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Ethiopian Bamboo Fiber Aging Process and Reinforcement: Advancing Mechanical Properties of Bamboo Fiber-Epoxy Composites for Automobile Applications

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Abstract: The purpose of this paper is to evaluate the properties of Ethiopian bamboo fibre polymer composites as headliners in the automobile industry. Bamboo fibres are developed using the roll milling technique, and bamboo fibre epoxy composites (BFEPCS) are developed using a compression mould and a hot press machine. The mechanical properties are measured based on the recommended procedure of the ASTM. In total, 40% of the volume fraction of fibres is used to produce polymer composites. An accurate evaluation of its mechanical properties is thus critical for predicting its behaviour during a vehicle's interior impact assessment. Conventional headliner materials are heavier, non-biodegradable, expensive, and non-sustainable during processing compared to the currently researched materials. Three representatives of bamboo plants are harvested in three regions of bamboo species, three groups of ages, and two harvesting months. Two-year-old bamboo fibres have the highest mechanical properties of all ages, and November has a higher mechanical properties compared to February. Inji-bara and Kom-bolcha have the highest and lowest mechanical properties, respectively. BFEPCs have high mechanical properties compared to BFPPCs. The mechanical properties of the current research findings have higher measured values compared to Jute felt PU, CFPU, GFMPU, BFPP, BFEP, PP foam, and TPU. The flexural strength of BFPCs has higher properties compared to their tensile strength. Ethiopian bamboo fibres and their polymer composites have the best mechanical properties for the composite industry, which is used for headliner materials in the automobile industry, compared to conventional headliner materials.

Keywords: Ethiopian bamboo; bamboo aging; mechanical properties; epoxy composites; automobile applications

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1. Introduction

Bamboo fibre composites with polymer matrices have successfully demonstrated their superior performance for engineering applications. However, when compared to synthetic fibres, natural fibers have generally poor mechanical properties; moreover, these composites were utilised to fabricate shelters, clothing, and weapons. Due to the high cost of synthetic fibres and the health risks associated with asbestos fibers, the exploration of plant fibres has become essential [1]. The outstanding performance and lighter weight, combined with the eco-friendly nature, are critical for natural fibre approval in high-volume engineering markets such as the aerospace and automotive industries [2]. Because of their high strength-to-stiffness and weight-to-stiffness ratios, fibre composites are widely used in different types of applications, such as structural, marine, aerospace, automobile, and windmill blades [3].

Automotive is one of the world's leading consumers of products [4]. Lightweight constructions are extensively used in the automotive, aerospace, and construction industries due to low-density materials allowing for a reduction in product structural weight. This could result in significant fuel savings and a lower carbon footprint in transportation, as well as easier manipulation of details in house construction applications [5]. The headliner of automobile parts is fabricated from glass fiber-reinforced polypropylene, and it has a distinct feature of thickness expansion. Lightweight and stiffness are important for headliners in Automotive. Customers have given them high marks for their light weight, formability, and low coefficient of thermal expansion. Since 1997, they have been widely used in automotive interior parts, particularly as headliner materials [4,6]. The headliner is an internal part of the vehicle's roof that has good sound absorption and insulation performance to prevent outside noise or engine noise from entering the passenger cabin, thereby improving passenger comfort. Furthermore, the headliner is used as a protective barrier for passengers during collisions. However, so far, the headliner has played an important role in the car's driving performance. During the product development stage, the headliner is normally only considered in terms of its appearance, design sensibility, and stability [6,7].

Headliners have developed into the most dynamic and multifunctional interior part of a car. The automotive industry has spent the last two decades focusing on interior design, aesthetics, and comfort as consumers' buying decisions have been confirmed to be more influenced by interior features. To meet the appearance, performance, and cost requirements in today's competitive market, several design factors for the headliner material have been developed [8].

Several commercially available headliner composites were tested. These included:

1. Urethane composites;
2. Fiberglass composites;
3. Formable Styrene Laminate composites;
4. Corrugated Kraft Liner composites;
5. Resonated Felt Headliner composites;
6. Thermoplastic Felt Headliner composites [9].

In recent years, three kinds of headliner material have been widely utilized: (1) glass fibres (GF) and polypropylene (PP) stampable sheet; (2) GF laminated polyurethane foam (substrate), which comprised a GF mat laminated on both sides with polyurethane foam; and (3) thermoplastic foam [10].

The features that must be present in headliner materials are as follows: (1) To improve the workplace environment, the process of moulding headliner parts from materials has a low release of harmful chemicals and foul odours. (2) high handling stiffness during the installation process in the automobile assembly process; (3) lightweight parts with minimal dimensional change in environmental environments, high durability, and high sound absorption; and (4) good recyclability when the vehicle is scrapped [11,12]. Material requirements for the development and manufacturing of automotive components:

- High strength;
- Energy intensity (the ability to absorb impact energy in the event of a collision);
- Manufacturability (the ability to manufacture complex parts with a minimal number of operations);
- Minimum car body weight (the lower the mass, the lower the gas flow, and the lower the number of congenital emissions);

- Corrosion resistance;
- Maintainability [13].

Foamed thermoplastic materials, which have recently received a lot of consideration in scientific and industrial research, are made up of a cellular core structure formed by the expansion of a blowing agent within a thermoplastic matrix. Foams can be used economically in a wider range of applications due to their cellular structure, including automotive parts, protective equipment, building and construction, the packaging industry, and electromagnetic wave insulators. Because of their greatest weight reduction, foamed plastics have excellent cost performance and strength-to-weight ratios when compared to their unfoamed counterparts [14,15]. However, in the case of PP-based foamed parts, the impact resistance is even lower than in solid PP. Even at high relative densities, PP-based foams typically achieve a significant reduction in impact strength. This is known as the "ductile-brittle transition" [16].

PS and PE foams are not suitable for applications that necessitate high service temperatures, such as contact with boiling water or sterilisation processes. PP foams have recently gained popularity as a low-cost alternative to PS and PE foams. Firstly, PP has been cheaper than PE over the last decade. Since PP is a semi-crystalline polymer, it has good flexibility and toughness while also having higher moduli and strengths. Secondly, since PP is in a room-temperature rubbery condition, it has a greater impact resistance than PS [15,17]. The purpose of the current research was to investigate and characterise bamboo fibre epoxy composites (BFEPCs) and bamboo fibre polypropylene composites (BFPPCs) based on the effects of age, harvesting season, and bamboo species, then compare and contrast the current researched materials with the traditional headliner's materials. Ethiopia has three visible seasons: rainy, cold, and dry. The properties of natural fibres are influenced by age, season, climate conditions, and type of species. The current research studies measured the flexural, tensile, and impact strengths using ASTM standards. BFEPCs and BFPPCs were prepared and manufactured from specimens for comparison with the traditional headliners' materials. The traditional headliners' materials are expensive, non-biodegradable, higher density, and environmentally unfriendly during production. Global warming increases from year to year due to carbon dioxide emissions from the transport sector, which consumes more fuel due to the higher weight of the body. Bamboo fibre polymer composites have a higher specific strength and lower density compared to glass fibre polymer composites, which are used for headliners in the automobile industry.

Bamboo plants in Ethiopia have a large coverage; however, they are used for structural and construction work in low-level technology. The current research studies are focused on the mechanical properties of Ethiopian bamboo fibres polymer composites, which are applied in the automotive industry. However, researchers have not investigated the mechanical properties of Ethiopian bamboo fibres polymer composites so far. The current research findings recommend that they should be utilised for polymer composite development in the automotive industry. Extraction of bamboo fibres is a challenging activity that extracts bamboo fibres from the culm; however, the current researchers developed their own bamboo fibres extraction machine in the workshop and produced bamboo fibres polymer composites based on various ages and harvesting seasons. A few previous researchers did not investigate the influence of age and harvesting seasons on the mechanical properties of BFPCs.

2. Materials and Procedures

2.1. Study Area

The geographic location and climatic circumstances of the testing sites are described in Table 1. The Inji-bara region is at a high altitude at sea level next to the Mekane-selam region; however, Kom-bolcha is at a low altitude with a high maximum temperature [18–20].

Table 1. Geographic location and climatic conditions of the testing sites.

