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Preparation and mechanical characterization of natural polymer composite material obtained from fox tail palm seeds

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Abstract
This experimental investigation reveals the preparation of natural composite material from foxtail palm tree seeds. The fruits from the foxtail palm tree are used for the extraction of oil, and the by-product of the extraction process is freely dumped. This study attempts to utilize the waste by-product of foxtail palm tree fruit as a valuable natural composite material. The fabrication was done using the hand lay-up method for the proposed reinforcement (4% and 8%) of filler materials. The obtained composite materials are subjected to significant mechanical characterization of tensile behaviour, flexural property, and hardness. In addition, the morphological study was also carried out by the scanning electron microscope (SEM). The results show that, as the reinforcement percentages of filler material increase, the mechanical properties are improved. This may be due to the uniform dispersion of natural fibres in the polymer. The tensile strength was improved by 22.43% and 29.08% for 4% and 8% filler reinforcement. Similarly, the stiffness property was improved by 9.32% for 4% reinforcement and 18.68% for 8% reinforcement when compared with neat composite. The SEM images reveal the failure analysis, bonding strength and fibre pull-out in the composites. Finally, the foxtail fruit fibre shows promise as a reinforcing agent in composite materials, improving their mechanical properties and making them suitable for various applications requiring strength, stiffness, and resistance to deformation.

Keywords:
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Mechanical Properties
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INTRODUCTION

Similar to the alloys, the definition of composite reveals that it is a combination of two or more different materials possessing varying properties. It is a known fact that individual materials may not possess good properties for particular applications. However, combining the different materials will result in superior materials with improved properties than the individual materials [1, 2, 3]. Therefore, composite materials are multiphase materials produced to meet the existing demand for super materials with enhanced properties [4, 5, 6]. In other words, the composite material is defined as a dispersed material consisting of fine insoluble particles distributed throughout a continuous phase known as a matrix, and the particles spread within the matrix are referred to as a particulate phase [7]. The particulate phase consists of spherical, small disk or plat shape particles ranging from nanometers to microns in diameter [8]. The commonly used matrix materials for composites are metals, polymers, and ceramics [9]. They are often called ceramic matrix composite, polymer matrix composite, and metal matrix composite [3]. With the advent of science and technology, industries are striving for new performance materials, and the physical blending of two immiscible polymers, known as polymer/polymer blending, has gained attention [10, 11, 12]. A recent review study by Idumah [13] investigated the advancements in polymer blends, self-healing polymers, and nanocomposites, revealing significant information and their applications with graphene-reinforced composites, carbon nanotubes, and halloysite nanotubes. Furthermore, the author discussed self-healing polymers' challenges, prospects, and future market disposition. Another study by Toh, H et al. [12] reveals the polymer blends and composites for cardiovascular implant applications. The authors narrate the polymer blending and polymer composite fabrication techniques and novel applications in cardiovascular implants.

The commercial and industrial applications of composite materials are too many [14], [15]. They are gaining rapid attention due to promising mechanical properties of high specific modulus, high strength-to-weight ratio, high damping capacity, corrosion resistance, fatigue resistance, impact resistance, thermal and acoustic insulation, and others [16]. Due to these deserving properties, they are widely used in different aerospace, aviation, automotive, construction, marine offshore, medical, electronics, and consumer goods sectors [2][4]. Furthermore, the industrial sector is considered to be built on materials of pure metals and alloys, and with the advent of composite materials with their improved properties, they are now widely employed to regulate dependency [17]. The utilization of composite materials has begun from the 1990s onwards, and due to their excellent properties, they are gaining gradual interest among research groups [18][19]. Rajak D K et al. [20] presented their review on the recent progress of reinforcement composite materials. As a future scope, the authors suggested incorporating synthetic or natural materials to discover a new generation of composites for an efficient manufacturing process. Synthetic fibre-based reinforced composites appear less expensive and have a good mechanical characterization [19], and they utilize glass fibre or carbon fibre as a reinforcement. Though synthetic fibres exhibit excellent mechanical properties, the concept of sustainability is a major concern in modern times for all researchers. Renewable and sustainable production and green manufacturing are in great need, and at the same time, they are challenging for most industries. With the implementation of sustainable production, the demand for non-sustainable products is decreasing, and because of the limited availability of conventional energy resources and rising stringent environmental regulations, researchers are shifting towards renewable raw materials to develop new components [21][22].

