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Research Article

Mechanical and FTIR Characterization of Hybrid Composites Reinforced with Coconut Coir Fiber and Pine Fruit Peel Powder

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Abstract

This research looks into the tensile, impact, and Fourier Transform Infrared Spectroscopy (FTIR) characteristics of hybrid composites reinforced using alkali-treated coconut coir fibers and pine fruit peel powder in an epoxy resin matrix. Coconut coir fibers were extracted using a four-day water retting method and then treated with 3 wt.% NaOH for 2 h to increase fiber-matrix interfacial adhesion. The volume fractions of coconut coir fibers (CF) (5%, 10%, and 15%) and pine fruit peel powder (SP) (10%, 20%, and 30%) were varied to form hybrid composites. The CF5/SP10 composite demonstrated the maximum tensile strength (25.61 MPa) and impact strength (46.5 kJ/m²) in the study. The CF15/SP20 composite has the highest modulus of elasticity (1.46 GPa). Increasing the fiber and filler contents beyond the optimal level often decreased mechanical performance, which may be associated with reinforcement agglomeration, insufficient matrix wetting, and the formation of stress concentration sites. FTIR examination revealed the existence of cellulose, hemicellulose, lignin, and epoxy functional groups. The lower intensity of hydroxyl-related absorption bands suggested potential improvement in fiber–matrix compatibility following alkali treatment. These studies show that coconut coir fiber and pine fruit peel powder can be used as sustainable reinforcements for lightweight engineering composites.

Keywords: Coconut coir fiber; Pine fruit peel powder; Hybrid composite; Tensile strength; Impact strength

The Technology Readiness Level (TRL) of this research is Level 3 (Proof of Concept), as the proposed technology has been successfully demonstrated through the fabrication of hybrid composites reinforced with coconut coir fiber and pine fruit peel powder using an epoxy matrix. Laboratory-scale validation was conducted through tensile, impact, and FTIR characterization. The results demonstrate that the developed material possesses favorable mechanical properties and chemical characteristics for sustainable composite applications, confirming the technology concept through experimental laboratory verification.

1. Introduction

Natural fiber-reinforced polymer composites have emerged as a promising alternative to synthetic fiber composites due to their low density, biodegradability, renewability, and cost-effectiveness. In recent years, growing environmental concerns and the demand for sustainable engineering materials have accelerated the adoption of natural fiber composites in automotive, construction, and consumer product applications. These materials offer a favorable balance between mechanical performance and environmental sustainability, making them attractive candidates for lightweight structural components [1], [2]. However, improving the mechanical properties and interfacial compatibility of natural fiber composites remains a significant challenge that must be overcome to expand their industrial utilization.

Among the various natural fibers available, coconut coir fiber has attracted considerable attention as a reinforcing material due to its high lignin content, excellent toughness, and resistance to microbial degradation. As an abundant agricultural byproduct in many tropical countries, coconut coir is a sustainable and low-cost reinforcement source for polymer composites [3], [4]. Previous studies have shown that coconut coir fiber can effectively enhance the mechanical performance of polymer matrices when adequate interfacial bonding is achieved. Hasan et al. [5] reported that coconut fiber-reinforced composites exhibited improved tensile and impact properties when sufficient fiber-matrix adhesion was established. To improve this adhesion, alkali treatment is generally applied to natural fibers to remove surface impurities, wax, hemicellulose, and some lignin while increasing surface roughness. This modification improves stress transfer between the reinforcement and the matrix, thereby improving the overall mechanical performance of the composite. In addition, epoxy resins are widely used as matrix materials due to their excellent mechanical properties and strong adhesion to natural fibers, which contribute to effective load transfer and structural integrity [6], [7].

Recent developments in sustainable composite technology also emphasize the utilization of agricultural and forestry waste as particulate fillers. Pine fruit peel is a lignocellulosic biomass containing cellulose, hemicellulose, and lignin, which can contribute to the strengthening effect when incorporated into a polymer matrix. Previous studies have shown that lignocellulosic fillers can improve stiffness, dimensional stability, and interfacial interactions while promoting waste utilization and sustainable material development [3]. To further improve composite performance, researchers are increasingly exploring hybrid reinforcement strategies by combining natural fibers with particulate fillers or additional fibers. Das et al. [8] reported that jute–coir hybrid composites showed significant improvements in tensile strength, tensile modulus, and impact strength compared to pure coir composites due to the synergistic interaction between the two natural fibers. Similarly, Fitri et al. [9] demonstrated that hybrid epoxy composites reinforced with coconut fiber and bagasse achieved improved tensile performance, with the optimal fiber combination yielding a tensile strength of 30.48 MPa. More recently, Sruthi et al. [10] revealed that hybrid composites reinforced with coconut fibers exhibited enhanced strength and energy absorption capabilities, highlighting the effectiveness of the hybrid reinforcement approach.

