Research Article

Development of Eco-Sustainable Silica-Reinforced Natural Hybrid Polymer Composites for Automotive Applications

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The increasing demand for eco-friendly materials and technology has made the industry focus on bio-compatible composites. This made the researchers explore the potential of eco-friendly, bio-degradable, and inexpensive banana fibre for automotive applications. This work reports the preparation and testing of banana fibre natural hybrid composite fibres randomly oriented with and without adding silica filler (5–15 wt.%) through a hand lay-up process. The mechanical properties such as tensile modulus, flexural modulus, hardness, impact strength, and water absorption capacity were measured. Composite specimens having a fibre length of 30 mm (15 wt.% of silica) exhibited better mechanical properties. The hardness, tensile, flexural, and impact strength measured were 46.74 HV, 54.71 MPa, 127.94 MPa, and 15.19 kJ/m². The results showed significant improvement in mechanical properties in silica-reinforced hybrid composite compared to composites without silica filler. The wt.% of banana fibre increases, and the number of free hydroxyls (-OH) groups increases in cellulose, increasing moisture absorption. The pattern in which the composite absorbs the moisture at room temperature is called “Fickian behaviour.” Furthermore, scanning electron microscope (SEM) characterisation studied the interaction between fibre matrix and the distribution of silica reinforcement. This research concludes that bio-composites that exhibit improved mechanical properties are eco-friendly and are found to be suitable for automotive applications that meet present-day requirements.

1. Introduction

Developing composites for engineering applications such as automotive, aerospace, and structural industries [1–3] is the need of the day. Composite materials have two or more chemically distinctive phases. The discontinuous phase, which is harder, is known as reinforcement [4]. The continuous phase in the composite is termed the matrix [5, 6]. The composites were prepared using resin reinforced with synthetic and natural fibres [7]. Today, natural fibres have started replacing synthetic fibres. The environment-friendly characteristic makes the composite material used in automobile and construction industries [6].

Natural fibres are sustainable, nonabrasive, compostable, have a high calorific value, exceptional mechanical properties, low density, are less expensive, and are less harmful to the environment [8]. At present, banana fibre is a waste product of banana cultivation [9] without any further cost, and banana fibres can be acquired for engineering purposes [5]. Banana fibres can be extracted
through retting, mechanical, and chemical extraction methods [9, 10]. Generally, fibres concentrated near the outer region are extracted by hand scraping, chemical extraction, retting, or using raspadors. The extracted leaf sheaths are boiled in a sodium hydroxide solution. Also, hand-scraped fibres represent better quality than other techniques. The fibres extracted are washed and dried to remove the moisture present [11]. The use of natural fibre helps in reducing the problem of environmental degradation due to the pollution caused by synthetic fibres. Banana peduncles and leaves are expected to contribute 20% of the plant’s total biomass [12].

In composites, the matrix is an essential element responsible for the positioning of fibres, as well as stress transmission from one fibre to another and protecting the fibres. Different matrices used are epoxy, polyester, etc. Epoxy resin offers low viscosity, good flowability, dimensional stability, and better productivity. Composites prepared using epoxy resin are used in numerous applications. The mechanical properties of the fibre-reinforced composite depend on two significant aspects: the fibre-matrix interface and the stress transfer ability of the matrix to all fibres. Enhanced properties can be obtained by using natural and artificial fibres in the same matrix [13, 14].

Some authors have reported comparing the tensile properties of bananas with different natural fibres [15]. The advantage of using banana fibre as a natural fibre for composite preparation is that it has a larger fibre diameter. As a result, the unit area of the composite is high. Hence, the efficiency of transferring stress from the matrix to the fibres is greater [16, 17]. Therefore, banana fibre is a good substitute for synthetic fibres [18].

Many attempts have been made to manufacture a composite using banana fibre and polyester resin as the matrix [17, 19]. An increase in the fibre’s weight fraction is reported to increase composites’ mechanical properties [8]. Due to the chemical composition of banana fibre, it has an appreciable value in breaking load, breaking extension, and persistence [20]. The physical, chemical, and mechanical characteristics decide the fibre quality [12]. Increasing the weight fraction of the composite fibres enhanced the mechanical properties [8].

The selection of suitable filler in the appropriate amount in the composite affects the mechanical, physical, and chemical properties and dimensional stability [21, 22]. The addition of silica particles increased the composite resin’s epoxy viscosity [23]. Silica and silicate-based fillers modify the properties of composites, like the hardness and elasticity of components [24–27]. The fabrication and application of polymer composites were reviewed [28].

