include (1) low release of harmful chemicals and foul odors in the process of molding headliner parts from material to improve the workplace environment, (2) high handling stiffness during installation in the auto assembly process, (3) lightweight and minimal dimensional change in parts in environmental atmospheres, high durability, and high sound absorption, and (4) biodegradability when the automobile is scrapped.

Therefore, the current research on bamboo fibres polymer composites is suitable for headliners production in the automobile industry due to the higher service properties of headliners materials compared to glass fibres polymer composites. The properties of bamboo fibres polymer composites are higher specific strength, low weight, biodegradable, low cost, low processing energy, and eco-friendly compared to glass fibres polymer composites.

Recommendation

Researchers should investigate matrix materials that are biodegradable and compatible to natural fibres. Epoxy is an expensive matrix and a non-biodegradable fossil fuel-based resin and polypropylene is poor interfacial interaction with natural fibres. It is suggested that future research look into various thermoset and thermoplastic matrix systems, preferably bio-based and compatible to natural fibres or using coupling elements to improve the interfacial interaction between fibres and polypropylene matrix.

Further research should be done on the creep behavior, fatigue, interfacial shear, moisture absorption, and hydrothermal properties of bamboo species in Ethiopia due to optimizing service reliability. The methods of fibre extraction are the main challenges, which produce the quality of fibres without damage, either physically or chemically. Further research should be done on fibre extraction, either process optimization on the current fibres extraction or a new technique to manufacture fibres, should be required.

The quality of the composite depends on the methods of manufacturing composite, so researchers should optimize the current composite manufacturing technique by either process parameters or utilizing a new composite manufacturing technique. Either unidirectional continuous or unidirectional discontinuous fibres affect the properties of the composite, so further research work should be investigated into the effect of fibre orientation on the properties of the composite.

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APPENDICES i

LIST OF PUBLICATIONS

Main Authors

1. **Yalew Dessalegn**& Dr. Balkeshwar Singh . ANALYSIS THE MORPHOLOGY OF BAMBOO FIBER: A REVIEW. INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY, 8(3): March, 2019, ISSN: 2277-9655.

2. **Yalew Dessalegn**, Balkeshwar Singh and Aart W. van Vuure. ANALYZE THE SIGNIFICANCE OF AGE AND HEIGHT ON THE PHYSICAL AND CHEMICAL PROPERTIES OF ETHIOPIAN GIANT TIMBER BAMBOO. American Journal of Engineering and Applied Sciences, 2021, 14 (2): 185.197.

3. **Yalew Dessalegn**, Balkeshwar Singh, , AartW. van Vuure , Ali A. Rajhi , Alaauldeen A. Duhduh ,Nazia Hossain and Gulam Mohammed Sayeed Ahmed, Mechanical Properties of Bambusa Oldhamii and Yushania-Alpina Bamboo Fibres Reinforced Polypropylene Composites, Polymers 2022, 14, 2733. https://doi.org/ 10.3390/polym14132733

4. **Yalew Dessalegn**, Balkeshwar Singh, ,Aart W. van Vuure , Ali A. Rajhi , Gulam Mohammed Sayeed Ahmed , and Nazia Hossain, Influence of Age and Harvesting Season on The Tensile Strength of Bamboo-Fibre-Reinforced Epoxy Composites, *Materials* 2022, *15*, 4144.https://doi.org/10.3390/ma15124144.

5. **Dessalegn, Y**.; Singh, B.; Vuure, A.W.v.; Badruddin, I.A.; Beri, H.; Hussien, M.; Ahmed, G.M.S.; Hossain, N. Investigation of Bamboo Fibrous Tensile Strength Using ModifiedWeibull Distribution. Materials **2022**, 15, 5016. https://doi.org/10.3390/ma15145016

6. **Yalew Dessalegn,** Balkeshwar Singh, Aart W van Vuure. Characterization of Morphological and Microstructural Properties of Bamboo Species for Composite Industry. Insi in Chem & Biochem. 2(2): 2022. ICBC. MS.ID.000532. DOI: 10.33552/ICBC.2022.02.000532.

7. **Yalew Dessalegn**, Balkeshwar Singh and Aart W van Vuure. Effect of Culm Age and Height on the Chemical Properties tf The Culm in Different Bamboo Species. Glob J Eng Sci. 10(1): 2022. GJES.MS.ID.000726. DOI: 10.33552/GJES.2022.10.000726.