Name of Testing Sites	Administrative Location of the Testing Site				Climate, Average Value		
	Zone	Region	Lat-Long	Alt. (m)	An. RF (mm)	Max. Temp. (°C)	Min. Temp. (°C)
Inji-bara	Awi	Amahara	10°59′ N 36°55′ E	2540–2865	1813	24	14
Kom-bolcha	S/wollo	Amahara	11°5′ N 39°44′ E	1842–1915	1027	26	20
Mekane-selam	S/wollo	Amahara	10°45′ N 38°45′ E	2605–3000	1048	21	10

2.2. Technique of Sampling

The bamboo culm was collected in February 2019 and November 2020 G.C. at Kombolcha and Mekane-selam cities in the South Woll Zone, as well as Inji-bara in the West Gojam zone of Amhara Region, Ethiopia. Three samples of bamboo plants were harvested at the ages of one, two, and three years old. The bamboo plant's age was known by skilled fieldmen by its colour and sheath in the culm. The culm was later subdivided into three parts, such as the bottom, middle, and top portions, according to the criteria of internode length and outer diameter. Bamboo fibres are extracted from the middle parts of each harvested sample at the time of harvesting to prevent moisture loss. The bamboo fibres dried in the oven for 72 h at 60 °C. The samples are conditioned in the conditional room before being prepared. A compression mould is used for the preparation of samples. BFEPCs and BFPPCs are prepared based on ASTM standards. The prepared samples are tested based on ASTM standards.

2.3. Epoxy and Hardener

Before producing and measuring, the fibres were put in the oven at 60 °C for 72 h. Hexion's Epikote 828 LVEL epoxy (Hexion, Columbus, OH, USA) with a 1,2-diaminocyclohexane (Dytek DCH-99, Specialty Intermediates INVISTA (Deutschland) GmbH, Hattersheim am Main, Germany) hardener has been used. The epoxy-to-hardener ratio is 100:15The resin is degassed for 10 min in a vacuum oven. Pre-curing was performed at 75 °C for 1 h, followed by 1 h of post-curing at 150 °C. Composites of 250 × 10 × 2 mm were manufactured with a volume fraction of 40% fibres, calculated depending on the mass as well as the density of the fibres. The neat resin system has a tensile strength of 70 MPa, a stiffness of 2.7 GPa, and a strain-to-failure rate of 4.1% [21].

2.4. Polypropylene

PP film with a density of 900 kg/m^3 and 20 µm thickness was supplied by Propex GmbH (Germany) (Gronau, Germany). The shaping, melting, and coefficient of thermal expansion are 115.7 °C, 160.6 °C, and 62.7–73.2 × 10^{-6}/k, respectively. The Young's modulus, strength, and strain to failure are 1.6–1.8 GPa, 55–65 MPa, and >300%, respectively.

2.5. Tensile Test

Tensile test samples were prepared according to ASTM D3039 [22]. An Instron 4467 machine with a load cell of 30 KN was used, and a crosshead speed of 2 mm/min was utilized. 150 mm of gauge length between the upper and lower clamps and 25 mm of gauge length on extensometers are used for tensile strength measurement. The specimens were mechanically clamped using sandpaper in the grips to remove slippage. The tensile test setup is presented in Figure 1a,b. All samples were conditioned at room temperature (22 °C ± 1 °C and 51 ± 1% RH) for 24 h before testing.

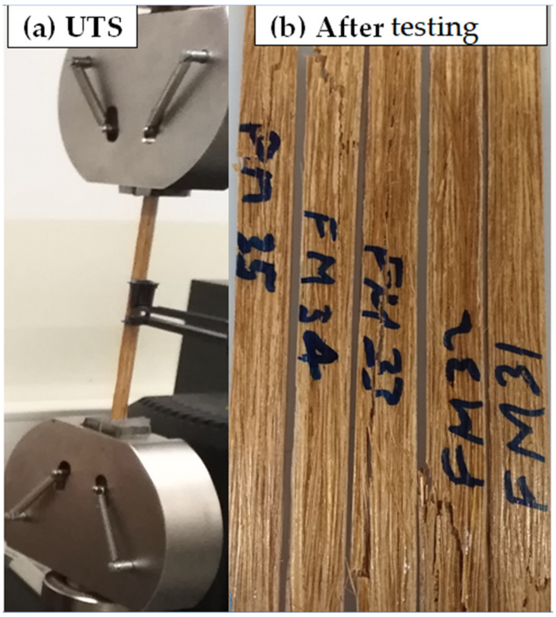

Figure 1. (**a**) Setup for the tensile test; and (**b**) Mode of fracture after testing.

2.6. Flexural Test

Flexural three-point bending tests (3PBT) were conducted in longitudinal fibre direction and performed on the model Instron 4426 based on the ASTM D790M [23] (see Figure 2a,b). The bending modulus of each sample was based on the slope of the stress-strain curve between 0.1 and 0.3% of the strain. The crosshead speed was adjusted at 1 mm/min, and a 1 KN load cell was used during the test. The load and the flexural displacement are registered during the complete test. At least five samples were tested for each bamboo species, age, and season. The dimensions of composites were 60 × 10 × 2 mm with a target volume fraction of 40% fibres, which was calculated using the weight and measured density of the fibres.

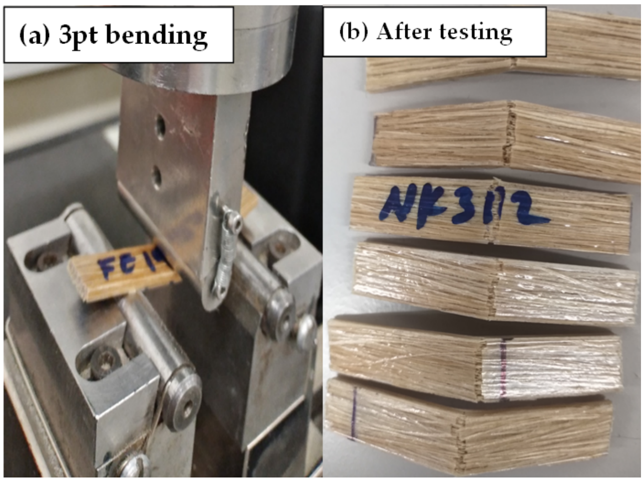

Figure 2. (**a**) Set-up for 3 pt bending test, (**b**) Mode of failure.

2.7. Izod Impact Test

The Izod impact test machine setup is demonstrated in Figure 3a,b. 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 is measured as the impact energy of the sample [24].

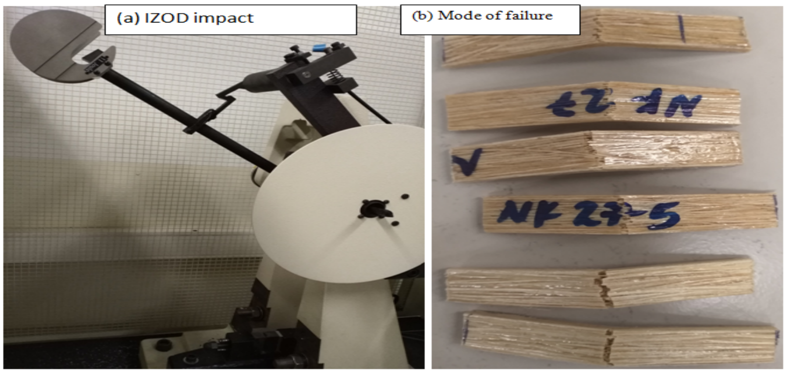

Figure 3. (**a**) Setup of the Izod impact test; (**b**) Mode of failure.

3. Results and Discussion

3.1. Mechanical Properties of BFEPCs

3.1.1. Tensile Strength of BFEPCs

The influence of age and harvesting month on the tensile strength of BFEPCs for Inji-bara, Kom-bolcha, and Mekane-selam is indicated in Figure 4. The highest and lowest tensile strengths are measured at the ages of 2 and 1, respectively. The different properties of bamboo age have come from the lignification processes being completed in one growing season, then deteriorating their properties after reaching full lignification [21]. The maximum and minimum tensile strengths of Inji-bara BFEPCs in February (Feb.) were 206 ± 23 MPa and 191 ± 20 MPa, whereas in November (Nov.), they were 227 ± 20 MPa and 171 ± 17 MPa, respectively. Moreover, the maximum and minimum tensile strengths of Kom-bolcha BFEPCs in Feb. were 198 ± 18 MPa and 139 ± 15 MPa, whereas in Nov they were 205 ± 18 MPa and 129 ± 11 MPa, respectively. Furthermore, the maximum and minimum tensile strengths of Meka-neselam BFEPCs in Feb were 199 ± 18 MPa and 151 ± 13 MPa, whereas, in Nov., they were 216 ± 19 MPa and 166 ± 17 MPa, respectively. The properties of natural fibres are influenced by environmental conditions during harvesting. November is a cold and humid month, whereas Feb. is a dry and hot month in all regions of Ethiopia. The current research findings show that Nov. has better properties compared to Feb. due to variations in environmental conditions. The tensile strength of Inji-bara, Kom-bolcha, and Mekane-sealm BFEPCs in Nov. was 9%, 10%, and 3% higher than in Feb., respectively. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs are 8%, 30%, and 24% higher tensile strength than the lowest in Feb., whereas in Nov., they have 25%, 37%, and 23% higher tensile strength than the lowest, respectively. Inji-bara BFEPCs have 4% and 3% higher tensile strength in Feb., whereas in Nov., they have 10% and 5% higher tensile strength than Kom-bolcha and Mekane-selam BFEPCs, respectively. The tensile strength of Mekane-selam BFEPCs was 1% and 5% higher than that of Kom-bolcha in Feb. and Nov., respectively. Inji-bara, Mekane-selam, and Kom-bolcha have the highest to the lowest tensile strengths, respectively. As indicated in Table 2, BFEPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher tensile strength compared to Jute felt PU (polyurethane), CFPU (carbon fibres polyurethane), GFPU (glass fibres polyurethane), BFPP, BFEP, PP foam, and TPU (thermoplastics polyurethane) [7,15,25–31], and are comparable with BFEP, GFPU, and GF laminated with PE (polyester) [3,28,32]. However, they have lower measured values compared to GFEP, GFPU840871, GFPU 90IK01, and Glass laminated. The current research findings show that the mechanical properties of Ethiopian bamboo polymer composites are equivalent or higher compared to the previous conventional automotive headliner and dashboard materials. Therefore, Ethiopian bamboo fiber polymer composites are used for the production of headliner and dashboard products in the automotive industry [17,26,33,34].

