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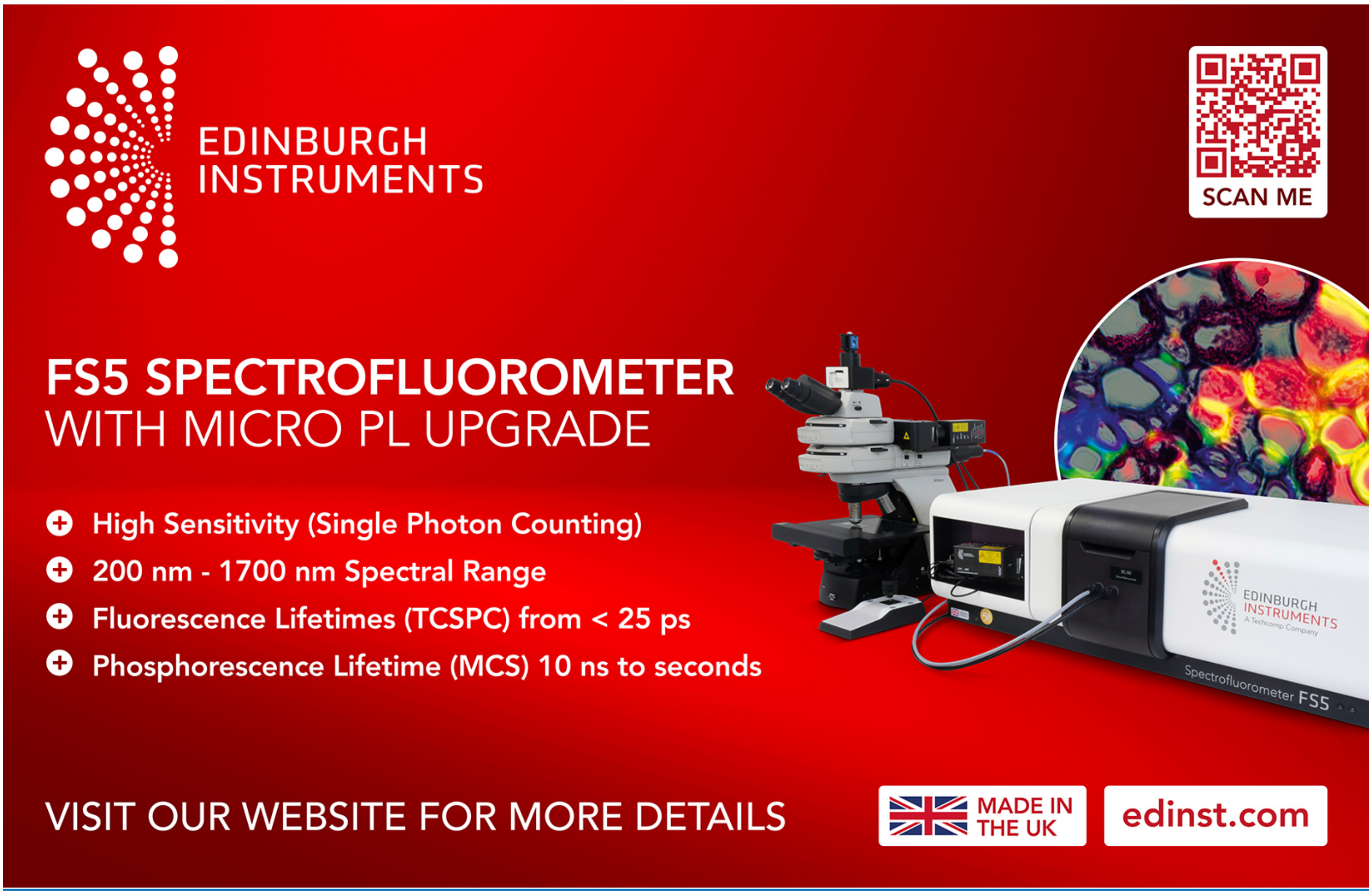

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# Mechanical, tribological and modal characteristics of eco-friendly coir/sugarcane fillers reinforced polymer composites

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**Keywords:** natural composite, coir and sugarcane, mechanical characterization, tribological analysis, modal response

## Abstract

Polymer-based composites have been drawing the attention of the research community for many decades, not only in academia but also in industry. However, continuously increasing environmental concerns have led the researchers to focus on natural composite materials. This is a challenge for researchers to develop a natural composite without compromising the composites' excellent mechanical properties and tribological performance. In this research, coir and sugarcane are selected as the natural fillers, and epoxy resin has been chosen for matrix material. To look into the crystallinity of composites, XRD analysis was done. In addition, a mechanical study was done to look at the manufactured composites' tensile and flexural characteristics. The tribological performance (i.e., wear rate and friction coefficient) of the composite samples is investigated by using a pin-on-disc setup. The parameters such as filler loading and normal load affecting the tribological performance of epoxy-based natural composites are studied. The results show that the wear and friction characteristics of the composite reinforced with sugarcane and coir were 10.78% and 57.80% lower than those of the neat composite, respectively.