Although substantial progress has been made in the development of hybrid natural fiber composites and those reinforced with coconut fiber, research on the combined use of coconut coir fiber and pine fruit peel powder as a hybrid reinforcement remains limited. Existing studies primarily focus on hybridization involving different natural fibers, while the potential contribution of pine fruit peel powder as a lignocellulosic particulate reinforcement has received less attention. Furthermore, information regarding the effect of pine fruit peel powder on tensile behavior, impact resistance, and chemical interactions in coconut fiber-based hybrid composites is still scarce. Consequently, the reinforcing potential of pine fruit peel powder and its interaction with the epoxy matrix is not yet fully understood.

Therefore, this study investigated the mechanical and chemical characteristics of hybrid epoxy composites reinforced with coconut coir fiber and pine fruit peel powder. Tensile testing was conducted to evaluate the strength, stiffness, and elongation behavior of the composites, while impact testing was conducted to assess their energy absorption capabilities. In addition, Fourier Transform Infrared Spectroscopy (FTIR) analysis was used to identify the functional groups present and to examine the chemical interactions between the composite constituents. The findings of this study are expected to contribute to the development of sustainable hybrid composite materials derived from agricultural and forestry wastes while providing a better understanding of the role of pine fruit peel powder in improving composite performance.

2. Methods

2.1. Materials

Coconut coir fibers for this investigation were sourced from local coconut processing trash. Prior to composite manufacturing, the fibers were alkalized with a 3 wt.% sodium hydroxide (NaOH) solution to promote fiber-matrix interfacial adhesion. Pine fruit peels were gathered from naturally falling pine fruits and ground into powder. Epoxy resin and its hardener were chosen as the matrix system due to their high mechanical qualities, low shrinkage, chemical resistance, and great adherence to natural fibers.

2.2. Preparation of Reinforcement Materials

The preparation procedures of coconut coir fibers and pine fruit peel powder are illustrated in **Figure 1**. The coconut coir fibers employed in this investigation were sourced from local coconut processing waste. Water retting was used to extract the coconut coir fibers. Coconut husks were soaked in water for four days to facilitate fiber separation from the lignocellulosic matrix and soften the husk structure. After retting, the softened coconut husks were manually processed using a combing technique to separate and extract individual fibers. The recovered fibers

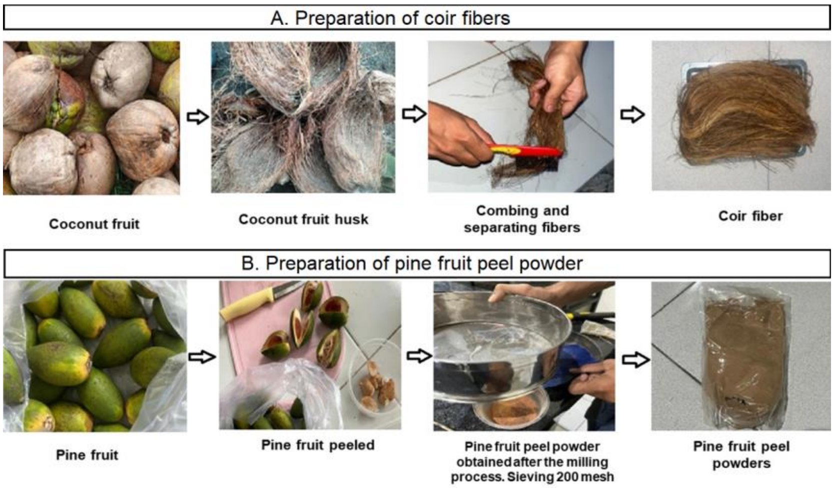

Figure 1. Preparation of coir fibers and pine fruit peel powders

were rinsed with clean water to remove contaminants and residual organic matter. The fibers were then air-dried under ambient conditions until a constant weight was achieved to reduce moisture content before further treatment.