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1. Yalew Dessalegn, Balkeshwar Singh, Aart W. van Vuureb. Morphological, chemical, and physical characteristics of the ethiopian highland (yushania alpina) bamboo. Elsevier, Materials Today: Proceedings Available online 28 May 2021. https://doi.org/10.1016/j.matpr.2021.05.303

2. Yalew Dessalegn, Balkeshwar Singh and Aart W. Vanuure, Assessment of the national bamboo resources and its properties in Ethiopia, AIP Conference Proceedings 2393, 020100 (2022); https://doi.org/10.1063/5.0074927 Published Online: 19 May 2022

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1. Delphine E.C. Depuydta, Jeroen Soeteb, **Yalew D. Asfawc**, Martine Weversb, Jan Ivensd, Aart W. van Vuurea. SORPTION BEHAVIOUR OF BAMBOO FIBRE REINFORCED COMPOSITES, WHY DO THEY RETAIN THEIR PROPERTIES? Elsevier, Composites Part A 119 (2019) 48–60.

2. Dr. Balkeshwar Singh, **Mr. Yalew Dessalegn** "Effect Analysis of Extraction Processes of Bamboo Fiber" Nat. Volatiles & Essent. Oils, 2021; 8(5): 4226 - 4246

SUBMITTED ARTICLES

1. **Yalew Dessalegn**, Dr. Balkeshwar Singh, Prof. Aart W. van Vuure "Characterization Of Mechanical Strength OF Bamboo Fibre Polymer Composite For Automotive Headliners" submitted May 2022
2. **Yalew Dessalegn**, Dr. Balkeshwar Singh, Prof. Aart W. van Vuure "Influence of age and harvesting season on the tensile and impact strength of bamboo fibres polypropylene composites" submitted May 2022
3. **Yalew Dessalegn**, Dr. Balkeshwar Singh, Prof. Aart W. van Vuure " Influence of Age and harvesting season on the Physical properties of Bamboo culm " submitted May 2022

APPENDICES ii

TABLES

Table I: Single fibre tensile test

	Maximum Load [N]	Tensile extension at Maximum Load [mm]	Modulus (Automatic Young's) [MPa]
1	79,9829	1,02383	3.095,18841
2	52,2954	0,73575	2.786,17084
3	71,4290	1,01063	3.108,24061
4	61,1407	0,66150	3.914,17520
5	33,5792	0,53580	2.482,24375
6	28,8451	0,43598	2.370,00089
7	87,1955	0,98587	3.324,93679
8	24,5853	0,47392	1.869,46578
9	8,4117	0,38573	838,30877
10	7,4679	0,42428	1.357,66013
11	38,0412	0,57368	2.576,67064
12	16,9724	0,72338	843,32030
13	18,3519	0,29873	2.295,37410
14	90,0241	1,03658	3.441,97207
15	13,5290	0,68625	1.587,75023
16	84,2224	0,68625	4.629,46931
17	43,3745	0,66113	2.501,59216
18	52,4014	0,54833	3.640,68426
19	44,9137	0,62295	2.537,24139
20	13,3651	0,49875	966,11541
21	40,2584	0,57285	2.537,08129
22	20,5143	0,62362	1.160,74551
23	57,1199	0,73635	3.058,50182
24	40,9197	0,68550	2.478,57518
25	43,6560	0,72308	2.319,86262
26	41,2985	0,42353	3.361,45602
27	25,4306	0,38685	2.762,22946
28	75,1018	0,89797	2.837,26172
29	4,7186	0,14775	2.003,02075
30	75,7468	0,77385	3.554,72917
31	28,0458	0,48585	2.498,07272
32	10,2652	0,18563	2.406,20352
33	62,4542	0,72308	3.420,73046
34	40,1863	0,72338	2.576,09102
35	41,6395	0,81105	2.233,45816
36	52,5545	0,83685	2.675,02964
37	46,0977	0,87360	2.611,76927
38	26,9664	0,41167	2.563,54877
39	36,8113	0,56122	2.249,38088
Median	40,9197	0,66113	2.537,24139
Maximum	90,0241	1,03658	4.629,46931
Minimum	4,7186	0,14775	838,30877