One major disadvantage of using natural fibre in composite preparation is that it absorbs moisture. As a result, the interface bond between the matrix and the fibre gets weakened. This ultimately leads to material failure in the loading condition. It leads to the degradation of the mechanical properties. The problem of water absorption can be reduced by treating the banana fibres chemically before using them for composite manufacturing. Researchers tried to characterise composites by adding different fillers to enhance their mechanical properties [29].

Natural fibre composites have many industrial and domestic applications, such as insulators of heat and electricity; they can also be used in fireproofing [30]. As a result, natural fibres have again started to gain importance. The banana stem that offers the source of fibre is available as waste in the world. The banana fibre, known for its high strength, can be used as reinforcement in composites for many applications. Similarly, an attempt to test the mechanical properties was reported using banana fibres subjected to a tensile load. The failure was due to the pull-out of the microfibrillar accompanied by the tearing of cell walls. The tendency of fibre pull-out can be reduced by increasing the testing speed [31].

In order to study the impact of lesser weight fraction of fibres on mechanical properties [8], the banana fibres with varying proportions (5–15 wt.%) and different fibre lengths (10–25 mm) along with silica (15 wt.%) as filler material were reinforced with epoxy resin to make the composites. The produced composites were tested to find the composites' tensile, flexural, impact strength, hardness, and water-resistant properties.

2. Experimental Procedure

2.1. Extraction of Banana Fibre. Fibre is obtained from the bark of the banana tree through the extraction process. The extraction of banana fibres was carried out by removing the outer layer of the banana stem. Then, the core part is cut into half horizontally and vertically, and pressure is exerted on the sliced parts, which get squeezed. Removing water partially from the fibres helps to separate the fibres easily.

After separating the fibres, it is placed in the hot air oven and exposed to a temperature of 80°C for 12 hours to dehydrate the banana fibre completely. In order to increase its stiffness, banana fibres were chemically treated with NaOH solution [32]. Fibres were submerged in the NaOH of concentration 1 N for 12 hours. The dehydration process is repeated by placing it in the hot air oven for 8 hours at 80°C. After, it transforms into strong banana fibres, cut into short lengths of 10, 15, 20, and 25 mm.

2.2. Composite Preparation. The extracted fibres were used as the reinforcement in the composite. The resin used as a matrix is commercially available epoxy (ARALDITE LY 554), and a hardener (HY 951) was used for composite preparation. The composites were processed in the mixing ratio of 100 parts by weight of epoxy and 10 parts of hardener. Hand lay-up is the oldest process of woven composite manufacturing [33]. The various steps involved in the hand lay-up process are described as follows: first, the mould surface is coated with the releasing agent to avoid sticking the matrix with the die. Then, a delicate plastic layer is employed at the mould’s top and bottom to make the composite’s smooth surface.

Banana fibres (weight fraction 5–15%) were prepared with different lengths (10, 15, 20, and 25 mm) with and
without the filler material silica flour (weight fraction 15%) added to the epoxy. Finally, the hardener was added and uniformly mixed with a stirrer. Then, the resin mixed with ingredients was poured into a die coated with the releasing agent to avoid sticking the matrix using a helping brush to uniformly spread it and pressed using a roller to get rid of any confined air foams and the excess polymer. Then, the mould is closed, and pressure is released to acquire a single mat. After curing at room temperature, the mould is opened, and the woven composite is removed from the mould surface. The schematic of the hand lay-up process and the fabricated specimen is shown in Figure 1.

2.3. Mechanical Properties Testing. Prepared composites were cut to the specimens of the desired shape to perform various mechanical tests. Five specimens were used to study the mechanical properties. Tests such as tensile, flexural, and impact tests were conducted to determine the composites' effectiveness. The tensile test was done on the bases of ASTM D 638–03 standard [34], and the test speed was 5 mm/min in Universal Testing Machine (UTM) (Make: Shimadzu). Specimen with dimensions [160 (l) × 12.5 (w) × 12 (t)] mm was used for the test. Finally, a comparative study was conducted to find the relationship between the fibre weight fraction and the tensile strength.

The flexural strength was found using ASTM D 790 standard [35], and the cross head was maintained at 1.3 mm/min. The three-point test was done on the UTM (Make: Shimadzu). Specimen prepared for the test with dimension [100 (l) × 25 (w) × 12 (t)] mm was placed between rollers 64 mm apart in a three-point bending test. The three-point test is chosen because it is straightforward to find the mid-point deflection. The composite's maximum stress and flexural modulus were found using relations in the literature [36]. The strain rate used in the test was 0.5 mm/min, measured with the help of an electronic tensometer.