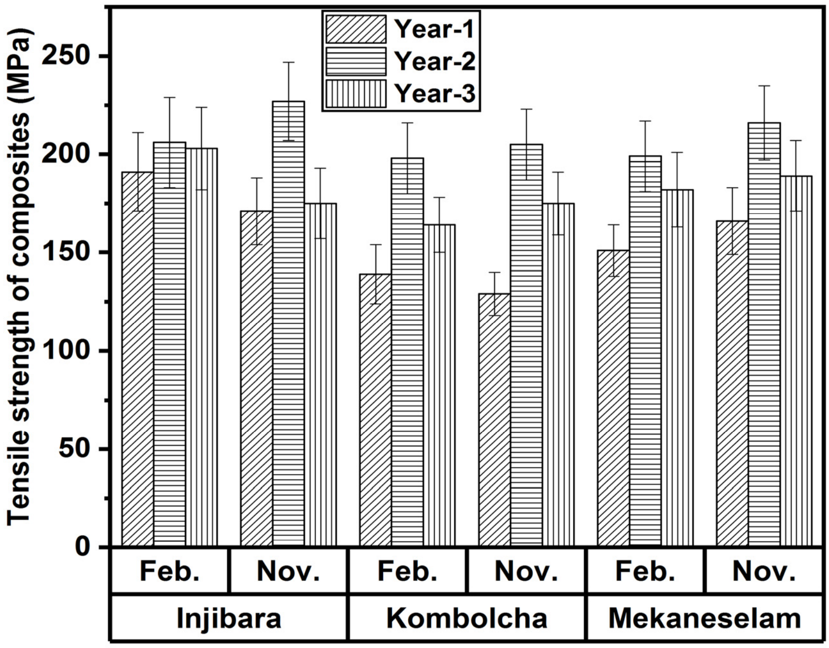

Figure 4. UTS of BFEPCs.

3.1.2. Tensile Modulus of BFEPCs

The influence of age and harvesting seasons on Young's modulus of Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs is indicated in Figure 5. The highest and lowest Young's modulus are measured at the ages of 2 and 1 year, respectively. The maximum and minimum tensile moduli of Inji-bara BFEPCs in Feb. were 19 $\pm$ 1.06 GPa and 17 $\pm$ 1.05 GPa, whereas in Nov., they were 21 $\pm$ 2.05 GPa and 16 $\pm$ 1.04 GPa, respectively. The maximum and minimum tensile moduli of Kom-bolcha BFEPCs bamboo in Feb. were 17 $\pm$ 1.06 GPa and 11 $\pm$ 1.02 GPa, whereas in Nov., they were 18 $\pm$ 2.05 GPa and 11 $\pm$ 1.03 GPa, respectively. The maximum and minimum tensile moduli of Mekane-selam BFEPCs in Feb. were 18 $\pm$ 1.06 GPa and 16 $\pm$ 1.02 GPa, whereas in Nov., they were 19 $\pm$ 1.07 GPa and 17 $\pm$ 1.03 GPa, respectively. From the highest to the lowest tensile modulus of BFEPCs, Inji-bara, Mekane-selam, and Kom-bolcha, respectively. Inji-bara BFEPCs have 11% and 5% higher tensile moduli in Feb., whereas in Nov., they have 14% and 10% higher tensile moduli than Kom-bolcha and Mekane-selam, respectively. Mekane-selam has a 6% and 5% higher tensile modulus than Kom-bolcha in Feb. and Nov., respectively. As indicated in Table 2, the tensile modulus of the BFEPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to GFEP, Jute felt PU, CFPU, GFMPU, BFPP, BFEP, GFEP, pp foam, GFPU, Glass laminated [3,7,12,15,35], and are comparable with GFPU840871, and GF laminated PE [32,34]. However, they have lower measured values compared to GFPU 90IK01 and TPU [30,36].

3.1.3. Stress-Strain of Ultimate Tensile Strength

As shown in Figure 6, 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 Nov. had the highest stress and the lowest strain to failure compared to February. From the highest to the lowest tensile stress are Inji-bara, Mekane-selam, and Kom-bolcha, respectively. As indicated in Figure 6, 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 made of hard materials that resist ductility failure.

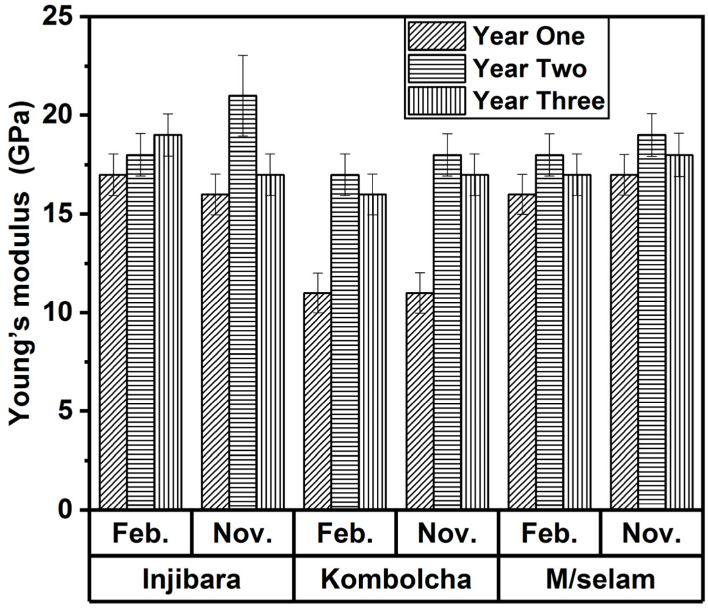

Figure 5. Tensile modulus of BFEPCs.

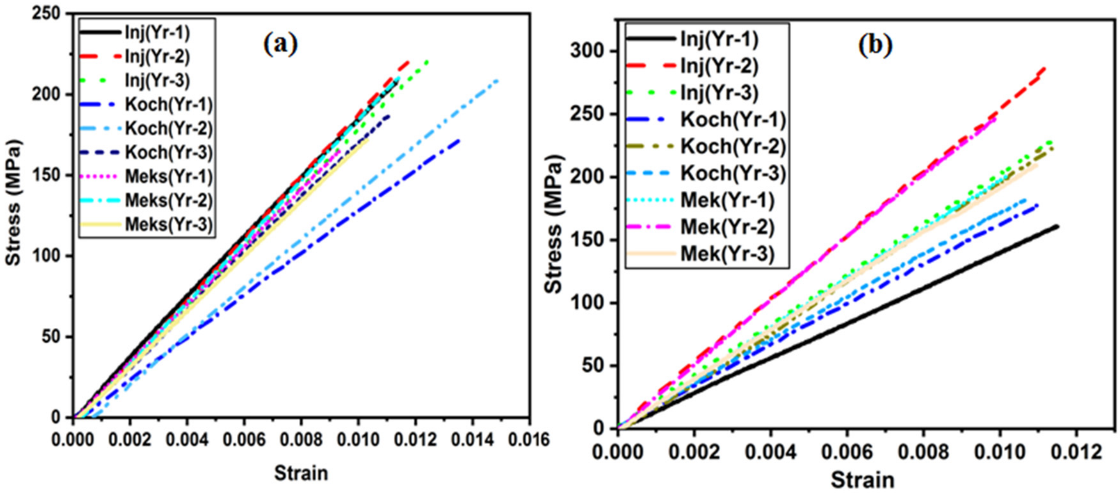

Figure 6. Stress-strain of BFEPCs: (**a**) February, and (**b**) November.