Subsequently, the coconut coir fibers were treated with a 3 wt.% NaOH solution for 2 h at room temperature. This treatment was intended to remove surface impurities, waxes, hemicellulose, and part of the lignin content, thereby increasing surface roughness and improving fiber–matrix interfacial adhesion. After alkali treatment, the fibers were thoroughly rinsed with distilled water until a neutral pH was reached and then air-dried to eliminate residual moisture. Finally, the fibers were cut into 40 mm lengths and used as reinforcement in the composite fabrication process. In parallel, pine fruits were peeled to obtain the peel material, which was subsequently cleaned, sun-dried, and oven-dried at 80°C for 24 h. The dried peels were then milled and sieved through a 200-mesh screen to obtain a uniform particle size before being stored in sealed containers to prevent moisture absorption.

2.3. Fabrication of Hybrid Composites

Hybrid composites were fabricated using a hand lay-up technique followed by compression molding. The epoxy resin and hardener were mixed according to the manufacturer's recommended ratio and stirred thoroughly until a homogeneous mixture was obtained. The treated coconut coir fibers (CF) and pine fruit peel powder (SP) were then incorporated into the epoxy matrix based on the formulations designed for this study. The volume fractions of CF, SP, and epoxy used in each composite formulation are presented in Table 1. The total reinforcement content varied from 15 to 45 vol.% depending on the composite composition.

The CF and SP reinforcements were gradually mixed into the epoxy matrix to promote uniform dispersion and minimize particle agglomeration. The resulting mixture was poured into a mold coated with a releasing agent and distributed evenly throughout the mold cavity. Compression molding was subsequently applied to improve matrix impregnation and reduce the possibility of void formation within the composite structure. After molding, the composites were cured at ambient temperature for 24 h and then post-cured at 80 °C for 2 h to ensure complete crosslinking of the epoxy matrix. Following the curing process, the composite laminates were removed from the mold and machined into standard specimens for tensile, impact, and FTIR characterization. For convenience, each composite formulation was identified using a sample code based on its coconut coir fiber (CF) and pine fruit peel powder (SP) contents, as presented in Table 1.

Table 1. Volume fractions of coconut coir fiber (CF), pine fruit peel powder (SP), and epoxy used in the hybrid composites

Sample Code	CF (%vol)	SP (%vol)	Epoxy (%vol)
CF5/SP10	5	10	85
CF5/SP20	5	20	75
CF5/SP30	5	30	65
CF10/SP10	10	10	80
CF10/SP20	10	20	70
CF10/SP30	10	30	60
CF15/SP10	15	10	75
CF15/SP20	15	20	65
CF15/SP30	15	30	55

2.4. Characterization techniques

2.4.1. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was used to determine the functional groups found in the hybrid composites and to look into potential chemical interactions between the matrix, CP, and SP. The FTIR spectra were obtained using an FTIR spectrometer within the wavenumber band of 4000-400 cm^{-1}, with a resolution of 4 cm^{-1}, and 32 scans per sample at room temperature. The acquired spectra were examined to identify typical absorption bands for cellulose, hemicellulose, lignin, and matrix epoxy constituents.

2.4.2. Tensile test

Tensile testing was performed to assess the tensile strength and modulus of the composites. The specimens were prepared in accordance with ASTM D3039 [11]. A Universal Testing Machine (UTM) was used for the test. at room temperature and a crosshead speed of 5 mm/min. Eq. (1) was used to compute the tensile strength [12].

$$\sigma = \frac{F}{A} \tag{1}$$

where, σ = tensile strength (MPa); F = maximum load applied (N); A = initial cross-sectional area of the specimen (mm^2). For each composition, three specimens were tested, and the average value together with the standard deviation was reported. Due to the limited number of specimens, statistical significance analysis was not performed and is acknowledged as a limitation of the present study.

2.4.3. Impact test

The hybrid composites' ability to absorb energy was evaluated by impact testing. The specimens were manufactured in accordance with ASTM D256 standards [13] utilizing a Charpy setup. A pendulum impact tester was used to carry out the test. The absorbed impact energy was measured directly from the testing equipment and utilized to calculate impact strength using Eq. (2) [14].

$$IS = \frac{E}{A} \tag{2}$$

where, IS = impact strength (kJ/m^2); E = absorbed impact energy (J); A = fractured cross-sectional area (m^2). Three specimens were tested for each composition, and the average value together with the standard deviation was reported. However, statistical significance analysis was not conducted because of the limited number of specimens.