The impact strength was determined by using an impact test. The standard procedure used for the impact test was ASTM D 256 [34]. Impact strength determination by the Izod impact test is preferred due to its simplicity and no threat to its credibility due to its detailed history. The hardness test was performed in a Vickers hardness tester (Make: Shimadzu). Composites fabricated were cut to 25 × 25 mm, and the load of 0.3 kgf was applied to the composite for 10 seconds.

2.4. Water Absorption Test. According to the ASTM D570 standard, the water absorption test was conducted to find the approach toward Fickian behaviour. The absorption % was calculated [37] using the following equation:

\[
\% \text{ of absorption} = \left( \frac{m_2 - m_1}{m_1} \right) \times 100, \tag{1}
\]

where \(m_1\) and \(m_2\) are the weight of the dry and wet specimens.

The kinetic parameter, the diffusion coefficient \(D\) (mm\(^2\)/s), is calculated using the following equation:

\[
D = \pi \left( \frac{h\theta}{4Q_\infty} \right), \tag{2}
\]

where \(\theta\) = slope of the linear portion of the sorption curve, \(h = \) initial specimen thickness (mm).

The ability of solvent molecules to move among the polymer segments depends on the diffusion coefficient. The sorption phenomenon of the fibre defines the permeability of water molecules through the composite specimen. Therefore, the sorption coefficient ‘\(S\)’ is calculated as follows [38]:

\[
S = \frac{Q_\infty Q_t}{S}, \tag{3}
\]

where \(Q_\infty = \) molar % of water uptake at time \(t = \infty\), \(Q_t = \) molar % of water uptake at time \(t\).

The permeability coefficient \(P\) (mm\(^2\)/s) gives the net impact of sorption and diffusion.

\[
P = D \times S. \tag{4}
\]

The water absorption kinetics was studied by first taking the initial measurement of the specimen to be tested after it is dehydrated for one hour. After recording the initial reading of weight, then it is dipped in water and taken out periodically. The surface is wiped, and then again, weight is measured. Finally, the percentage increase in water absorption is computed and recorded. The microstructure of the composite sample was observed through SEM to observe the distribution of fibres and internal structure of the tested composite samples.

3. Mechanical and Water Absorption Properties

Mechanical properties like hardness, tensile strength, flexural strength, impact strength, and water absorption behaviour were examined. Composites’ mechanical properties mainly depend on fibre content and length.

3.1. Hardness. The effect of silica content, banana fibre volume fraction, and fibre length on the hardness of hybrid composites is presented in Figure 2. The hardness of polymer composite increases by 8.57%, 5.47%, and 10.1% for 15%, 10%, and 5% vol. fraction of banana fibre reinforcement with the addition of 15 wt.% of silica. The increase in hardness is due to an increase in restricting the movement of polymer chains with silica content. The hardness of silica-polymer hybrid composite increases by 36.01%, 40.12%, and 47.83%, with a rise in fibre length from 5 mm to 20 mm for 15%, 10%, and 5% vol. fraction of banana fibres reinforcement, respectively. The hardness increases ascribed to increased interfacial adhesion between polymer and banana fibres and improved surface hardness.

From Figure 2, it was found that the hardness improved with an increase in fibre length, and it is highest at 10 mm fibre length with silica filler and neat composite. However, with the increase in fibre up to 15 wt.%, it was found that...
hardness increased. It is well known that in hybrid composite material, filler weight fraction significantly affects the hardness value of the hybrid composite material. This was observed from the results of this research, which showed a superior hardness to the neat composites. The hardness of the specimen with fibre length 25 mm and 15 wt.% of silica filler (15 wt.%) measured 46.74 HV was found to be maximum. The result obtained in this research may be due to the excellent compatibility between the silica filler and composites [37].

3.2. Tensile Properties. Figure 3 shows the influence of silica content, fibre volume fraction, and fibre length on the tensile properties of the composites. The tensile strength increased approximately 12.5%, 10.5%, and 10.2% for 15%, 10%, and 5% vol. fraction of banana fibres reinforced with 15 wt.% of silica. The increase in tensile strength is attributed to silica content in hybrid polymer composites, which restrain the flow of the polymer chain and consequently improve the tensile strength of the silica-reinforced banana fibre reinforced composite compared with the composites without silica. The tensile strength of hybrid composite increases by 48.38%, 23.91%, and 41.1%, with a rise in fibre length from 5 mm to 20 mm for 15%, 10%, and 5% vol. fraction of banana fibre reinforcement, respectively. The percentage increase in the tensile strength in silica-reinforced banana polymer composites with a 10% banana vol. fraction is the lowest. This is due to poor adhesive bonding between banana fibre and polymer matrix.