From the above discussions, it is evident that the replacement of synthetic fibres with natural fibres promotes sustainable development. Also, natural fibres have other benefits of low cost, relatively low density, low specific gravity, high impact resistance, high flexibility, low greenhouse gas emission, eco-friendly, less health hazard, recyclability, carbon neutrality, and others [22]. Due to these promising benefits, especially safe for the environment, the applications of natural fibre-based composites include the automotive sector and electronics. Satish Geeri et al. [23][24] studied the influence of magnetic wood on the electromagnetic wave absorption property and mechanical characterization with natural composite material. The results of the vector network analyzer in the frequency range of 8.2 to 12.4 GHz reveal that the reflection losses increase with the immersion time, and the best results are achieved for the natural specimen with an immersion time of 72 hours. Due to the light weight of natural fibre, composite material finds applications in automotive body building, lightweight bicycles, tennis rackets, laptop cases, and others. Recent literature reveals that automotive composite bumper beam material from natural fibres and its hybrid as reinforcement in a synthetic polymer matrix. This experimental investigation was carried out by Adesina et al. [25] and observed low-impact properties with the hybrid natural fibre compared to conventional glass mat thermoplastics. Another study by Marichelvam et al. [26] developed a novel palm (sheath) and sugarcane bagasse fibre-based hybrid composite for automotive applications. Likewise, the research on natural fibre-based polymer composites is gaining wide attention at present.

Therefore, this study investigates the significant mechanical properties of natural polymer composite material obtained from the fibre of foxtail tail palm tree fruits. The scientific name of the foxtail palm tree is Wodyetia Bifurcata, and it is a popularly grown tree native to the northeastern parts of Queensland in Australia. Due to the unique appearance of their fronds which resemble a fox's tail, these trees are called foxtail palm trees. These trees can be grown in tropical and subtropical regions where the temperatures do not drop below freezing points, and they can adapt to a wide variety of soils, including sandy, loamy, and clayey. The fox tail palm tree fruits appear round, orange-red, and contain a single seed. They can reach a maximum height of 9 meters, and their trunk is typically slim, greyish-brown, and slightly swollen at the base [27]. As there is no evident literature on composite material preparation from foxtail tail palm tree fruits, this experimental study is mooted.

METHOD

The filler material selected for the present experimental study was obtained from the fruits of foxtail palm tree (Wodyetia Bifurcata) which are available on our campus (Raghu Engineering College) located at 17° 59' 38" north latitude and 83° 24' 56" east longitude as shown in Figure 1(a). The obtained fruits are cleaned with deionized water and dried under natural light for six days to remove moisture content, as shown in Figure 1(b). From the dried fruits of the foxtail palm tree, the fibres are extracted, and they are converted to micro level by using a mechanical grinding machine, as shown in Figure 1(c & d). This powder state of filler material was considered for proposed percentages (0%, 6% & 8%) of weight-based to the polymer during the fabrications of composites.

These filler materials were added to the resin (LY 556), and for uniform dispersion of filler materials, a mechanical stirrer was used. Later, hardener (HY 951) was added to the foxtail palm fibre-based resin, as shown in Figure 1(e). The resin/polymer and hardener are obtained from Merck-Industrial & Lab Chem., Visakhapatnam.

In the present work, an E-glass mat (650 gsm) was considered for six layers in the fabrication process, and fabrication was done layer by layer with the combination of foxtail palm fibre-based polymer. After the fabricating layer by layer, the air bubbles present in the matrix material were removed by passing a roller over the composites. The composites are allowed to solidify for 24 hours under a hydraulic press, and the final solidified composites are in the dimensions of 300 X 300 X 6 mm, as shown in Figure 1(f). Mechanical characterization like tensile, flexural, and hardness are performed on the fabricated composites by following the standards of ASTM D-638 for tensile on UTM, ASTM D-790 for flexural, and ASTM D-790 for hardness, and a sample specimen under failure is shown in Figure 2.

RESULTS AND DISCUSSION

Morphological Study

The morphological study was carried out by scanning electron microscope (SEM); with these SEM images, the failure analysis on the specimen can be examined. After the failure took place on the specimen for tensile and flexural, the analysis was carried out under the magnification of 500 µm and hence the presence of pores presents in the matrix material and the debonding phenomenon was studied.

When the polymer (epoxy, filler material & hardener) is applied over E-glass mat's during the fabrication process, some air bubbles are trapped in polymer near the E-glass mat fibres. These air bubbles can be removed by passing the roller over the composites and even then, some voids/pores will be present. By these voids, during the characterization process, the fibres (E-glass) can be easily pulled out due to not having proper bonding. This phenomenon was observed from Figure 3 for the specimen of 8% filler material reinforcement composites.