## 1. Introduction

Natural plant fibers have become more significant in the recent past, whereas the utilization of manufactured fibers like glass and other synthetic fibers in plastics has been reduced [1]. Natural plant fibers are extremely rigid and strong [2]. All natural plant fibers contain cellulose fibrils, which provide mechanical strength to the fiber. The structure, microfibrils angle, cell size and defects, and cannabinoid makeup of plant fibers are the most important factors influencing their overall properties [3]. Plant fibers generally exhibit an increase in Young's modulus and tensile strength in proportion to their cellulose content. Natural fiber can be thought of as a composite material composed of cellulose, hemicelluoses, phytic acid, lignin, and waxes. Natural fiber composites have an advantage over synthetic fiber composites because of their cost effectiveness, lower density, higher strength, superior thermal insulating qualities, less tool wear, availability of renewable resources, and capacity for recycling without harming the environment [4, 5]. Growing public awareness of the harm synthetic materials pose to the environment has led to the development of eco-friendly materials. Researchers' attention has been sparked by the development of such materials that can substitute synthetic materials [6, 7]. Consequently, there has been a rise in demand in recent years for natural nutrient composites for commercial usage across a range of industrial industries [8, 9]. Natural fibers have excellent specific characteristics and are inexpensive, lightweight, and biodegradable. They are also readily available and ecologically acceptable materials [10]. Natural fiber-based composite materials are becoming more and more popular in a variety of production sectors due to their sustainability. Different types of nature-based fibers that include sisal, coconut fibers, banana fibers, jute, and many others are being used by the researchers for developing the green composites having improved mechanical properties and better tribological performance [11, 12].

Leitner *et al* [13] extracted the nanofibrils from sugar beet cellulose sources by a high-pressure homogenization process. Thus obtained nanofibrils were made into sheet form by slowly evaporating water content from the cellulose nanofibrils. The cellulose nanosheets were tested for strength and stiffness and compared with cellulose sheets made of non-homogeneous cellulose nanofibers. The composites gave better results. Uetani and Yono [14] reported the successful isolation of nanofibrils from cellulose pulp sources by chemical pretreatment followed by the homogenization process and compared them with the nanofibrils obtained from the grinding process. The nanofibrils from the homogenization process were highly crystalline compared with the fibrils from the grinding process. Phong *et al* [15] extracted cellulose microfibrils from raw bamboo fiber using steam explosion and alkaline treatment. Their findings demonstrated that, in comparison to the mechanical qualities acquired by the steam explosion technique, the fibrils derived from the alkaline treatment demonstrated superior performance. Tensile, flexural, and impact characteristics of natural composites produced from powdered coconut shell and sugarcane bagasse were investigated by Gokul *et al* [16].

Kumar *et al* [17] conducted a study on bio-filler-based polymer composites and found that the incorporation of bio-filler up to 9% significantly improved the mechanical performance of epoxy composites. Green filler-reinforced polymer composites have the best tribological performance, making them suitable for biomedical, aerospace, and automotive applications [18]. On the one hand, rising environmental awareness and the need for more adaptable polymer-based materials have sparked growing interest in polymer composites with natural-organic fillers, or fillers derived from renewable sources and biodegradable [19]. Theja and co-workers [20] explored the potential of tea dust filler to be used in the development of epoxy composite. They discovered that adding tea dust fillers to the epoxy matrix up to 40% volume resulted in excellent mechanical behavior in the developed composites. In a study, two types of natural fillers, viz., corn straw powder and jasmine leaf powder, were used for developing a polyester-based composite and tested the developed composite for its tribological properties. The results showed a remarkable improvement in the composite's tribological behavior [21]. In another study, two natural fillers (i.e., powder of palm leaves and mango leaves) were used as the natural fillers to develop polyester composite. The results indicated that these natural fillers were effective in reducing both the water absorption rate and the friction coefficient of the developed composites [22].

The manufacture of a polymer composite with an epoxy matrix and micron-sized bamboo filler is examined by Kumar *et al* [23]. Their findings demonstrated that the filler content had a substantial impact on the composite's static and dynamic characteristics. The effect of nano-oil palm empty fruit bunch (OPEFB) fillers on the dynamic mechanical characteristics of epoxy composites is assessed by Saba *et al* [24]. According to their findings, adding 3% of nano-OPEFB filler considerably enhances the dynamic characteristics of the composites. The wear and frictional characteristics of treated microcoir filler-reinforced polymer composites were studied by Paul and Bhowmik [25]. Their findings indicate that filler reinforcement and operation settings have a significant impact on wear behavior. The mechanical and wear behavior of agricultural waste thorn nanoparticles reinforced with epoxy was investigated by Balakrishnan *et al* [26]. According to their findings, filler-containing nanocomposites increase wear resistance by 9.03%. The wear characteristics of composite reinforced with coconut coir, rice straw, jute fiber, sugarcane bagasse, and neem wood powder were investigated by Kumar *et al* [27]. Their results show that an increase in neem wood powder content improves the composite's wear properties. The wear and friction properties of polyester composites reinforced with banana fiber and fly ash were investigated by Kannan *et al* [28]. They discovered that the main factors influencing wear rate and coefficient of friction were load and filler content. Gopalan *et al* [29] used experiments to examine the tensile and flexural properties of fly ash, coir fiber, and sugarcane fiber reinforced polymer composites. The effects of coconut shell filler on the characteristics of polyester composites made of banana fiber were studied by Kannan Thangaraju [30]. Their findings indicate that the addition of coconut shell filler enhances the tensile, flexural, and thermal stability of the material.

Following diverse literature investigations, several studies on natural filler-based composites to measure mechanical behavior were discovered. Thus, it is crucial to comprehend how natural filler reinforcement affects the modal, tribological, and mechanical characteristics of composites. In order to fabricate the hybrid composite, a variety of techniques are taken into consideration, including heat treatment, chemical treatment, and crushing the fibers. Once the material has been fabricated, assess its crystallinity and conduct experimental mechanical characterization to determine its tensile and flexural characteristics. Tribological behavior is assessed using a digital display-controlled pin-on-disc test. Using the impulse hammer test, the produced hybrid composite's modal behavior was also evaluated.