3. Results and Discussion

3.1. FTIR analysis

The FTIR spectra of the hybrid composites reinforced with alkali-treated coconut coir fibers and pine fruit peel powder are presented in **Figure 2**. The spectra exhibit several characteristic absorption bands associated with the lignocellulosic constituents of the natural reinforcements and the epoxy matrix. Although variations in fiber and filler content were introduced, the overall spectral profiles remain similar, indicating that the composite constituents are chemically compatible and no new functional groups were formed during the fabrication process. A broad absorption band observed in the range of 3200–3400 cm^{-1} corresponds to the stretching vibration of hydroxyl (O–H) groups originating from cellulose, hemicellulose, and residual lignin present in the CF and SP [15]. The presence of this peak confirms the lignocellulosic nature of the reinforcements. However, the relatively reduced intensity of the O-H band is consistent with previous studies on alkali-treated coir fibers, where NaOH treatment partially removes hemicellulose, waxes, and surface impurities from the fiber surface [16]. Similar observations have been reported in alkali-treated natural fiber composites, where NaOH treatment reduces non-cellulosic components and improves fiber–matrix interfacial bonding. The

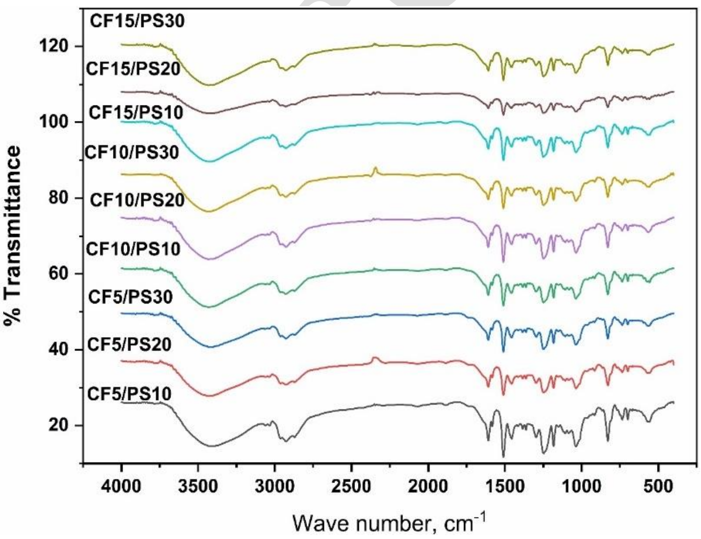

Figure 2. FTIR spectra of hybrid composites reinforced with alkali-treated coconut coir fibers and pine fruit peel powder at different reinforcement compositions (CF5/SP10, CF5/SP20, CF5/SP30, CF10/SP10, CF10/SP20, CF10/SP30, CF15/SP10, CF15/SP20, and CF15/SP30)

absorption peaks located around 2920–2850 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrations of aliphatic C–H bonds [17]. These bands are commonly associated with cellulose, hemicellulose, lignin, and organic compounds present in both the natural reinforcements and the epoxy matrix. The presence of these peaks indicates the retention of the lignocellulosic backbone structure after alkali treatment.

In the region of 1600–1500 cm^{-1}, distinct absorption bands are observed and can be assigned to aromatic C=C stretching vibrations originating from lignin and the aromatic rings present in the epoxy resin structure. The persistence of these peaks indicates that lignin is still present within the reinforcement materials despite partial removal during alkali treatment [12]. Furthermore, the aromatic structure of the epoxy matrix contributes significantly to the intensity of this region. The absorption bands detected between 1450 and 1370 cm^{-1} are associated with CH_2 and CH_3 bending vibrations [18]. These peaks are commonly observed in natural fiber-reinforced epoxy composites and indicate the presence of both lignocellulosic constituents and polymeric matrix components. The relatively consistent intensity of these bands across all composite compositions suggests that the incorporation of pine fruit peel powder does not significantly alter the fundamental chemical structure of the composite.

Although no new functional groups were detected, slight differences in peak intensity were observed among the composite formulations. Increasing the coconut coir fiber content from 5 vol.% to 15 vol.% tended to increase the intensity of cellulose-related absorption bands due to the greater contribution of lignocellulosic constituents. Similarly, increasing the pine fruit peel powder content slightly enhanced lignin-associated absorption bands, reflecting the lignocellulosic nature of the filler. These observations indicate that the reinforcement loading mainly influences the relative abundance of existing functional groups rather than inducing new chemical interactions within the composite system.