Figure 1. Flow chart of the composite fabrication process: (a) Foxtail palm tree with ripened fruits; (b) Dry tree fruits; (c) Fiber extracted; (d) Fibers converted to micro level (powder); (e) Reinforced in polymer; and (f) Cutting of specimen as per ASTM standards

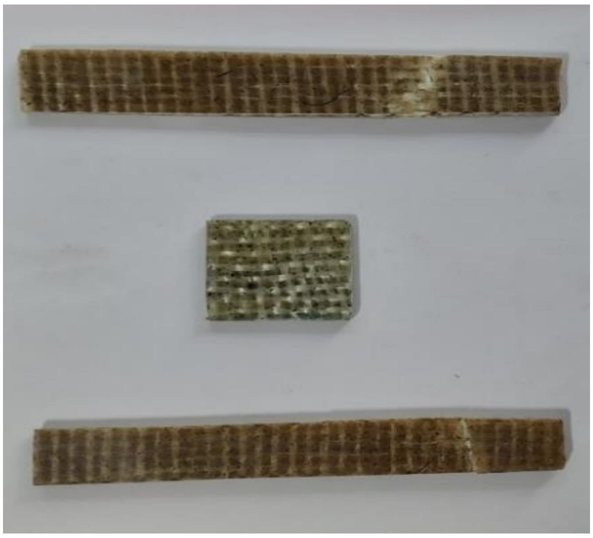

Figure 2. Foxtail composite material as per international standards (ASTM)

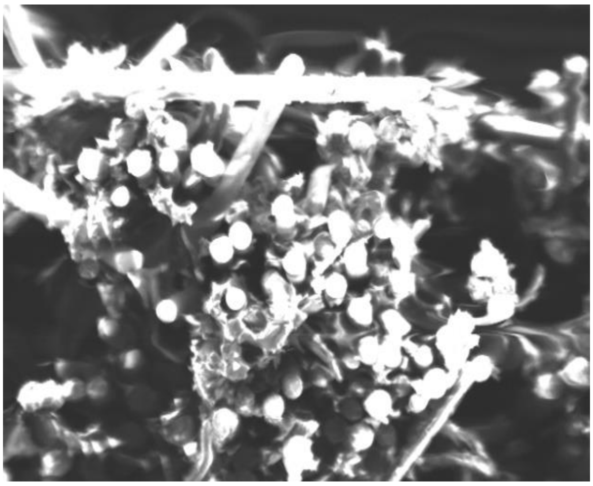

Figure 3. Voids present in matrix material

During the tensile testing, the crack propagation starts at 90 °C to the applied load in the fibre direction (longitudinal) and the voids present near the crack also reduce the strength of the composites. The matrix material breaking, and fibre pullout can be observed in Figure 4. In the flexural testing, the applied load is acting in the lateral direction to the composites. By the presence of good bonding force between the matrix material and E-glass mat, the impact on the stiffness property and failure of matrix and fibre can be examined in Figure 5.

Mechanical Characterization

The main aim of the present work is to find out the mechanical properties (tensile, flexural, and hardness) of foxtail palm fibre-based composites and to know the influence on the properties by varying the filler material percentages. It was observed that, by increasing the reinforcement percentages, the mechanical properties also improved. The strength of the specimen was determined by conducting a tensile test on UTM at a speed of 2mm/min. Based on the experimental data, as the reinforcement percentages increase, the strength of the composites is also increased. Compared to the neat composites, the 4% reinforcement of filler material specimen was improved by 21.55%, and for 8% reinforcement, it was improved by 29.08% as shown in Figure 6.