## 2. Fabrication of composites

The primary materials used are sugarcane and coir fibers, which have been treated with 5% NaOH and left to dry. A matrix consisting of hardener (HY 951) and epoxy resin (LY 556) was utilized. The composite specimens were created using the open-mold casting technique. Using this technique, the composite components are poured into a mold, allowed to cure, and then taken out to be processed further. The coir and sugarcane fibers had been treated with 5% NaOH for 1 h [31], and then the treated fibers were washed with distilled water to remove any residual alkalies. Next, the fibers are placed for sun drying for 24 h, followed by an oven at 60 °C for 1 h. After that, the treated fibers were crushed using a mechanical crusher. Following crushing, the materials were sieved to ensure a consistent particle size of 1–2 mm. To construct the composite specimens, the fillers were combined with a resin matrix and then poured into the mold of size 200 × 100 mm. The finished composite underwent three hours of post-curing at 70 °C in an oven. Improving the composite material's mechanical qualities requires the post-curing procedure. Better adherence between the fillers and resin matrix is made possible by this approach, which produces a finished product that is stronger and more durable. After that, the composites were cut to the proper sizes in compliance with ASTM guidelines so that mechanical testing could be done. Figure 1 displays the composite specimens that were prepared. Table 1 shows the composition of the fabricated composites.

## 3. Characterization of composites

### 3.1. X ray diffraction

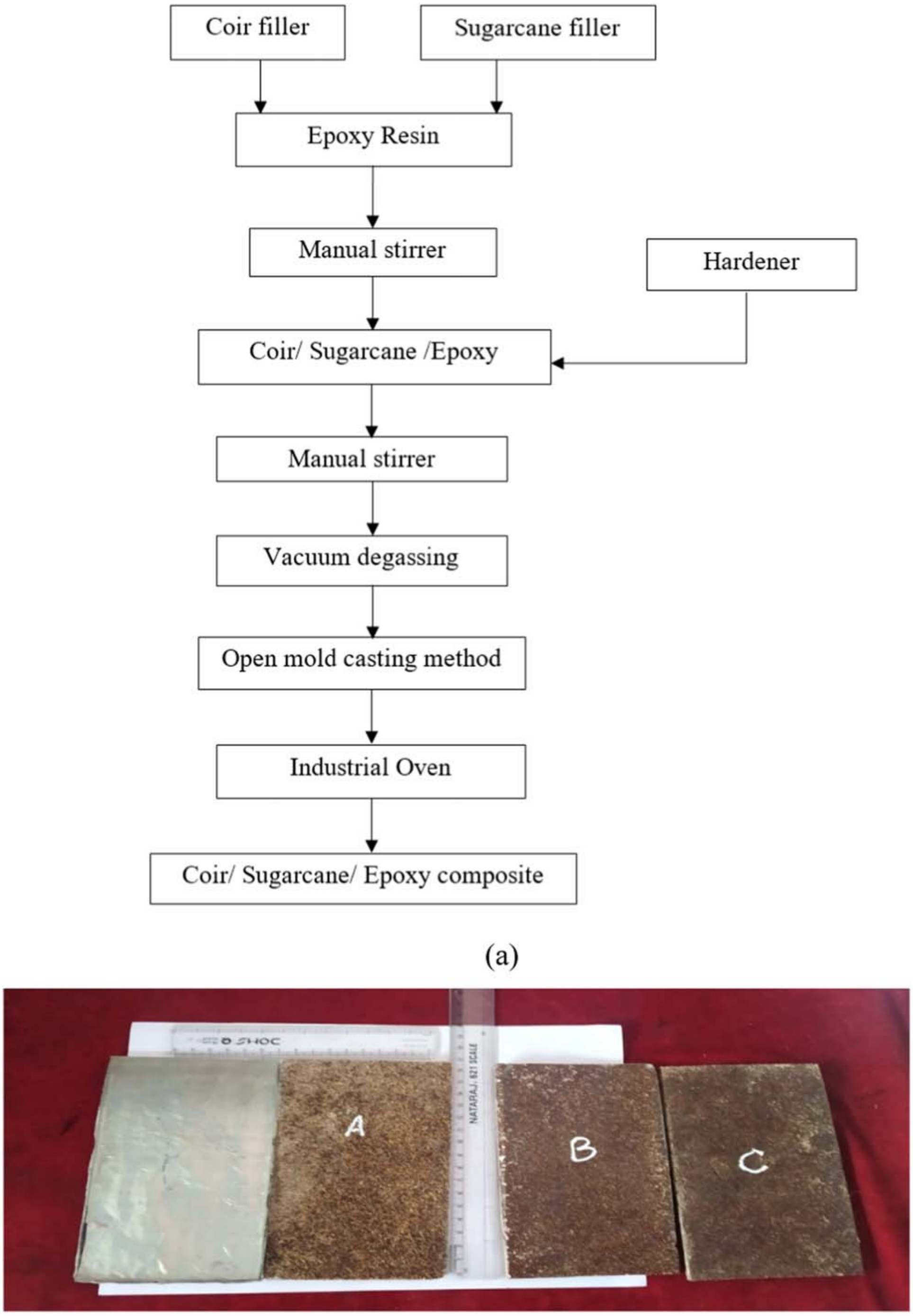
The XRD patterns (figure 2) of the NaOH-treated fibers got a new peak around 25°, and its intensity got reduced, and a new peak emerged around 30°. With an increase in treated coir fiber content, the peak around 25° was diminished. The crystallinity of the composite is the result of interchain hydrogen bonding. As a result of NaOH treatment, bagasse fibers have active hydrogen groups that form strong bonds with epoxy functionalities. The full width at half maximum intensity (FWHM) on the corrected diffraction profile can be used to determine the crystallite size and the highest crystallite size obtained with high sugar cane content, and this subsided with a decrease in sugarcane content. The crystallinity index (Icr) of three different compositions is: C10S10 obtained 83.59%, C12S8 obtained 28.3%, and C15S5 obtained 91%. Thus, the highest concentration of coir content received the highest crystalline structure. The crystal sizes for C10S10, C12S8 and C15S5 composites are 0.0582, 0.0697, and 0.0672. A lower crystallite size results in a broader peak intensity. The crystallite size is independent of the sample's crystallinity index.