3.1.4. Flexural Strength of BFEPCs

The influence of age and harvesting month on the flexural strength of BFEPCs for Inji-bara, Kom-bolcha, and Mekane-selam is presented in Figure 7. The highest and lowest flexural strengths of BFEPCs are measured at the ages of 2 and 1 year, respectively. The maximum and minimum flexural strengths of Inji-bara BFEPCs in Feb. were 211 $\pm$ 21 MPa and 156 $\pm$ 17 MPa, whereas in Nov., they were 234 $\pm$ 21 MPa and 166 $\pm$ 14 MPa, respectively. The maximum and minimum flexural strengths of Kom-bolcha BFEPCs in Feb. were 129 $\pm$ 10 MPa and 81 $\pm$ 7 MPa, whereas, in Nov., they were 190 $\pm$ 18 MPa and 124 $\pm$ 13 MPa, respectively. The maximum and minimum flexural strengths of Mekane-selam BFEPCs in Feb. were 189 $\pm$ 17 MPa and 139 $\pm$ 12 MPa, whereas in Nov., they were 198 $\pm$ 21 MPa and 116 $\pm$ 12 MPa, respectively. The flexural strengths of Inji-bara, Kom-bolcha, and Mekane-selam BFEPCS in Nov. were 10%, 32%, and 5% higher than in February, respectively. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs have 26%, 37%, and 26% higher flexural strength than the lowest in Feb., whereas, in Nov., they have 29%, 35%, and 41% higher flexural strength than the lowest in Nov., respectively. Inji-bara BFEPCs had 39% and 10% higher flexural strength in Feb., whereas in

Nov., they had 19% and 15% higher flexural strength than Kom-bolcha and Mekane-selam, respectively. The flexural strength of Mekane-selam BFEPCs was 32% and 4% higher than that of Kom-bolcha in Feb. and Nov., respectively. As indicated in Table 3, the flexural strengths of the BFEPCs and BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to Jute felt PU, CFPU, GFMPU, BFPP, BFEP, GFPE, and GFPU [3,7,21,27,31,37,38]. and are comparable with UDMA and BFEP [28,39,40]. However, they have lower measured values compared to GFEP, GFPU840871, GFPU 90IK01, Glass laminated PE [12,28,32,34].

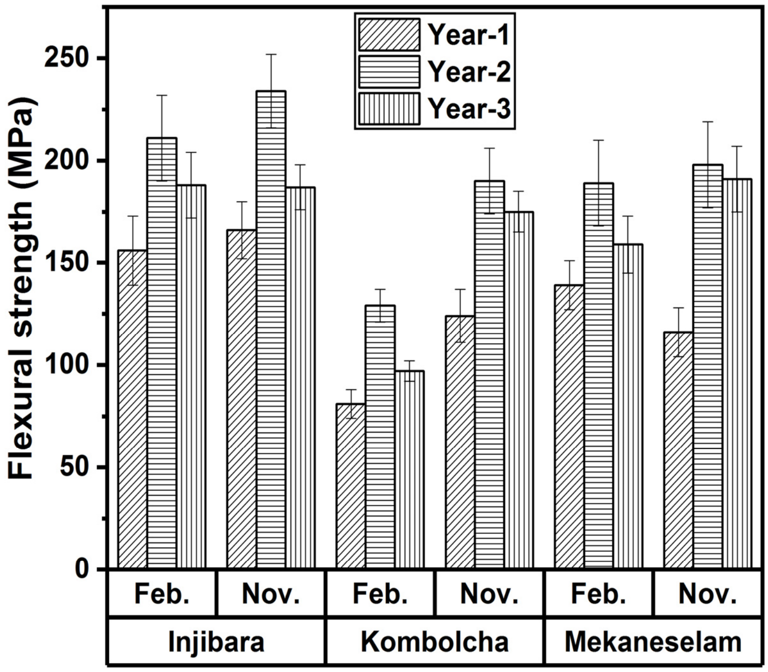

Figure 7. Flexural strength of BFEPCs.

3.1.5. Flexural Modulus of BFEPCs

The influence of age and harvesting seasons on the flexural modulus of BFEPCs for Inji-bara, Kom-bolcha, and Mekane-selam bamboo is indicated in Figure 8. The highest and lowest flexural moduli are measured at the ages of 2 and 1 year, respectively. The maximum and minimum flexural moduli of Inji-bara BFEPCs in Feb. were 19 ± 1.76 GPa and 14 ± 1.59 GPa, whereas in Nov., they were 17 ± 1.49 GPa and 13 ± 1.19 GPa, respectively. The maximum and minimum flexural moduli of Kom-bolcha BFEPCs in Feb. were 12 ± 0.87 GPa and 8 ± 0.26 GPa, whereas in Nov., they were 13 ± 1.21 GPa and 10 ± 1.34 GPa, respectively. The maximum and minimum flexural moduli of Mekane-selam BFEPCs in Feb. were 13 ± 1.11 GPa and 10 ± 0.87 GPa, whereas in Nov., they were 15 ± 1.19 GPa and 11 ± 0.73 GPa, respectively. Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs in Nov. had 11%, 8%, and 13% higher flexural moduli than in February. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs have 18%, 33%, and 23% higher flexural modulus than the lowest in Feb., whereas, in Nov., they have 32%, 23%, and 27% higher flexural modulus than the lowest, respectively. Inji-bara BFEPCs have 29% and 24% higher flexural moduli in Feb., whereas in Nov., they have 32% and 21% higher flexural moduli than Kom-bolcha and Mekane-selam, respectively. The flexural modulus of Mekane-selam BFEPCs is 8% and 13% higher than that of Kom-bolcha in Feb. and Nov., respectively. As indicated in Table 3, the flexural modulus of the BFEPCs and BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to Jute felt PU, CFPU, GFMPU, UDMA, BFPP, and GFPU and are comparable with GFEP, BFEP, GFEP, and GFPE [28,32,37,39,40]. However, they have lower measured values compared to GFPU840871, GFPU 90IK01, and glass laminated PE.

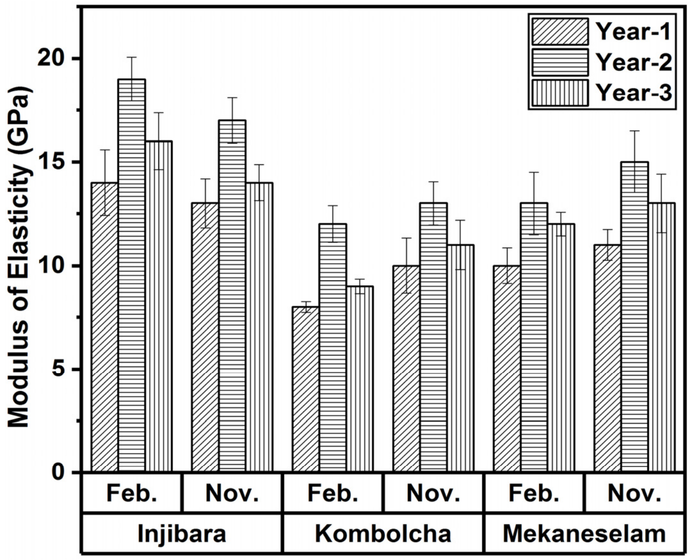

Figure 8. Flexural modulus of BFEPCs.

3.1.6. 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 is indicated in Figure 9. The flexural stresses of 200–250 MPa are measured in February, whereas in November 250–300 MPa are 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 behaviours. From the highest to the lowest tensile stress of BFEPCs, Inji-bara, Mekane-selam, and Kom-bolcha, respectively.

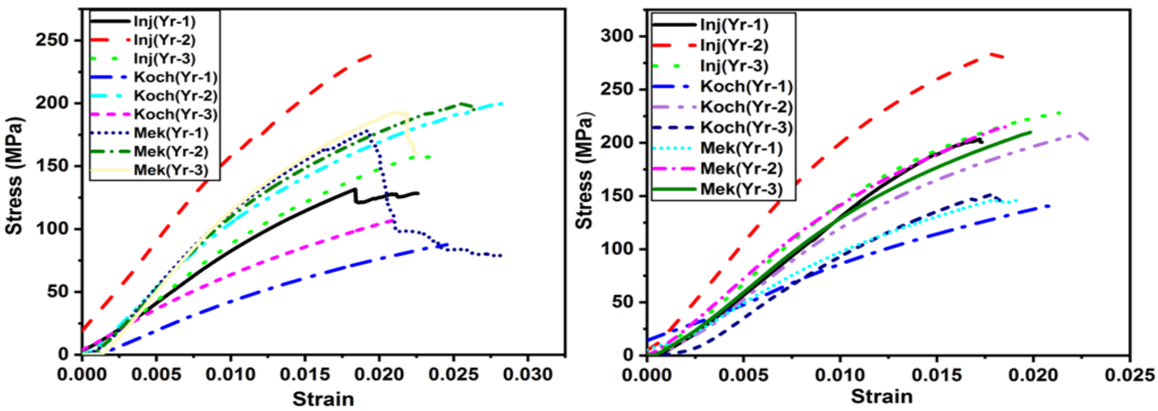

Figure 9. Flexural stress-strain curve of BFEPCs.