Figure 3 shows the results of tensile strength comparisons for specimens of fibre lengths 10, 15, 20, and 25 mm for neat and silica-filled composites. The results confirmed that the weight fraction and the tensile strength have a linear relationship. As the wt.% fraction of the banana fibre increases in the epoxy matrix, its tensile strength is enhanced, which leads to the desired more robust material. Observed data reveal that composites' tensile strength increases with fibre length and weight fraction. The tensile strength of the specimen for a 15 wt.% showed an increase from...
38.93–54.71 MPa for the silica-filled natural hybrid composite. The results of this research were consistent as the chemical and silane treatments improved the compatibility between natural fibres and polymer matrices could be the reason for the increase in tensile strength [39]. The results show that the tensile increased with the increase in fibre length (Figure 3). The fibres that take up the load from the matrix are distributed uniformly. Furthermore, a higher amount of reinforcement may lead to agglomeration [40]. The results reported a higher strength than previous work on a hybrid composite of banana/sisal [39]. The tensile strength obtained was appreciable and substantial owing to the surface treatment of fibres and adding the filler material as silica flour compared with the neat composites. The tensile strength of the specimen was found to increase by 40%. The results show that composites possess mechanical features such as mobility, stiffness, and modulus. The role of silica filler in the composite is justified by the dispersion toughened phase formed observed as micron-sized particles in the composite [36]. The composite containing microsized fillers reported that the epoxy matrix increased the young’s modulus and lowered the % elongation [26, 41]. Hence, silica fillers were used to fabricate composites using epoxy resin [42]. The results conclude that exploring inexpensive natural fibres treated chemically offers good stiffness and strength, which is better than artificial glass fibre. The research findings indicated the growing demand for lighter parts made using natural fibres.

3.3. Flexural Properties. The flexural strength of the specimen measured showed that 25 mm fibre length with 10 wt.% exhibited the highest value of 127.94 MPa (Figure 4). Similar results were obtained in the previous literature [43]. From the results, it is clear that as the weight fraction of the composite increased, the flexural strength increased up to a fibre weight fraction of 10 wt.%. Beyond this, flexural strength decreased for the 15 wt.% fibre weight fraction. The reason for the decrease in strength is that as the fibre wt.% increases, water absorption increases and confirms the debonding of fibres and weak fibre interphase. Hence, interfacial strength between the fibre and matrix is vital to achieving effective fibre reinforcement. There is an increase in flexural modulus by 36% for the composite prepared. However, the flexural strength decrease was appreciable owing to the fibres’ surface treatment. Silica showed the existence of good adhesion and appropriate bonding between the filler and matrix, which enhances the strength of the composite. A similar trend was found in the literature [44].

3.4. Impact Properties. The impact energy of material shows its ability to absorb and dissipate energies under sudden loading. The effect of silica content, fibre volume fraction, and fibre length on the tensile properties of polymer hybrid composites is shown in Figure 5. The results show that the NaOH-treated banana fibre/epoxy composite’s impact strength is significant. The impact energy of hybrid composite increases by 11.11%, 12.32%, and 4.3% for 15%, 10%, and 5% vol. fraction of banana fibre reinforcement with the addition of 15 wt.% of silica. The restriction of polymer composite chain movement increases the rigidity in the hybrid composite, resulting in improved impact energy absorption.

The impact strength of the composite material was found to be minimum for the composite specimen with 5 wt.% and a fibre length of 10 mm. The reason may be due to the presence of fibre in low wt.%, and also the resin due to its brittleness. Similarly, it was found to be maximum for a weight fraction of 15% and fibre length of 25 mm 15.19 kJ/m² (Figure 5). The previous work reported 13.25 kJ/m² for a
hybrid composite [39]. There has been an enhancement in the impact strength by 48%, which is appreciable by using reinforcement as banana fibres. The increase in impact resistance was due to the increased density of fibres in the matrix, and their random orientation as the fibre carried the load. This caused an increase in resistance to the impact load. Also, the presence of silica filler increased the rigidity that absorbs more energy could be the other cause for the improved impact strength compared with the neat composites. The addition of silica creates a noteworthy difference in the impact strength of the banana fibre-reinforced epoxy composites. Hence, this study shows that the impact strength is directly proportional to the weight fraction.