### 3.2. Flexural test

Flexural testing is carried out in accordance with ASTM D790 standard using the universal testing apparatus. A span length of 50 mm between the supports was selected for every sample. Figure 3 displays the photograph of the fabricated flexural test samples. The loading rate used for testing was 2 mm per minute. Three identical samples were inspected and the corresponding average results were used for the analysis. Figure 4 shows the load-deflection data for the composites with varying filler weight percentages. According to the data, the C15S5 composite outperformed the other composites in terms of maximum load carrying capacity. This increase in load carrying capacity may be due to the higher weight percentage of coir in the composite material. The flexural properties of the manufactured composite at various filler loadings are shown in figure 5. The composite exhibits a 57.85% gain in flexural strength compared to the neat composite, rising from 7.64 MPa to 12.06 MPa. It can also be observed that the flexural strength of the C10S10 composite is higher than that of the C12S8 composite. This significant increase in flexural strength is caused by the fillers' reinforcing activity. Overall, the findings imply that adding fillers can greatly enhance the composites' flexural characteristics.

### 3.3. Tensile test

The ASTM standard D638-14 was applied for the tensile testing of the hybrid composite. A load rate of 1 mm $\text{min}^{-1}$ was used for this test. This test is performed on the Shimadzu agx plus equipment with the tensile test attachment. In figure 6, the testing setup for tensile testing is displayed. An average result was obtained after three identical specimens with different filler weight fractions were assessed for composite construction. The tensile test was performed in order to investigate how the hybrid composites' tensile characteristics were affected by the filler reinforcement. Figure 7 makes it clear that, in comparison to the other composites, the C15S5 composites handled the most load. This is due to the fact that a higher percentage of coir filler appears to increase load carrying capacity, whereas a higher percentage of sugarcane filler has the opposite effect. Additionally, it can be seen that filler-reinforced composites have larger loads than neat composites. Figure 8 displays the tested materials' tensile strength. It has been shown that the addition of filler increases the tensile properties of composites. The C10S10, C12S8, and C15S5 composites had tensile strength improvements of 11.76%, 19.57%



(a)

(b)

**Figure 1.** (a) Flow chart of the fabrication process (b) Fabricated composite specimens.

**Table 1.** Composite composition (wt%).

| Composite identification | Composite composition |
|---|---|
| C0S0 | Neat Epoxy |
| C10S10 | 80% Epoxy + 10% Coir + 10% Sugarcane |
| C12S8 | 80% Epoxy + 12% Coir + 8% Sugarcane |
| C15S5 | 80% Epoxy + 15% Coir + 5% Sugarcane |

and 38.84% respectively. The alkali treated surface of the fiber enhanced the interfacial contact between the filler and matrix, contributing to an increase in the tensile properties. According to early reports, the greatest improvement in tensile characteristics was obtained with a 5% NaOH treatment [31]. This may be as a result of