3.1.7. Impact Strength of BFEPCs

The influence of age and harvesting seasons on the impact strength of BFEPCs for Inji-bara, Kom-bolcha, and Mekane-selam bamboo is indicated in Figure 10. The highest and lowest impact strengths are measured at the ages of 2 and 1 year, respectively. The maximum and minimum impact of Inji-bara BFEPCs in Feb. were 55 ± 4.9 KJ/m^2 and 31 ± 3.4 KJ/m^2, whereas in Nov., they were 70 ± 5.8 KJ/m^2 and 43 ± 4.2 KJ/m^2, respectively. The maximum and minimum impact strengths of Kom-bolcha BFEPCs in Feb. has 55 ± 4.5 KJ/m^2 and 43 ± 3.8 KJ/m^2, whereas in Nov., they were 63 ± 6.4 KJ/m^2 and 48 ± 4.2 KJ/m^2, respectively. The maximum and minimum impact strengths of Mekane-selam BFEPCs in Feb. were 53 ± 4.9 KJ/m^2 and 42 ± 3.6 KJ/m^2, whereas in Nov., they were 66 ± 5.8 KJ/m^2 and 51 ± 4.6 KJ/m^2, respectively. Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs in Nov. had 21%, 13%, and 20% higher impact strengths than in Feb., respectively.

The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFEPCs are 44%, 22%, and 21% higher impact strength than the lowest in Feb., whereas in Nov., they have 39%, 24%, and 23% higher impact strength than the lowest, respectively. The impact strength of Inji-bara BFEPCs is 1% and 4% higher in Feb., whereas in Nov., it is 10% and 6% higher than Kom-bolcha and Mekane-selam, respectively. The impact strength of Mekane-selam BFEPCs bamboo in Feb. was 4% lower than that of Kom-bolcha; however, in Nov., it was 5% higher than Kom-bolcha.

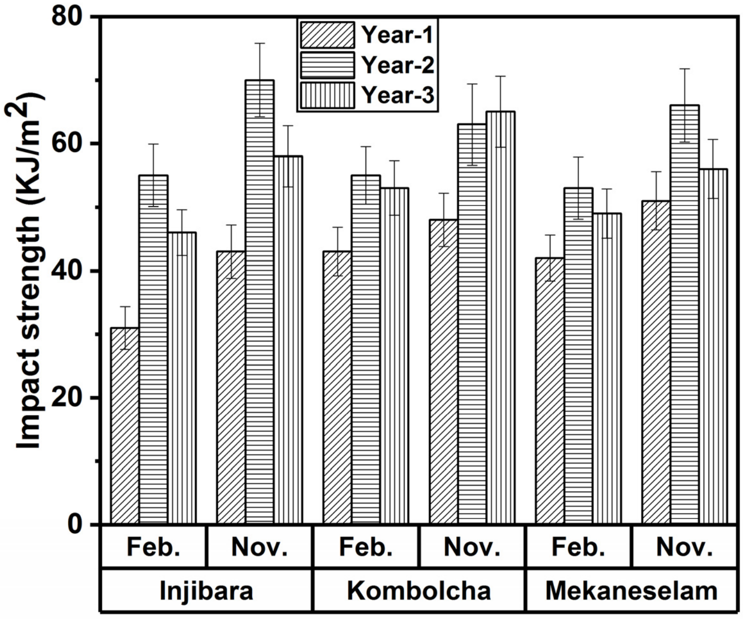

Figure 10. Impact strength of BFEPCs.

3.2. Mechanical Properties of BFPPCs

3.2.1. Tensile Strength of BFPPCs

The influence of age and harvesting seasons on the tensile strength of BFPPCS for Inji-bara, Kom-bolcha, and Mekane-selam is indicated in Figure 11. The highest and lowest tensile strengths of Inji-bara BFPPCs are measured at the ages of 2 and 1 year, respectively. The maximum and minimum tensile strengths of Inji-bara in Feb. were 116 ± 11 MPa and 91 ± 8 MPa, whereas in Nov., they were 125 ± 12 MPa and 99 ± 8 MPa, respectively. The maximum and minimum tensile strengths of Kom-bolcha BFPPCs in Feb. were 104 ± 11 MPa and 60 ± 7 MPa, whereas in Nov., they were 111 ± 12 MPa and 93 ± 8 MPa, respectively. The maximum and minimum tensile strengths of Mekane-selam BFPPCs in Feb. were 116 ± 10 MPa and 111 ± 5 MPa, whereas in Nov., they were 101 ± 10 MPa and 85 ± 7 MPa, respectively. The tensile strengths of Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs in Nov. were 7%, 6%, and 13% higher than in February, respectively. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs are 22%, 42%, and 16% higher tensile strength than the lowest in Feb., whereas in Nov., they have 21%, 16%, and 4% higher tensile strength than the lowest, respectively. The tensile strength of Inji-bara BFPPCs is 10% and 13% higher in Feb., whereas, in Nov., it is 11% and 7% higher than Kom-bolcha and Mekane-selam, respectively. The tensile strength of Mekane-selam BFPPCs was 1% and 4% higher than that of Kom-bolcha in Feb. and Nov., respectively. As indicated in Table 2, the tensile strengths of the BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to Jute felt PU, CFPU, GFMPU, BFPP, BFEP, PP foam, and TPU [7,16,21,25,27–29,31], and are comparable with BFEP, Glass laminate, and PE. However, they have lower measured values compared to BFEP, GFEP, GFPU840871, GFPU90IK01, GFPU, and Glass laminated [3,12,28,34,35].

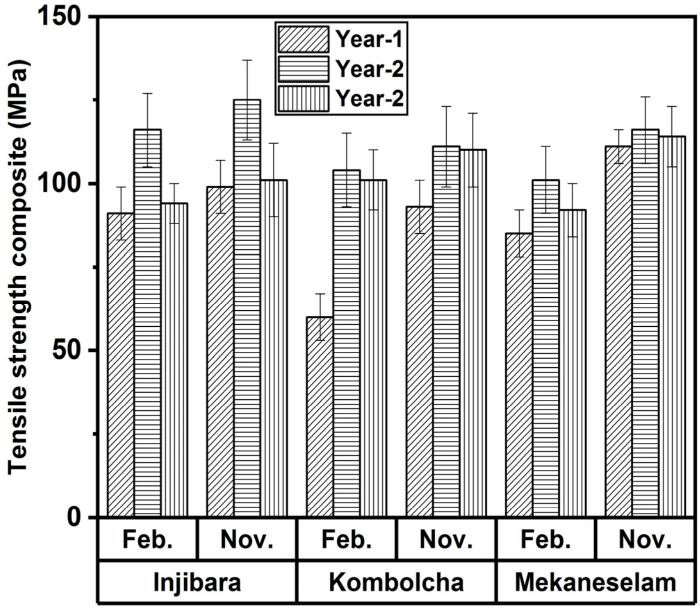

Figure 11. UTS of BFPPCs.

3.2.2. Tensile Modulus of BFPPCs

As indicated in Figure 12, the maximum tensile modulus of BFPPCs for Inji-bara, Kombolcha, and Mekane-selam in Feb. is 25 ± 1.18 GPa, 13 ± 1.95 GPa, and 16 ± 1.85 GPa; however, the minimum tensile modulus is 15 ± 1.71 GPa, 10 ± 0.92 GPa, and 9 ± 0.82 GPa, whereas, in Nov., they are 23 ± 2.9 GPa, 17 ± 2.56 GPa, and 14 ± 1.86 GPa; however, the lowest tensile modulus is 11 ± 0.71 GPa, 7 ± 0.51 GPa, and 8 ± 0.75 GPa, respectively. Two years old has the highest tensile modulus of BFPPCs compared to 1 and 3 years old. The tensile modulus of BFPPCs in February had higher values measured compared to Nov. for Inji-bara and Mekane-selam, whereas, for Kom-bolcha in Nov., higher values were measured compared to February. Inji-bara and Kom-bolcha had the highest and lowest tensile moduli of BFPPCs in Feb.; however, Inji-bara and Mekane-selam measured the highest and lowest tensile moduli in Nov., respectively.