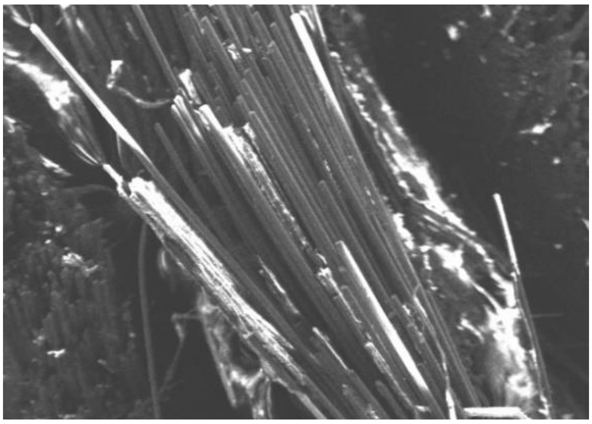

Figure 4. Fiber pulls out and a crack opening leads to failure

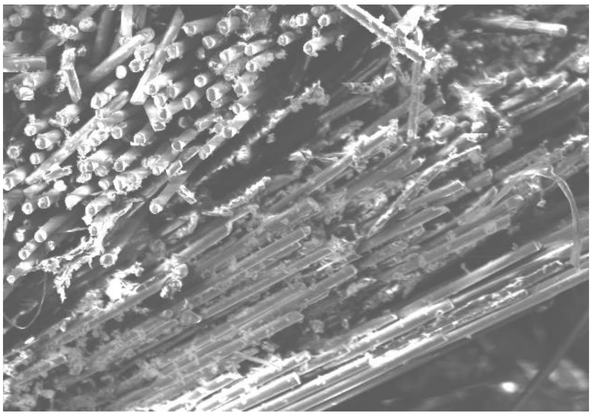

Figure 5. Fiber debonding with matrix material

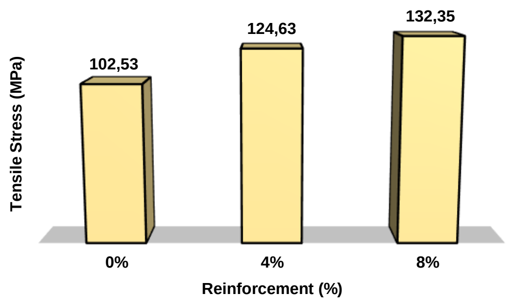

Figure 6. Tensile strength for fabricated composites

As the reinforcement of filler increased from 0% to 8%, the uniform dispersion takes place in the polymer which improves the bonding between the fibres and matrix materials. Hence it leads to an increase in the strength of the composites as shown in Figure 6. Initially load will be acting in the fibre direction and later the same load was transferred to the matrix material during the tensile test [16]. By having these foxtail palm fibres in the polymer, the bonding was improved and hence the load-carrying ability was also improved as shown in the stress-strain diagram of the tensile properties of three composites in Figure 7 [24].

The comparison of tensile strength for the proposed reinforcement percentages with previous works [28, 29, 30] are better, it is clear that, the stress transformation takes place and which leads to the improvement of the strength.

Flexural strength is also one of the most important properties, which provides the bending stiffness in the material, and the experiment was conducted on UTM as 3-point bending test. It was noticed that, as the foxtail palm fibres induced percentage increase, there was a gradual improvement in the flexural strength as shown in Figure 8. As the reinforcement increased from 0% to 4%, the flexural strength improved from 139.06 MPa to 152.03 MPa and for the next level of reinforcement, it was improved to 165.04 MPa as shown in Figure 8.

Based on the uniform dispersion of filler material in polymer, the strength of the composites was improved. By adding these natural fibres (foxtail palm), the adhesive force developed between fibres, matrix, and E-glass mat was improved, which in terms improves the flexural strength [24].

During experimentation, the load acts at the centre of the specimen at a speed of 3 mm/min. Due to the presence of strong bonding in the matrix material and fibres, which leads to transfer of the stresses and hence the flexural stress improved for the specimen [4].

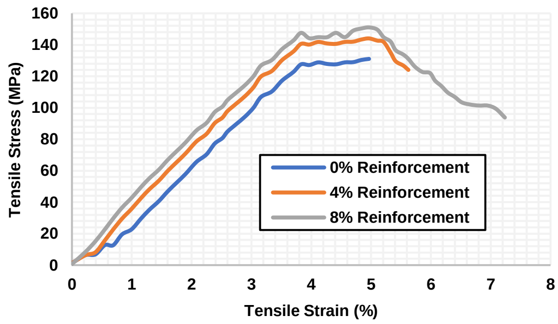

Figure 7. Stress-strain diagram during tensile testing

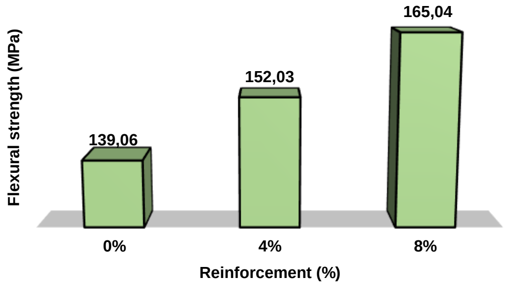

Figure 8. Flexural strength for fabricated composites

The stress-strain diagram of flexural properties for the three specimens is shown in Figure 9. By comparing the experimental flexural strength data with previous work [28, 30, 31], it was notice that better values were obtained with lesser reinforcements of other natural fibres.