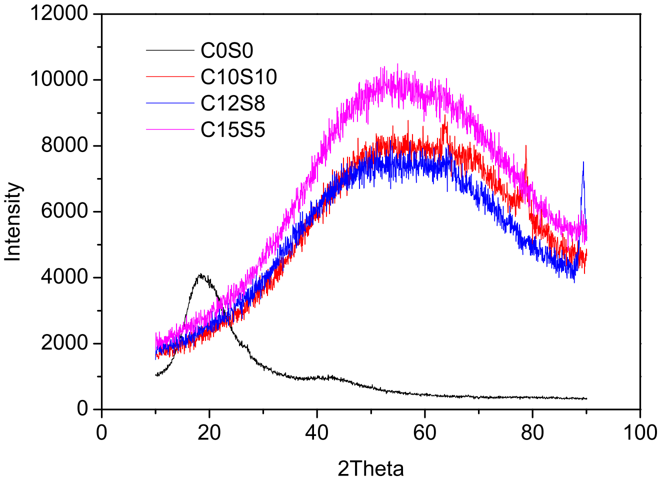


**Figure 2.** X-ray diffraction spectra of hybrid composites.

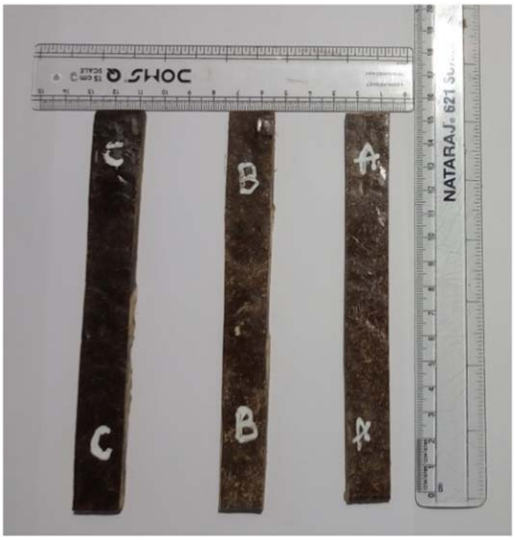


**Figure 3.** Fabricated samples.

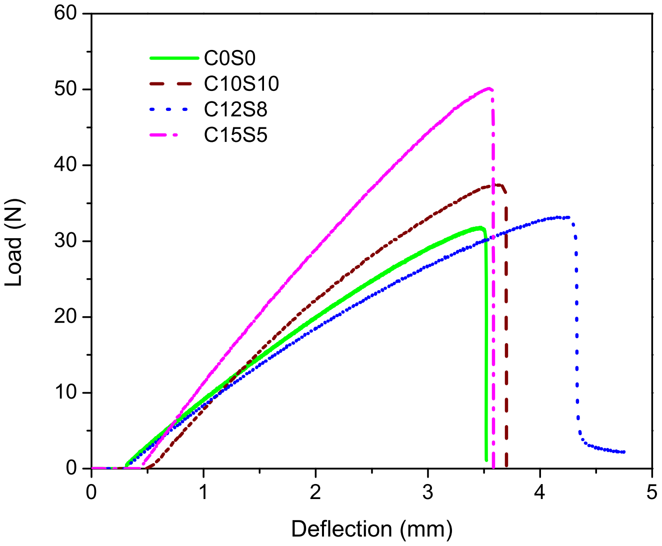


**Figure 4.** Flexural load deflection graph.

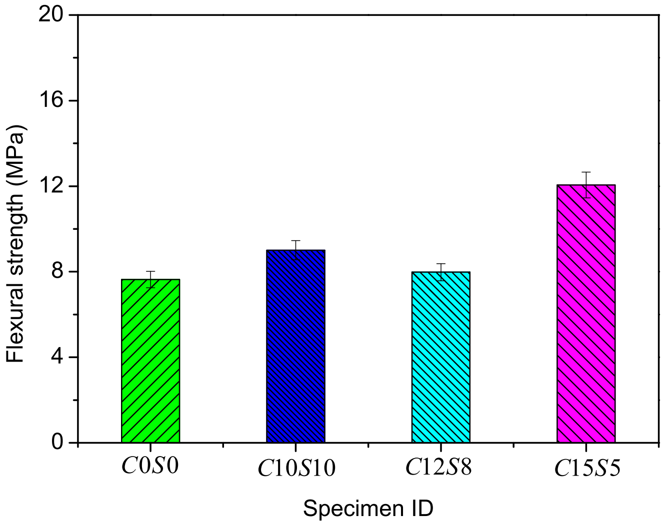


**Figure 5.** Flexural test results of various composite.

**Figure 6.** Tensile test setup.

the fillers' increasing load-bearing capacity in the composite sample. The outcomes showed that, in comparison to the individual components, the hybrid composite had better tensile characteristics.

## 4. Tribological characterization

A pin-on-disc tester shown in figure 9 was used to assess the tribological characteristics of hybrid composite specimens under dry sliding contact conditions. A pin-on-disc tester under dry sliding (ambient temperature) contact conditions was used for the test set up. The test pin is pressed against the surface with corresponding loads.

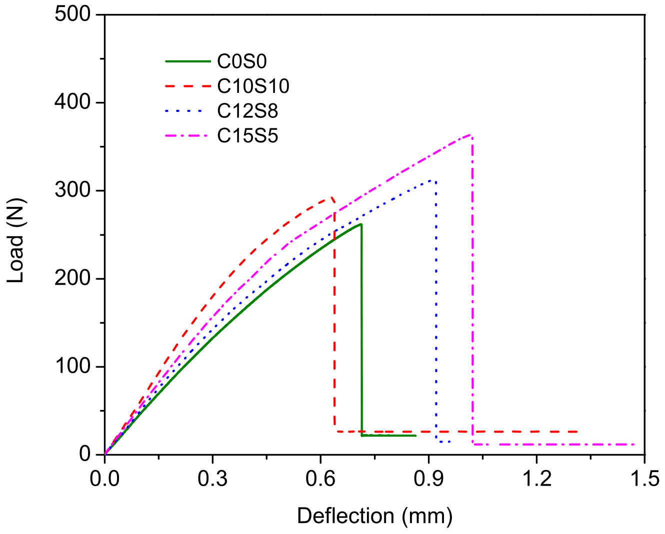


**Figure 7.** Tensile load deflection graph.

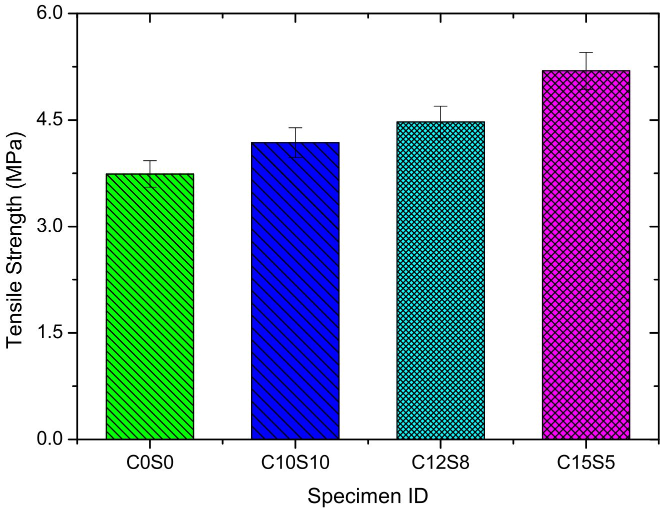


**Figure 8.** Tensile test results of various composite.

The friction disk got a diameter of 165 mm and a depth of 8 mm, EN-31 hardened steel with a hardness of 50–62 HRC and a surface roughness value (Ra) of 0.55–0.65 micrometers. The experiments were carried out at different loads (5, 10, 15, and 20 N) in order to assess the hybrid composites' wear and friction characteristics. A test pin with matching loads is placed up against the surface. According to ASTM G99 standards, the composite pin has dimensions of 12 mm in diameter and 20 mm in length. The parameters used for the testing are shown in table 2.