Another important spectral region appears between 1240 and 1030 cm^{-1}, where several peaks are attributed to C–O, C–O–C, and ether group vibrations. These functional groups are characteristic of cellulose and epoxy resin networks [19], [20]. The presence of these bands confirms the interaction between the hydroxyl groups of the natural reinforcements and the epoxy matrix. Although no new absorption peaks are observed, slight variations in peak intensity among different compositions indicate changes in intermolecular interactions and interfacial adhesion resulting from variations in fiber and filler loading. In the lower wavenumber region, approximately 900–700 cm^{-1}, several absorption bands are observed corresponding to aromatic ring deformation and out-of-plane C–H bending vibrations associated with the epoxy matrix [21], [22]. These peaks further confirm the successful incorporation of epoxy resin within the hybrid composite structure. Finally, the FTIR spectra reveal that the fabricated composites contain the characteristic functional groups of cellulose, hemicellulose, lignin, and epoxy resin. The absence of significant peak shifts or the formation of new absorption bands suggests that the interaction between the CF, SP, and epoxy matrix is predominantly physical rather than chemical. Nevertheless, the observed variations in peak intensity may indicate improved interfacial compatibility following alkali treatment; however, this interpretation is inferred from the composite spectra and supported by previous literature because untreated fiber spectra were not analyzed in the present study. These findings support the tensile and impact test results, where the effectiveness of reinforcement depends largely on the quality of interfacial bonding and stress transfer between the matrix and reinforcement phases. The major FTIR absorption bands identified in the hybrid composites are summarized in **Table 2**.

The FTIR results are consistent with the mechanical characterisation findings. The FTIR results suggest that NaOH treatment may have contributed to improved interfacial adhesion between the CF and the epoxy matrix, consistent with observations reported in previous studies [16], [18]. As a result, composites with balanced reinforcement levels had superior tensile and impact capabilities, whereas excessive filler loading impaired mechanical properties due to agglomeration and the creation of stress concentration sites. A direct comparison between untreated and alkali-treated

Table 2. Main FTIR absorption bands identified in the hybrid composites

Peak (cm^{-1})	Assignment	Constituent	Refs.
3200–3400	O-H stretching	Cellulose, hemicellulose	[16]
2920–2850	C-H stretching	Cellulose, lignin	[17]
1600–1500	Aromatic C=C stretching	Lignin, epoxy	[18]
1450–1370	CH_2 / CH_3 bending	Lignocellulosic structure	[18]
1240–1030	C-O-C stretching	Cellulose, epoxy	[19], [20]
900–700	Aromatic deformation	Epoxy resin	[21], [22]

coconut coir fibers was not conducted in the present work. Therefore, the effect of NaOH treatment was inferred from the observed spectral characteristics and relevant literature reports.

3.2. Tensile strength analysis

Figure 3 shows the tensile strength of hybrid composites reinforced with coconut coir fiber (CF) and pine fruit peel powder (SP). Overall, variations in fiber and filler content affect the tensile strength of the composites. For the composite containing 5 vol.% CF, the highest tensile strength was obtained at SP10 (25.61 MPa), indicating that the relatively low filler loading promotes more efficient stress transfer between the epoxy matrix and the reinforcement. However, increasing the SP content to 20 and 30 vol.% reduced the tensile strength to 16.26 MPa and 18.86 MPa, respectively. This decrease may be related to particle agglomeration and weaker interfacial bonding, which are commonly observed in natural fiber composites with high filler content. For the composite containing 10 vol.% CF, the tensile strength was relatively stable, with the highest value recorded at SP20 (22.28MPa). These results indicate that a balanced combination of fiber and particulate reinforcement can improve the load transfer efficiency in composite structures. However, further increasing the filler content to SP30 decreased the tensile strength to 16.12 MPa, possibly due to increased void formation and fiber-matrix discontinuities. The tensile strength of composites containing 15 vol.% CF ranged from 15.01 to 22.35 MPa, with the highest value obtained for SP20. This finding suggests that increasing fiber content does not always improve tensile performance, especially when the reinforcement dispersion becomes less uniform. Excessive fiber loading can lead to neps and insufficient wetting by the epoxy matrix. Overall, the highest tensile strength was achieved by CF5/SP10 (25.61 MPa), indicating that excessive reinforcement loading does not always improve mechanical performance. Nevertheless, CF10/SP20 provided a balanced combination of tensile strength, elastic modulus, and elongation.