3.5. Water Absorption Behaviour. Composites prepared for application come in contact with water and have fundamental importance attached to the effect of water absorption. Hence the water absorption behaviour depicts the characteristics of composites’ usefulness. The water absorption test results are shown in Table 1 for different wt.% for the fibre length of 25 mm. The percentage moisture absorption calculated shows a minimum of 5 wt.% is 23.57%. It was interesting to note that as the fibre wt.% increases, the weight of the specimen increases by some significant amount due to moisture absorption. The present banana fibres have maximum water absorption capacity compared with silica and epoxy resin. However, as the wt.% of banana fibre increases, the number of free hydroxyls (-OH) groups increases in cellulose. Thus, an increase in moisture absorption is observed. The OH groups in connection with humidity form hydrogen bonding, resulting in weight gain in the composites. After 24 hours, the water absorption coefficient becomes stable.

The hydrophilic nature of fibres well elucidated this phenomenon, it is because of the fact the cellulose fibres. Furthermore, the swelling and cracks in the fibre increase the water transport by diffusion. The active capillary mechanism makes the water molecules flow through the fibre-matrix interface [45]. The water absorption behaviour can be decreased by increasing the reinforcement and making a strong adhesive bond between the fibre and matrix, which provides minimal micropores to diffuse the water molecules [7].

3.6. SEM Analysis. Figure 6 shows the micrograph for 10–25 wt.% banana fibre-reinforced epoxy composite. The images revealed the reasons behind the variation in the mechanical properties of the composites. The study indicated a change in mechanical properties due to changes in fibre length and wt.% and filler dispersion. The micrograph for 10 wt.% (Figure 6(a)) showed sample voids and non-uniform distribution of fibre leading to agglomeration. The agglomeration, a collective stacking of fibres together in the matrix, reduces the strength by non-uniform stress transfer [46].
A similar trend was observed in Figure 6(b), which showed less porosity. The less porosity may be the reason for low mechanical properties, leading to early failure. The micrograph shown in Figures 6(c) and 6(d) indicated the uniform distribution of fibres and fillers. The dispersion fibres and fillers were uniform, indicating good bonding between banana fibres and epoxy resin. Also, good fibre-matrix adhesion is visible. The well-known fact of dispersion toughening of fillers and uniform distribution of reinforcement in resin improves the properties of the composites [47].

4. Conclusions

Banana fibres are one of the cheapest and most abundantly available from the waste part of banana trees. Hence it is one of the most economical and robust natural fibres. The extraction process of the banana fibres is simple too. This research assisted in discovering the variation in the mechanical properties of the banana fibre-reinforced composite without and with different wt.% silica filler and for the varied fibre wt.% and length. From the above-obtained results of the specimens, the conclusion is as follows:

(i) Fabrication of banana fibre-based epoxy composites with various wt.% and fibre lengths were successfully fabricated using a hand lay-up procedure.

(ii) The results revealed that fibre loading, length, and addition of silica filler play a significant role in the mechanical characteristics. The composite reinforced with 25 mm fibre length and 15 wt.% fibre offered enhanced mechanical properties.

(iii) The hardness, tensile strength, flexural strength, and impact strength measured were 46.74 HV, 54.71 MPa, 127.94 MPa, and 15.19 kJ/m². 15 wt.% of silica addition in hybrid composites increases hardness by 8.57%, 5.47%, and 10.1% for 15%, 10%, and 5% vol. fraction of banana fibre reinforcement.

(iv) Furthermore, it is also found that the tensile strength improves by 12.5%, 10.5%, and 10.2% for 15%, 10%, and 5% vol. Fraction of banana fibre reinforcement. This reveals that the presence of silica in a hybrid composite restricts the mobility of the polymer chain, resulting in improved mechanical properties.

(v) Adding silica along with fibre length and wt.% significantly improved the mechanical properties. Also, the adequate bonding amongst the fibre, matrix, and silica filler significantly enhanced the mechanical properties. The results showed the improved mechanical properties of silica-filled natural fibre composite compared with neat.
(vi) The water absorption behaviour for the banana fibre-reinforced epoxy follows Fickian and non-Fickian characteristics, and the composite’s water absorption becomes stable after 24 hours. Due to the water absorption, the bonding between the fibres and the epoxy resin decreases, and the composite becomes weaker.

(vii) Therefore, the environmentally friendly nature of the hybrid composite material remains a substitute for engineering applications.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