Table 3 shows the weight loss of C0S0, C10S10, C12S8 and C15S5 composites under various loads. The weight loss of the C0S0, C10S10, C12S8, and C15S5 composites at 5 N load are 0.1285, 0.0288, 0.0028 and 0.0021 respectively. The C15S5 composite obtained the lowest weight loss compared to all the composites under different loads. This suggests that when exposed to varying loads, the C15S5 composite exhibits the most resistance to weight loss. Further, the wear rate of composites is analyzed, and the results are presented in figure 10. It can be observed that the C15S5 and C12S8 composites obtained the lowest wear loss, and the C10S10 and C0S0 composites received the highest wear rate. These results imply that the wear resistance of the composites is greatly impacted by the addition of sugarcane and coir in various ratios. According to the findings, wear loss increases with the amount of coir in the composite. Because of the tensile characteristics of coir fibers, composites with a higher coir content are therefore more susceptible to wear.

Figures 10 and 11 show that the C10S10, C12S8, and C15S5 composite achieved a 10.78%, 59.90%, 78.14% reduction in wear rate and a 57.80%, 39.60%, 12.43% decrease in friction factor (FF) under the 5 N load configuration compared to neat composite. For the 20 N load configuration, there was an 18.82%, 9%, 14.02%

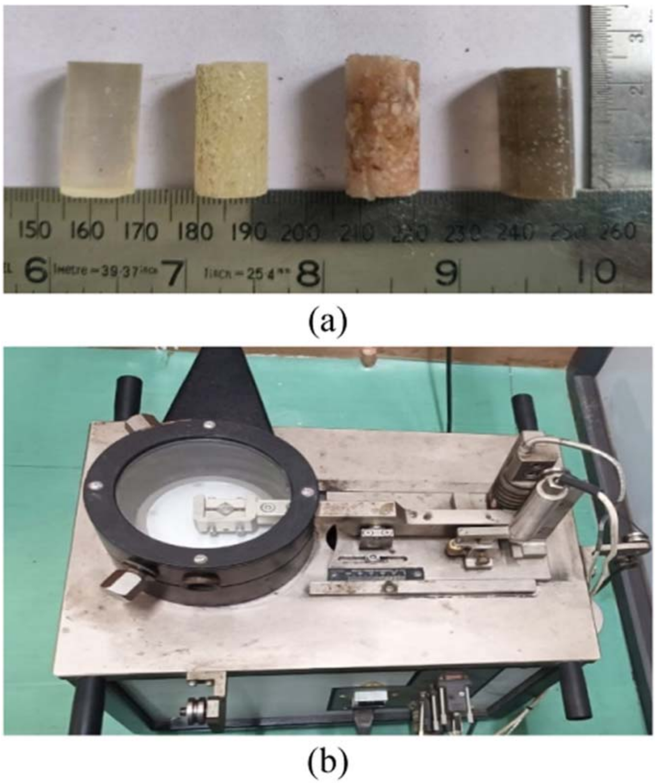


**Figure 9.** (a) Test specimens (b) Pin on disc wear test setup.

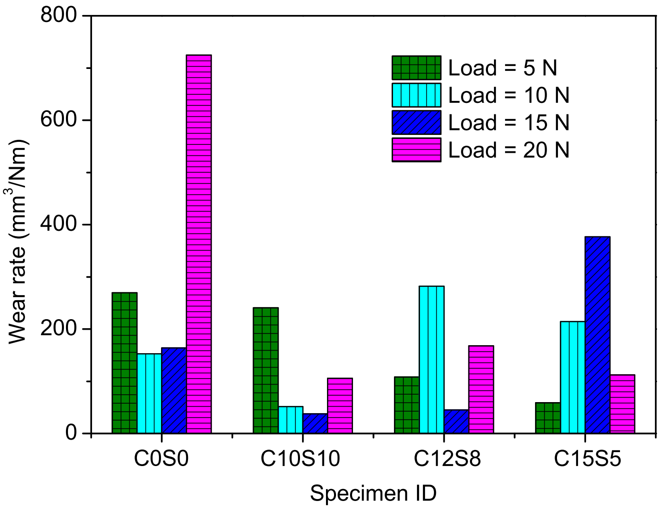


**Figure 10.** Wear rate ($mm^3$/Nm) for different samples.

**Table 2.** Testing conditions of the different tribological tests.

| Parameter | Pin on disc |
|---|---|
| Contact condition | sliding |
| Average circumferential speed | 5–20 rpm |
| Contact load | 5, 10, 15, 20 N |
| Test duration | 15 min |

reduction in FF and an 85.42%, 76.83%, 84.52% reduction in wear rate obtained for the C10S10, C12S8, and C15S5 composites. Equal concentrations of filler are responsible for the decreased wear rate for 5 N and 20 N loads. For 10 N and 15 N loads, the wear rate subsided due to an increase in the concentration of coir fiber, where