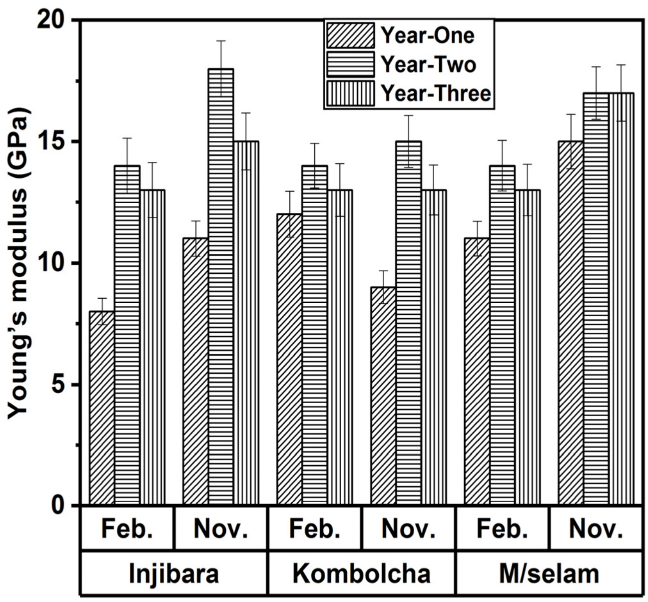

Figure 12. Tensile modulus of BFPPCs.

As indicated in Table 2, the tensile modulus of BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to GFEP, Jute felt PU, CFPU, GFMPU, BFPP, BFEP, PP foam, and GFPU [3,7,15,16,25,27,29], and are comparable with BFEP, Glass laminated with PE, and GFEP [28,35,40]. However, they have lower measured values compared to GFPU840871, GFPU90IK01, glass laminated, and TPU [30,32,34].

Table 2. Tensile strength of composite materials for automobile headliners.

Composite Materials	Tensile Strength (MPa)	Young's Modulus (GPa)	Strain to Failure (%)	Reference
GF epoxy	330	3.29	0.1	[33]
10% jute felt PU	4.15	0.104	-	[40]
10% carbon fibres PU	14.86	0.156	-	[40]
10% Glass fibres mat PU	4.51	0.066	-	[40]
GFPU840871 composite	351.77	19.53	0.024	[34]
GFPU 90IK01 composite	309.06	21.43	0.023	[34]
20% BPP	21.92	2.31	-	[27]
BFEP, Vf 65%	87–165	3–15	-	[28]
GFEP, Vf 65%	180–220	5–10	-	[28]
BFPP, 40%	26.27	1.776	-	[7]
BFEP	86	6.736	-	[29]
BFEP	138.88	4.96	2.7	[29]
BFPP, 39%	16.9	2.9	-	[25]
BFPP, 50%	14.4	2.8	-	[25]
BFPP	40.25	1.29	-	[21]
BFPP	5.43	1.3	-	[31]
PP foam	20	0.795	-	[16]
40% E glass PU	225	1.5	-	[3]
Glass laminated	321	5.166	-	[17]
Glass laminated PE	178	16.328	0.856	[32]
PP foam	23.83	1.528	4.29	[15]
TPU	26.27	20.84	-	[32]
Inji-bara BFREP, Feb.	191–206	17–19	1.07–1.13	Study
Inji-bara BFREP, Nov.	171–227	16–21	1.01–1.08	Study
Inji-bara BFRPP, Feb.	111–166	16.71–26.18	0.41–0.95	Study
Inji-bara BFRPP, Nov.	85–101	11.07–25.9	0.46–0.89	Study
Kom-bolcha BFREP, Feb.	139–198	11.31–18.1	1.16–1.35	Study
Kom-bolcha BFREP, Nov.	129–255	11.51–18.8	1.14–1.17	Study
Kom-bolcha BFRPP, Feb.	93–111	10.92–14.95	0.83–0.98	Study
Kom-bolcha BFRPP, Nov.	60–104	7.51–19.56	0.63–0.96	Study
Mekane-selam BFREP, Feb.	151–199	16.82–18.92	0.98–1.07	Study
Mekane-selam BFREP, Nov.	166–206	17.75–18.86	0.92–1.13	Study
Mekane-selam BFRPP, Feb.	99–125	9.82–17.85	0.76–1.32	Study
Mekane-selam BFRPP, Nov.	91–116	8.75–15.86	0.71–1.21	Study

3.2.3. Stress-Strain of BFRPPCs

The stress-strain plot of BFPPCs is shown in Figure 13. The stress-strain curve is influenced by age, harvesting seasons, and the type of bamboo species. In February, the ultimate tensile stress of Inji-bara, Kom-bolch, and Mekane-selam bamboo fibre pp composites increased by 21%, 42%, and 16%, whereas in November, they increased by 21%, 16%, and 4%, respectively. The highest and lowest tensile stresses are at the ages of 2 and 1 year, respectively. This increase in tensile strength and a decrease in maximum allowable strain can be attributed to the improved crystallinity and cellulose content of bamboo fibres when matured at one growth season of age, as well as to improved interface bonding between the fibre and PP resin.

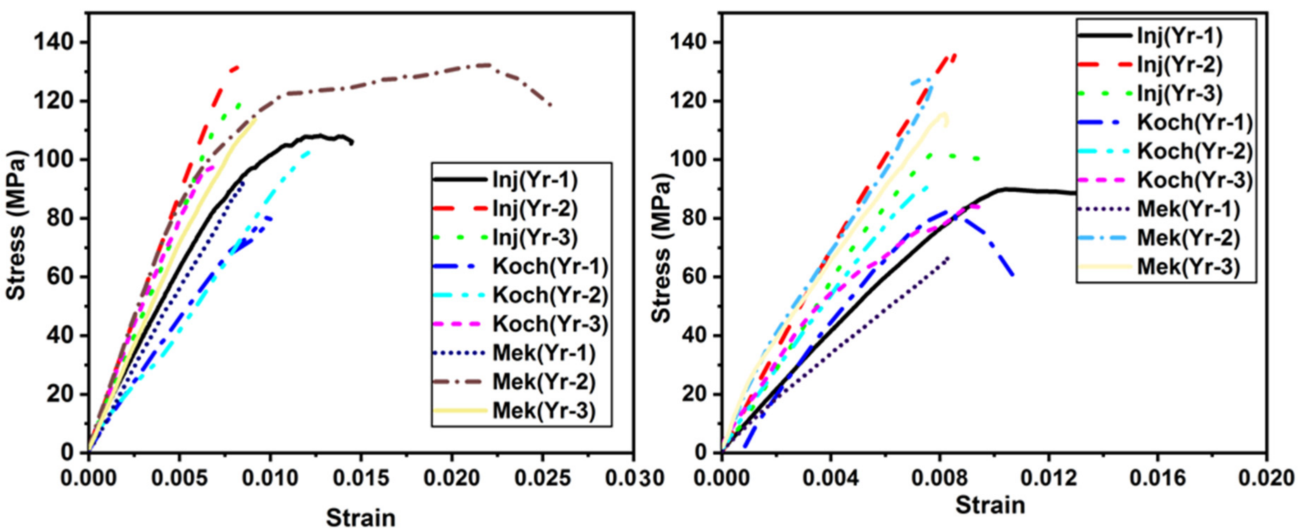

Figure 13. Tensile stress-strain curve of BFPPCs.

3.2.4. Flexural Strength of BFPPCs

The influence of ages and harvesting seasons on the longitudinal flexural strength of BFPPCs for Inji-bara, Kom-bolcha, and Mekane-selam bamboo is indicated in Figure 14. The highest and lowest longitudinal flexural strengths are measured at the ages of 2 and 1 year, respectively. The maximum and minimum flexural strengths of Inji-bara BFPPCs in Feb. were 138 ± 4 MPa and 92 ± 10 MPa, whereas in Nov., they were 159 ± 8 MPa and 113 ± 12 MPa, respectively. The maximum and minimum longitudinal flexural strengths of Kom-bolcha BFPPCs in Feb. were 96 ± 10 MPa and 72 ± 13 MPa, whereas, in November, they were 99 ± 7 MPa and 66 ± 12 MPa, respectively. The maximum and minimum longitudinal flexural strengths of Mekane-selam BFPPCs in Feb. were 127 ± 13 MPa and 89 ± 6 MPa, whereas in Nov., they were 152 ± 15 MPa and 105 ± 16 MPa, respectively. The longitudinal flexural strengths of Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs in Nov. were 13%, 3%, and 16% higher than in Feb., respectively. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs are 33%, 25%, and 30% higher flexural strength than the lowest in Feb., whereas, in Nov., they have 29%, 33%, and 31% higher flexural strength than the lowest, respectively. Longitudinal flexural strength of Inji-bara BFPPCs is 30% and 8% higher in Feb., whereas, in Nov., it is 38% and 4% higher than Kom-bolcha and Mekane-selam, respectively. The flexural strength of Mekane-selam BFPPCs was 24% and 35% higher than that of Kom-bolcha in Feb. and Nov., respectively. As indicated in Table 3, the flexural strength of the BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam has higher measured values compared to Jute felt PU, CFPU, GFMPU, UDMA, BFPP, and GFPU [3,7,12,21,27,31,40], and is comparable with BFEP, GEEP, and GFPE [12,25,28,32,37]. However, they have lower measured values compared to GFPU840871, GFPU 90IK01, and glass laminated PE.