Table II: Density measurment result

Multipycnometer — Quantachrome PycData 1.30

measurement No.:	**3634**
sample:	Mselam3
comment:	1
date:	05.05.2021
time:	17:56:31
Produkt:	
Kunde:	

sample weight:	2.7376 g
sample volume:	2.1513 cm³
density:	1.2727 g/cm³

used MeasSetup:	small lid
cell-volume:	27.2239 cm³
reference-volume:	11.0400 cm³
measurements:	4
standard deviation:	0.0159 g/cm³

serial-No.:	
company:	Quantachrome GmbH
username:	Yalew Desu
user-info:	

partial results

	sample volume:	density:
1	2.1633 cm³	1.2655 g/cm³
2	2.1605 cm³	1.2671 g/cm³
3	2.1117 cm³	1.2964 g/cm³
4	2.1694 cm³	1.2619 g/cm³

FIGURES

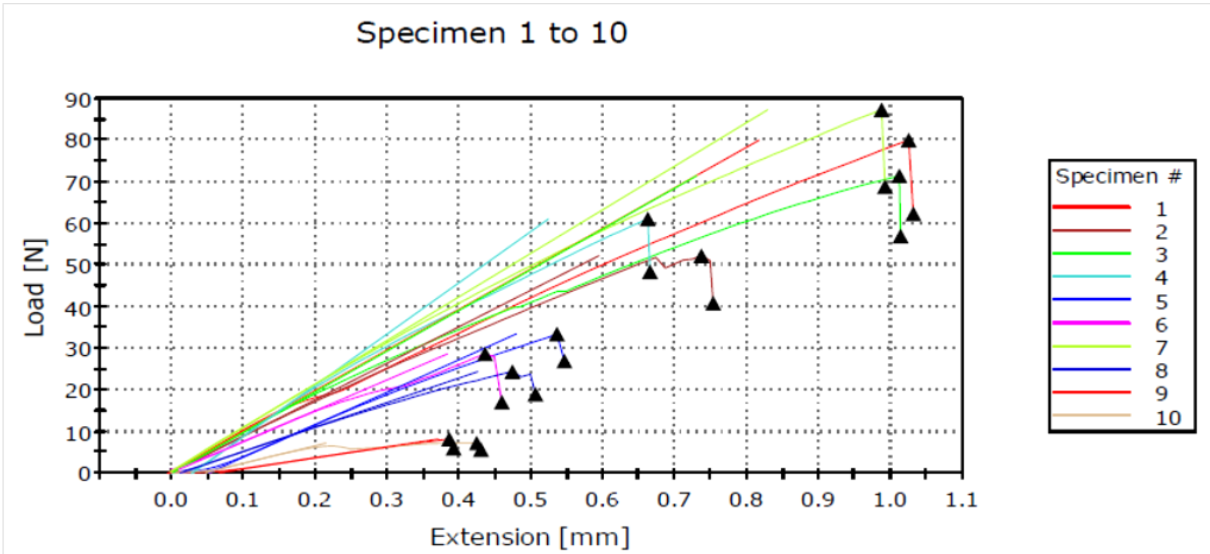

Figure I: single fibre tensile test chart

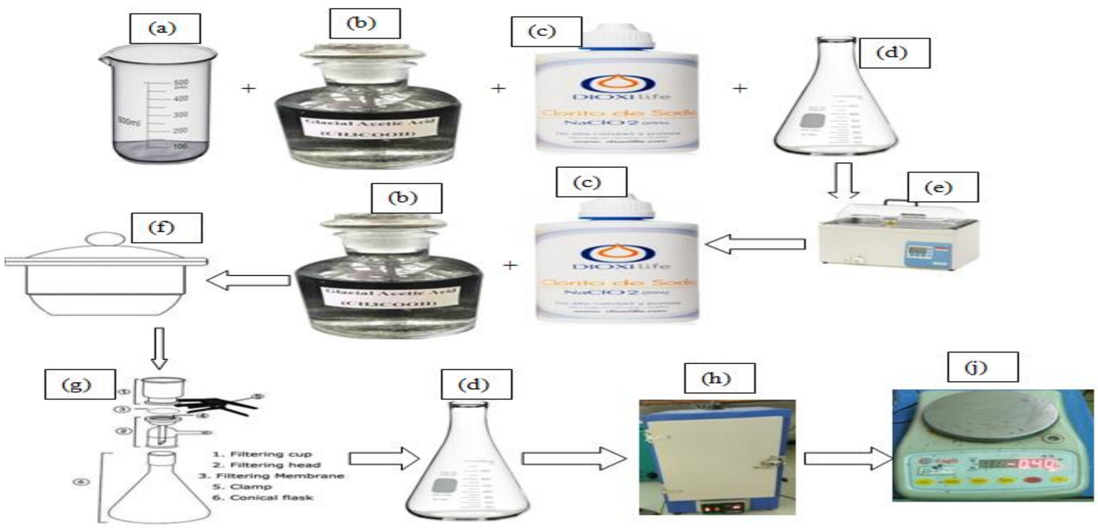

Fig. setup of Holocellulose content measurement (a) beaker, (b) acetone, (c) $NaClO_2$, (d) flask, (e) water bath, (f) desiccators, (g) crucible (h) oven, and (j) digital balance

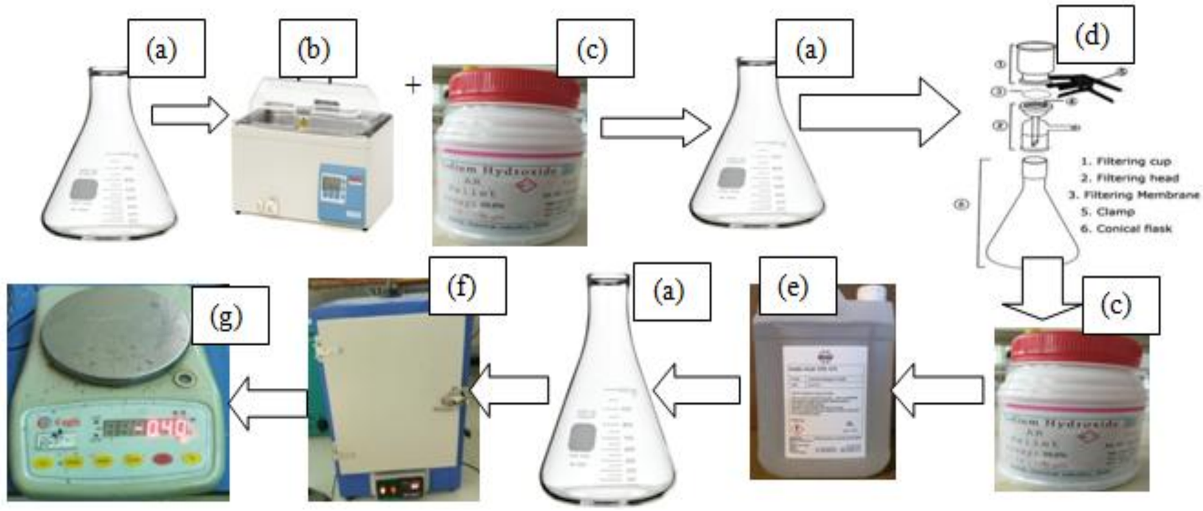

Figure setup of flow chart in the evaluation of cellulose content (a) beaker, (b) H_2O bath, (c) NaOH, (d) vacuum suction equipment, (e) acetic acid, (f) Oven, (g) balance