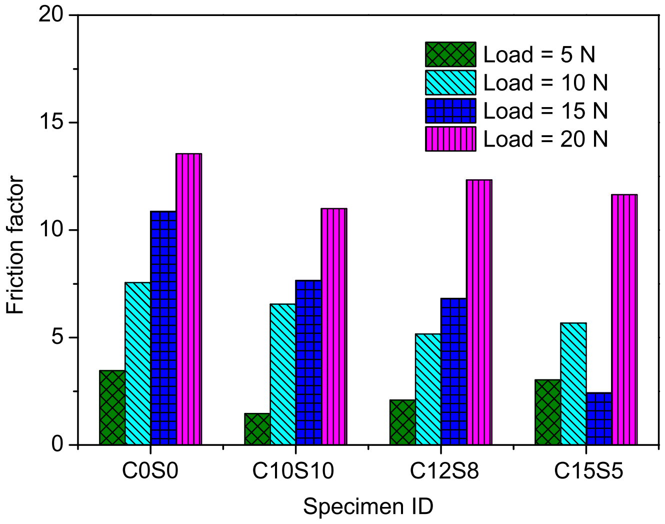


**Figure 11.** Friction factor for different concentration.

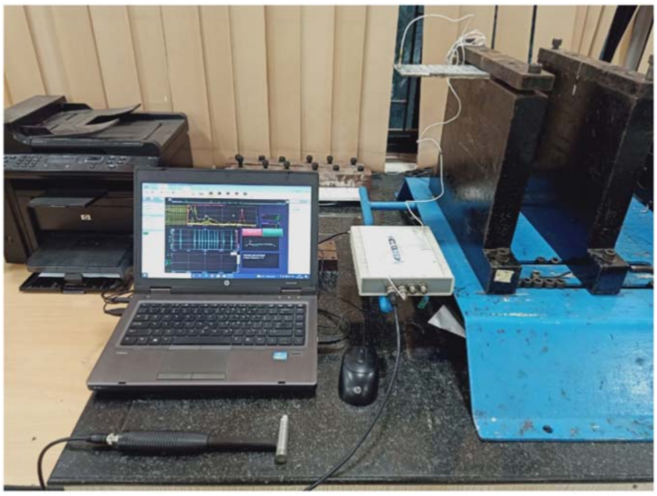
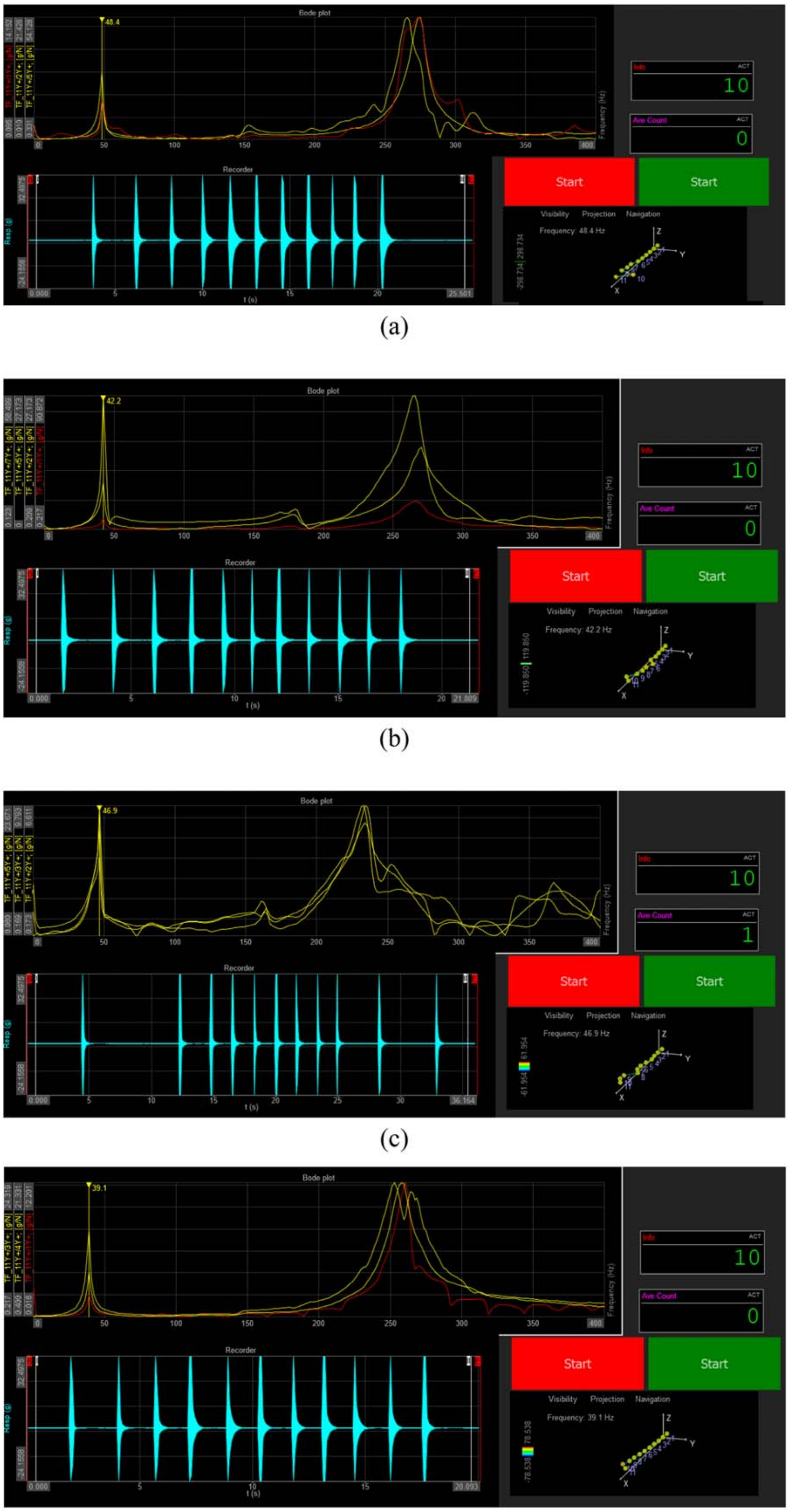