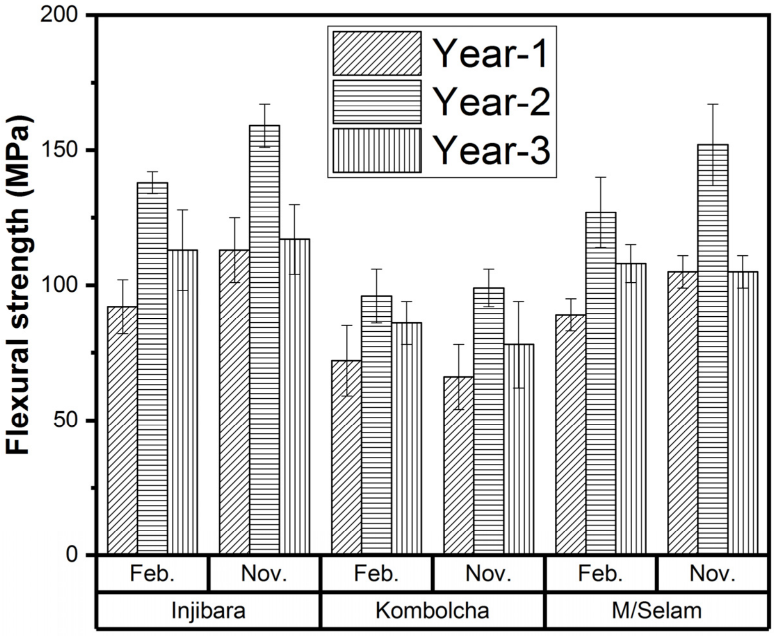

Figure 14. Flexural strength of BFPPCs.

3.2.5. Flexural Modulus of BFPPCs

The influence of ages and harvesting seasons on the longitudinal flexural modulus of BFPPCs for Inji-bara, Kom-bolcha, and Mekane-selam is indicated in Figure 15. The highest and lowest longitudinal flexural moduli are measured at the ages of 2 and 1 year, respectively. The maximum and minimum longitudinal flexural moduli of Inji-bara BFPPCs in Feb. were 8 ± 0.22 GPa and 6 ± 0.55 GPa, whereas in Nov., they were 11 ± 0.76 GPa and 7 ± 0.29 GPa, respectively. The maximum and minimum longitudinal flexural moduli of Kom-bolcha BFPPCs in Feb. are 6 ± 0.35 GPa and 4 ± 0.26 GPa, whereas in Nov., they are 7 ± 0.41 GPa and 4 ± 0.28 GPa, respectively. The maximum and minimum longitudinal flexural moduli of Mekane-selam BFPPCs in Feb. were 8 ± 0.29 GPa and 5 ± 0.24 GPa, whereas in Nov., they were 9 ± 0.22 GPa and 6 ± 0.28 GPa, respectively. Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs in November had 27%, 14%, and 11% higher longitudinal flexural moduli than in February. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs are 25%, 33%, and 38% higher longitudinal flexural modulus than the lowest in Feb., whereas in Nov. they are 36%, 43%, and 33% higher longitudinal flexural modulus than the lowest, respectively. The longitudinal flexural modulus of Inji-bara BFPPCs is 25% higher than Kom-bolcha; however, Mekane-selam has a similar longitudinal flexural modulus with Inji-bara in Feb., whereas in Nov., it is 36% and 18% higher than Kom-bolcha and Mekane-selam, respectively. The longitudinal flexural modulus of Mekane-selam BFPPCs is 25% and 22% higher than that of Kom-bolcha in Feb. and Nov., respectively.

As indicated in Table 3, the flexural strength of different synthetic and natural fibre polymer composites. The current research findings have lower flexural strength than GFEPCS, GFPU840871, and glass laminated PE, however, they have higher flexural strength than other fibre composites listed in Table 3.

3.2.6. Flexural Stress-Strain of a 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 is shown in Figure 16. 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 behaviours. From the highest to the lowest flexural stress of BFPPCs, each year has the highest and the lowest longitudinal flexural stress of BFPPCs, respectively. February has lower tensile stress but higher longitudinal flexural strain, leading to the failure of BFPPCs.

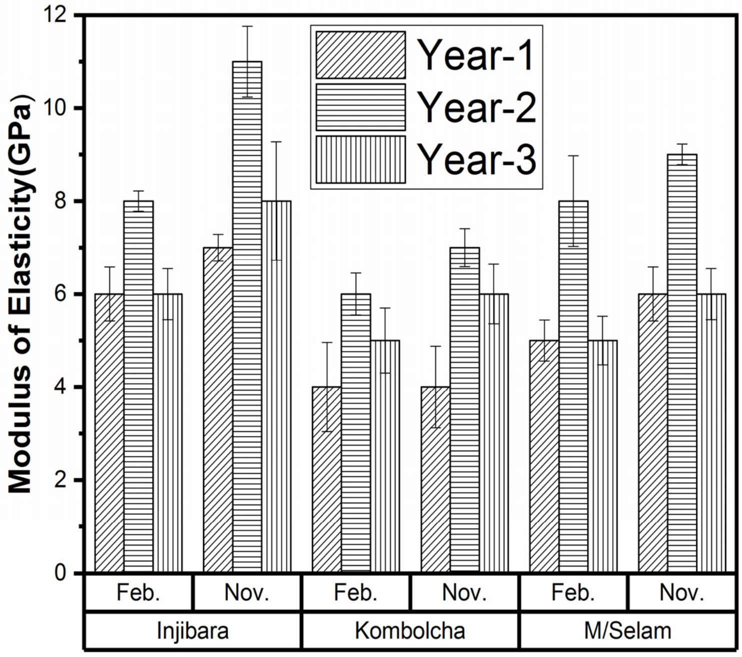

Figure 15. Flexural modulus of BFPPCs.

Table 3. Flexural strength of composite materials for Automobile headliners.

Composite Materials	FS (MPa)	MOE (GPa)	Strain to Failure (%)	Reference
GF epoxy	255	8.47	0.0279	[12]
10% jute felt PU	6.99	0.214	-	[40]
10% carbon fibres PU	13.47	0.308	-	[40]
10% Glass fibres mat PU	7.86	0.358	-	[40]
GFPU840871 composite	642.34	14.56	4.96	[34]
FPU 90IK01 composite	618.88	17.11	3.82	[34]
UDMA	133.8	1.8	-	[12]
20% BPP	38.74	1.27	-	[27]
BFEP, Vf 65%	107–140	12–10	-	[28]
GFEP, Vf 65%	195–250	7–12	-	[28]
BFPP, 40%	46.6	2.432	-	[7]
BFEP	107	11.901	-	[37]
BFEP	119	11.901	-	[29]
GFPE, vf 30%	80	6.01	2.22	[38]
BFPP	43.8	1.975	-	[21]
BFPP	26.1	1.43	-	[31]
40% E glass PU	95	0.50	-	[3]
Glass laminated PE	289	14.222	-	[32]

Table 3. *Cont.*

Composite Materials	FS (MPa)	MOE (GPa)	Strain to Failure (%)	Reference
Inji-bara BFEPCs, Feb.	139–198	6.56–11.51	2.11–2.22	Study
Inji-bara BFEPCs, Nov.	116–191	4.73–10.49	2.01–2.31	Study
Inji-bara BFPPCs, Feb.	89–152	6.5–13.2	3.02–3.61	Study
Inji-bara BFPPCs, Nov.	105–127	6.8–13.4	3.31–4.25	Study
Kom-bolcha BFEPCs, Feb.	81–190	5.36–10.87	2.08–2.64	Study
Kom-bolcha BFEPCs, Nov.	124–175	8.05–12.18	1.96–2.05	Study
Kom-bolcha BFPPCs, Feb.	92–138	6.7–12.12	2.61–3.63	Study
Kom-bolcha BFPPCs, Nov.	113–159	13.6–19.4	2.61–3.02	Study
Mekane-selam BFEPCs, Feb.	188–234	14.37–19.06	1.75–2.07	Study
Mekane-selam BFEPCs, Nov.	156–187	11.09–13.88	1.96–2.05	Study
Mekane-selam BFPPCs, Feb.	72–96	8.45–10.15	2.43–3.31	Study
Mekane-selam BFPPCs, Nov.	66–99	6.42–12.42	2.23–3.04	Study

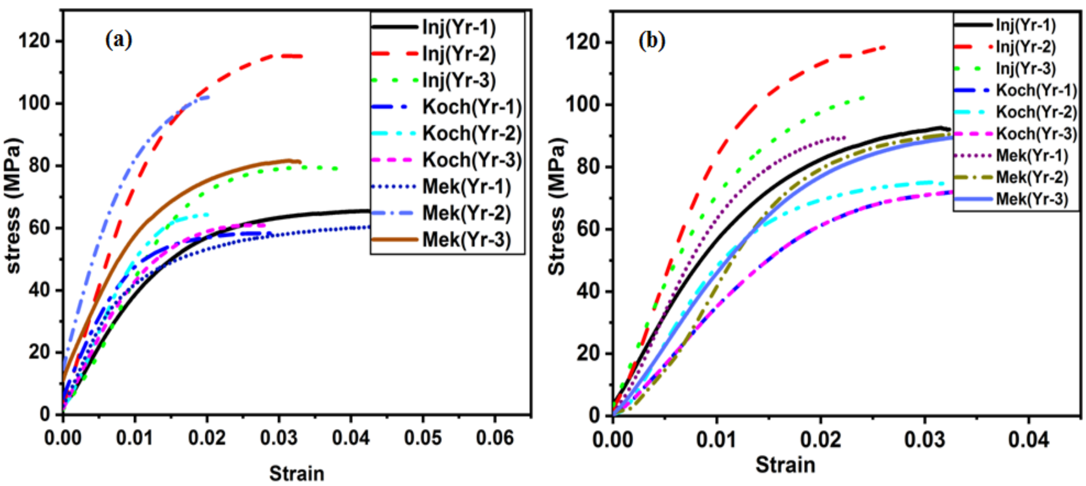

Figure 16. Flexural stress-strain curve (**a**) February, (**b**) November.