Hardness is also an important material property, which defines resisting against the penetration of an object into the specimen. Based on the experimental results, the hardness property also follows the same trend as tensile and flexural. The hardness property was improved by the filler material reinforcement percentages as shown in Figure 10. The hardness properties improved by 6.32% for 4% reinforcement and 12.65% for 8% reinforcement of filler material. The present experimental data on mechanical properties are compared with the previous work and it was noticed with good agreement as shown in Table 1f. From Table1, it is observed that the tensile strength for 12% foxtail millet husks is recorded as 135 MPa whereas our study reported 135.35 MPa for 8% reinforcement level which is very close. Likewise, the flexural strength for a 10% coir filler material varied from 110 to 180 MPa and the present study reported 165 MPa. The high flexural strength for natural composite materials is due to stress transformation. Finally, the hardness

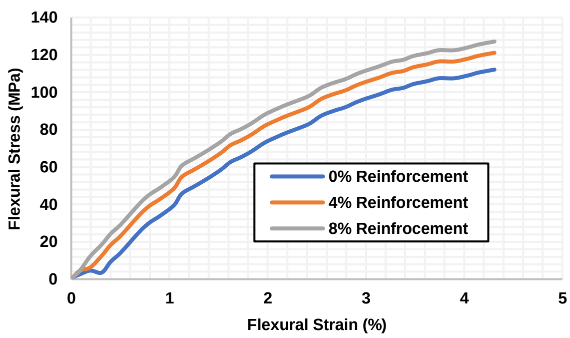

Figure 9. Stress-strain diagram during flexural testing

Table 1. Comparison with the previous works

S. No.	Filler Material	Reinforcement Level	Tensile Strength (MPa)	Flexural Strength (MPa)	Hardness	Ref.
1	Foxtail Palm Fibres	0%, 4% & 8%	102.53, 124.63 & 132.35	139.06, 152.03 & 165.04	79, 84 & 89	Present work
2	Pineapple leaf-based fibers	10%	79.98	138.45	79.58	[28]
3	Coir	10%	131-220	110-180	-	[29]
4	Pineapple	10%	170-1627	-	-	[30]
5	Banana	10%	161.8	-	-	[30]
6	Piassava	9%	134–143	-	-	[30]
7	Date palm	10%	135	-	-	[30]
8	Agave/pine	12%	24.0	28.5	-	[30]
9	Sisal/banana	10%	57	91	-	[30]
10	Fox tail millet husks	12%	135	231	93	[31]

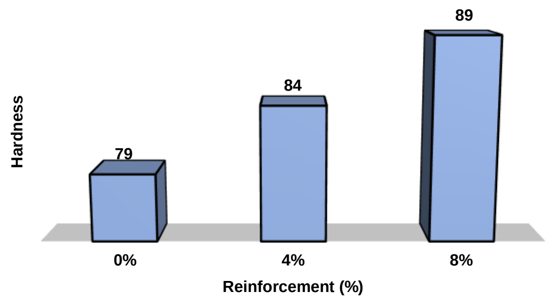

Figure 10. Hardness property

results for 10% pineapple leaf-based fibers and 12% foxtail millet husks results are near to 8% foxtail palm fibers. Analyzing the mechanical property for the natural composite materials helps in producing fully green composites which may help in the construction of green building materials.

CONCLUSION

In this work, the mechanical properties like tensile strength, stiffness, and hardness properties were evaluated and it was observed that an increase in the proportion of foxtail palm fiber reinforcement (0%, 4%, 8%) led to improved mechanical properties. The tensile strength was improved by 22.43% and 29.08% for 4% & 8% filler reinforcement. The stiffness property was also improved by 9.32% to 18.68% for 4% & 8% of foxtail fibres. Similarly, the hardness property was improved by 6.32% & 12.65% respectively.The SEM analysis reveals the interfacial bonding between the reinforcement and fiber pullout and crack propagation. Overall, foxtail fruit fibre shows promise as a reinforcing agent in composite materials, improving their mechanical properties and making them suitable for various applications requiring strength, stiffness, and resistance to deformation.

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