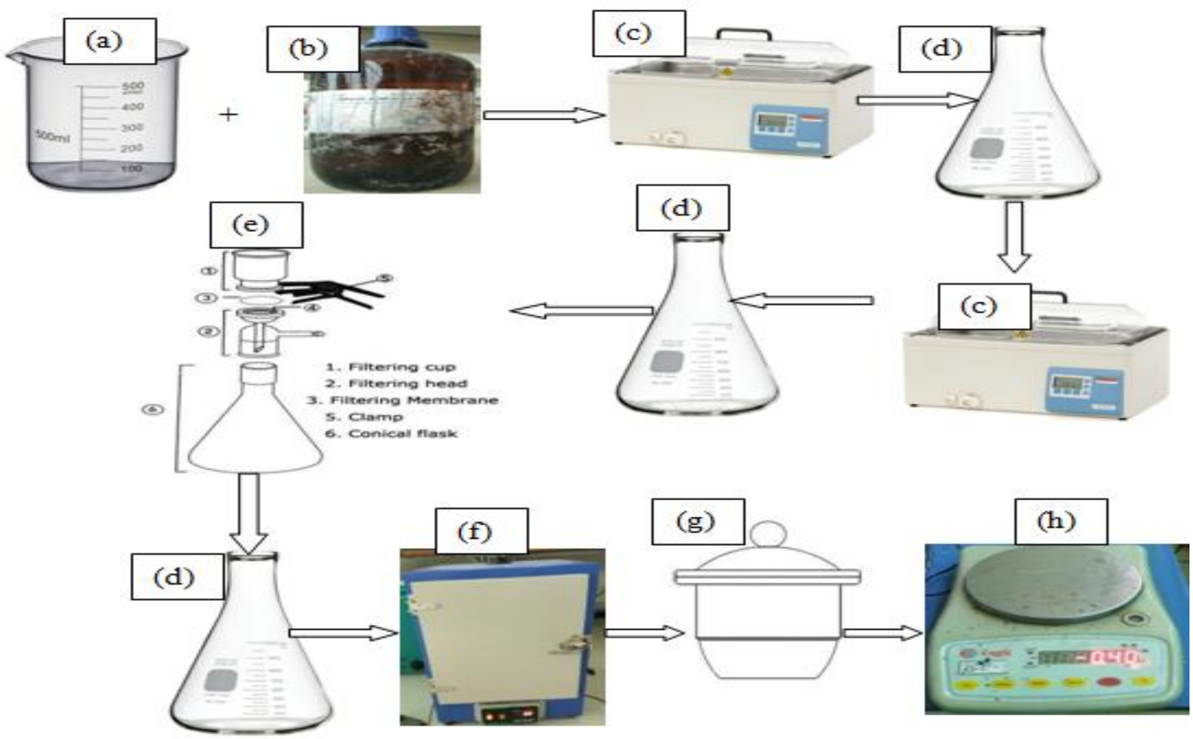

Figure setup of flow chart in the evaluation of Lignin content (a) beaker, (b) H2SO4, (c) H2O bath, (d) flask, (e) fritted glass crucible, (f) Oven, (g) desiccators, (h) balance

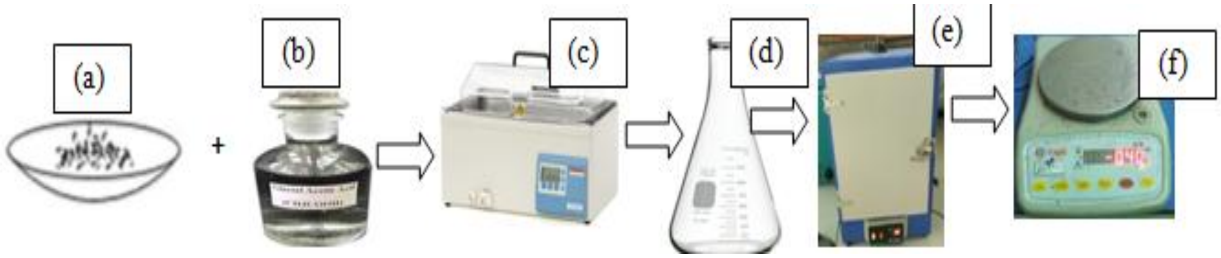

Figure setup of evaluation of extractive content (a) fibres powder, (b) acetone, (c) H2O bath, (d) flask, (e) Oven. (f) balance

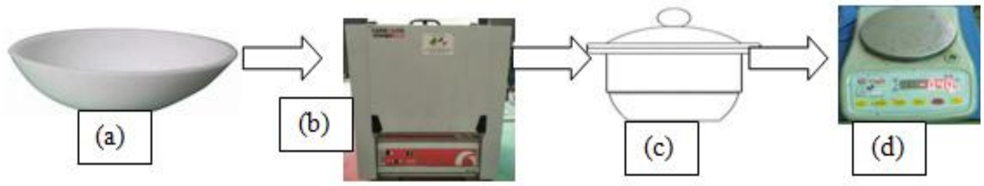

Figure setup of ash measurement (a) powder, (b) muffle furnace, (c) desiccators, (d) Oven