3.2.7. Impact Strength of BFPPCs

The influence of age and harvesting month on the impact strength of BFPPCs for Inji-bara, Kom-bolcha, and Mekane-selam is indicated in Figure 17. The highest and lowest impact strengths are measured at the ages of 2 and 1 year, respectively. The maximum and minimum impact strengths of Inji-bara BFPPCs in Feb. were 52 ± 6.4 KJ/m^2 and 34 ± 3.8 KJ/m^2, whereas in Nov., they were 57 ± 6.96 KJ/m^2 and 47 ± 5.45 KJ/m^2, respectively. The maximum and minimum impact strengths of Kom-bolcha BFPPCs in Feb. were 38 ± 3.86 KJ/m^2 and 26 ± 3.34 KJ/m^2, respectively. Whereas in Nov., it had 44 ± 5.68 KJ/m^2 and 39 ± 4.15 KJ/m^2, respectively. The maximum and minimum impact strengths of Mekane-selam BFPPCs in Feb. were 40 ± 4.62 KJ/m^2 and 34 ± 3.38 KJ/m^2, whereas in November, they were 46 ± 5.51 KJ/m^2 and 37 ± 4.35 KJ/m^2, respectively. Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs in Nov. had 9%, 14%, and 13% higher impact strengths than in Feb., respectively. The highest measured values for Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs have 35%, 32%, and 15% higher impact strength than the lowest in Feb., whereas, in Nov., they have 18%, 11%, and 20% higher impact strength than the lowest, respectively.

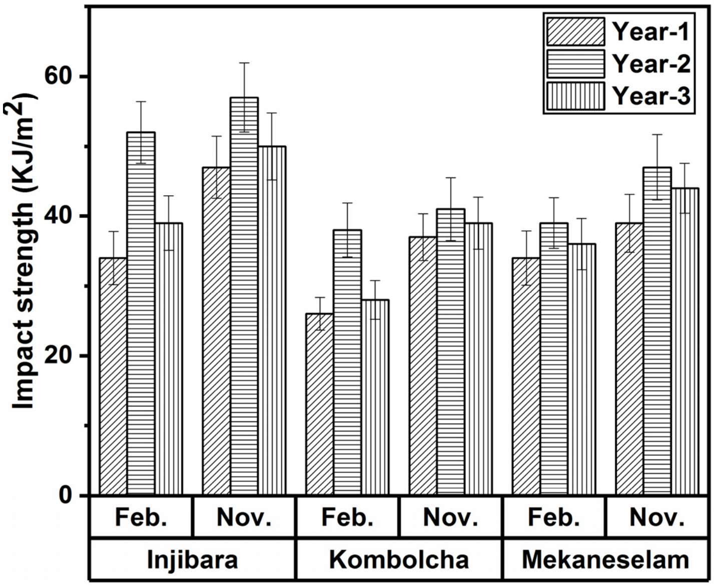

Figure 17. Impact strength of BFPPCs.

As indicated in Table 4, the impact strengths of the BFEPCs and BFPPCs of Inji-bara, Kom-bolcha, and Mekane-selam have higher measured values compared to Jute felt PU, CFPU, GFMPU (glass fibre mat polyurethane), BFPP, BFEP, Glass laminate, GFPE, GFPU [3,7,25,27,31,36,40], and are comparable with BFPP, GFPE [21,38]. However, they have lower measured values compared to Glass laminated PE [32].

Table 4. Impact strength of composite materials for Automobile headliners.

Composite Materials	Impact Strength, (KJ/m^2)	Reference
PU	3.39	[36]
jute felt PU, Vf 10%	3.31	[40]
carbon fibres PU, Vf 10%	8.21	[40]
Glass fibres mat PU, Vf 10%	6.73	[40]
BPP, Vf 20%	1.42	[27]
BFPP, Vf 40%	27.54	[7]
BFEP	15.56	[37]
GFPE, vf 30%	38	[38]
BFPP, Vf 39%	3.4	[25]
BFPP, Vf 50%	3.2	[25]
BFPP	48.7	[25]
BFPP	10.1	[31]
E-Glass laminate	17.82	[1]
40% glass PU	18	[3]
Glass laminated PE	99.71	[32]
Inji-bara BFEPCs, Feb.	43–66	Study
Inji-bara BFEPCs, Nov.	31–55	Study
Inji-bara BFPPCs, Feb.	50–57	Study
Inji-bara BFPPCs, Nov.	34–52	Study

Table 4. *Cont.*

Composite Materials	Impact Strength, (KJ/m^2)	Reference
Kom-bolcha BFEPCs, Feb.	48–70	Study
Kom-bolcha BFEPCs, Nov.	43–55	Study
Kom-bolcha BFPPCs, Feb.	39–47	Study
Kom-bolcha BFPPCs, Nov.	26–38	Study
Mekane-selam BFEPCs, Feb.	51–66	Study
Mekane-selam BFEPCs, Nov.	42–66	Study
Mekane-selam BFPPCs, Feb.	37–41	Study
Mekane-selam BFPPCs, Nov.	34–39	Study

4. Conclusions

The mechanical properties of Ethiopian bamboo fibre polymer composites were investigated based on age, harvesting season, and types of bamboo species. The mechanical properties of bamboo fibre polymer composites are highest at 2 years old, but they are lowest at 1 year old. The difference in mechanical properties is due to the lignification process of bamboo fibres, which matures after one growing season. The month of November is the best harvested season for Ethiopian bamboo culm due to the influence of environmental variations during harvest. The highest to the lowest mechanical properties of bamboo fibre polymer composites are Inji-bara, Mekane-selam, and Kom-bolcha, respectively. BFEPCs have higher mechanical properties compared to BFPPCs. The tensile strength of Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs in the age range of 1–3 years old is 111–166 MPa, 93–111 MPa, and 99–125 MPa in Feb., as well as, in Nov., 85–101 MPa, 60–104 MPa, and 91–116 MPa, whereas BFEPCs in the age range of 1–3 years old have 191–206 MPa, 139–198 MPa, and 151–199 MPa in Feb., as well as, in Nov., they have 171–227 MPa, 129–255 MPa, and 166–206 MPa, respectively. The flexural strength of Inji-bara, Kom-bolcha, and Mekane-selam BFPPCs at the age of 1–3 years old is 89–152 MPa, 92–138 MPa, and 72–96 MPa in Feb., as well as 105–127 MPa, 113–159 MPa, and 66–99 MPa in Nov., whereas BFEPCs at the age of 1–3 years have 139–198 MPa, 81–190 MPa, and 188–234 MPa in Feb., as well as, in Nov., they have 116–191 MPa, 124–175 MPa, and 156–187 MPa, respectively. The impact strength of Inji-bara, Kom-bolcha, and Mekane-selam of BFPPCs at the age of 1–3 years old is 50–57 KJ/m^2, 39–47 KJ/m^2, and 31–47 KJ/m^2, in Feb., as well as, in Nov., 34–52 KJ/m^2, 26–38 KJ/m^2, and 34–39 KJ/m^2, whereas BFEPCs at the age of 1–3 years have 43–66 KJ/m^2, 48–70 KJ/m^2, and 51–66 KJ/m^2, in Feb., whereas in Nov., they have 31–55 KJ/m^2, 43–55 KJ/m^2, and 42–66 KJ/m^2, respectively. In situations involving head impacts into the interior car roof area, the material of the headliner plays an important role in occupant protection. An accurate evaluation of its mechanical properties is indeed critical for predicting its behaviour during a vehicle's interior impact analysis. The mechanical behaviours of Ethiopian bamboo fibre composites are suitable for composite production, which is used in the Automobile industry for headliners.

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