**Figure 12.** Experimental test setup.

**Table 3.** Weight loss in the sample.

| Sample | Load | Before weight | After weight | Difference |
|---|---|---|---|---|
| C0S0 | 5 | 3.8484 | 3.7199 | 0.1285 |
| | 10 | 3.8094 | 3.7199 | 0.0895 |
| | 15 | 3.8162 | 3.7312 | 0.085 |
| | 20 | 3.8321 | 3.7227 | 0.1094 |
| C10S10 | 5 | 3.8664 | 3.8376 | 0.0288 |
| | 10 | 3.8484 | 3.8373 | 0.0111 |
| | 15 | 3.9183 | 3.1382 | 0.0699 |
| | 20 | 3.8664 | 3.8484 | 0.018 |
| C12S8 | 5 | 3.7227 | 3.7199 | 0.0028 |
| | 10 | 3.7524 | 3.7312 | 0.0212 |
| | 15 | 3.7312 | 3.7227 | 0.0085 |
| | 20 | 3.7199 | 3.705 | 0.0149 |
| C15S5 | 5 | 3.8094 | 3.8073 | 0.0021 |
| | 10 | 3.8162 | 3.8094 | 0.0068 |
| | 15 | 3.8321 | 3.8162 | 0.0159 |
| | 20 | 3.8073 | 3.7977 | 0.0096 |



(a)

(b)

(c)

(d)

**Figure 13.** Experimental vibration response (a) C10S10 (b) C12S8 (c) C15S5 (d) C0S0.

the alkali-treated coir fiber epoxy bonding was responsible for the decrease in wear rate. However, the C12S8 composite had the lowest reduction in FF and wear rate at 20 N and 10 N, respectively. Thus, an increase in sugarcane filler hardly contributes to the wear resistance; this can be due to the low-density nature of the sugarcane filler and easy flocculation.

From figure 11, it can be observed that the friction factor increased linearly in all composites as the load increased. The friction coefficient generates heat between the two surfaces, causing the polymer surfaces to wear. However, the filler-reinforced composite surfaces dissipate and absorb this heat, preventing it from spreading. The wear life of a material is determined by contact pressure and sliding velocity. The NaOH reacts with the hydroxyl groups of the hemicellulose, thereby destroying the cellular structure and further splitting the fibers into filaments. As a result, the filler matrix exhibits a higher level of interfacial interaction. At lower concentrations, alkali treatment resulted in better interfacial adhesion along with better fibrillation of the fillers, thereby enhancing their mechanical properties.

The average friction factor was 6.7 for C10S10, 6.6 for C12S8, 5.69 for C15S5 composites, and the average wear rate was 108 for C10S10, 151 for C12S8, and 191 for C15S5 composites, where the wear rate increased with the coir content and the friction factor decreased. The wear rate influences linearly with time and increased loads. The contact temperature will slightly increase, thereby causing the polymeric chains to break at a temperature of 300 °C–450 °C. The degradation temperature of coir fibers (degradation in 358–469 °C) is less than that of sugarcane fiber (degradation starts above 500 °C). The degradation temperature of coir falls in the range of epoxy, thereby the breakage of the chemical bonds will be delayed compared to the surface functionalities of coir filler-epoxy. Thus, the wear rate is lower with increased sugarcane filler. The findings showed that, in comparison to the individual components, the hybrid composite specimens had better tribological performance. This shows that the hybrid composites' friction and wear characteristics were improved by the synergistic effects of the components' combination.

## 5. Modal characterization

The fabricated composite specimen is used to demonstrate the modal analysis of the hybrid composites (figure 12). For the experiments, C0S0, C10S10, C12S8 and C15S5 composites were employed. The data acquisition system (DAQ) was linked to the computer system before the composite specimen was set on the fixed free boundary condition. The accelerometer, which was positioned at the top layer of the composite specimen and could receive reaction signals from the stimulation, was used to measure the impact hammer's effect on the specimen. The response signal was converted into a frequency response function (FRF) by means of the DAQ, as demonstrated by the Dewesoft software display unit. Figure 13 shows the experimental findings for the composites C0S0, C10S10, C12S8, and C15S5. The fundamental natural frequencies of the C0S0, C10S10, C12S8, and C15S5 composites are 39.1, 48.4, 42.2, and 46.9, respectively. The C10S10 composite exhibited the highest natural frequency among the composites tested. This is due to the fact that the higher percentage of sugarcane in the C10S10 may contribute to a higher stiffness, while the higher percentage of coir in the C15S5 may result in a higher load-withstand capacity. Overall, the addition of filler material positively impacted the stiffness of the composite.

## 6. Conclusions

The tensile, flexural, tribology, and modal characteristics of polymer composites filled with natural fillers were investigated in this work. An open mold casting method was employed to create the hybrid composite. By adjusting the weight percentage of coir and sugarcane fillers, several compositions may be produced. The following summarizes and presents the key conclusions:

- Polymer composites' tensile strength increased by 38.84% with the inclusion of filler. Among the composites reinforced with filler, the one with 15% coir and 5% sugarcane filler had the maximum strength.
- Furthermore, the flexural strength was 57.85% higher than neat composites. This is due to the enhanced surface bonding between the fillers and the matrix material.
- The composite sample with fillers had 10.78% lower wear characteristics than the neat composite. It was also found that the friction characteristics of filler-reinforced composites are 57.80% less than those of neat composites.
- In addition, compared to the composite without filler, hybrid composites show an increase in natural frequencies.

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## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Declaration of competing interest

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

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