Figure 3 also presents the elastic modulus of the hybrid composite. Variations in CF and SP content were found to affect the stiffness of the composite. For the CF5 composite, the modulus increased from 1.11 GPa at SP20 to 1.36 GPa at SP30, indicating that higher filler loading contributed to increased stiffness due to the relatively stiff nature of lignocellulosic particles. In contrast, the CF10 composite showed a fluctuating trend, with the highest modulus recorded at SP10 (1.31 GPa) and the lowest at SP30 (0.90 GPa). This decrease suggests that excessive filler loading can introduce structural imperfections that reduce stress transfer efficiency. For the CF15 composite, the modulus reached a maximum value of 1.46 GPa at SP20, indicating that the appropriate balance between fiber and filler content contributed to the increased stiffness of the composite. The increase in modulus can be attributed to enhanced reinforcement interactions and more effective stress transfer within the epoxy matrix. Overall, the results indicate that particle dispersion and fiber-matrix interactions have a greater influence on composite stiffness than fiber content alone.

Figure 3 further illustrates the elongation behavior of the composites. Elongation provides an indication of the composite's ductility and ability to deform before failure. For the CF5 composite, the elongation decreased from 3.43% in SP20 to 2.56% in SP30, indicating that increasing filler content tends to reduce ductility due to limited polymer chain mobility. For the CF10 composite, the highest elongation was observed in SP30 (5.54%), indicating that weak interfacial bonding may have contributed to the increased deformation before failure. Elongation values for the CF15 composite ranged from 2.87% to 4.87%, indicating variations in stress distribution within the composite structure. The relatively high ductility observed for CF15/SP10 may be related to the increased flexibility

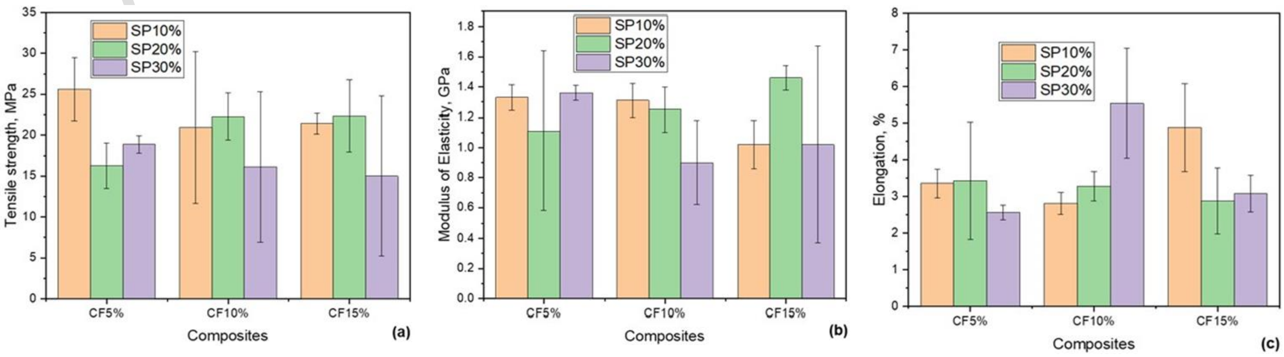

Figure 3. Mechanical properties of hybrid CF/SP composites epoxy, (a) Tensile strength, (b) Modulus of elasticity, and (c) Elongation

of the reinforcement network and greater energy absorption before failure. Overall, elongation behavior is influenced by the combined effects of fiber content, filler loading, and fiber-matrix interactions. An appropriate level of hybrid reinforcement can provide a balance between stiffness and deformability.

The findings clearly show that the mechanical properties of hybrid composites are highly influenced by the interplay of coconut coir fiber and pine fruit peel powder concentration. The combination of natural fiber with particle filler creates a hybrid reinforcing effect; nevertheless, excessive filler loading causes agglomeration, void formation, and poor interfacial bonding, all of which have a detrimental impact on mechanical performance. CF10/SP20 exhibited a balanced combination of tensile strength, modulus of elasticity, and elongation. However, the highest tensile strength was achieved by CF5/SP10. The maximum tensile strength obtained in the present study (25.61 MPa) is comparable to values reported for coir fiber-reinforced epoxy composites in previous studies, which generally range from approximately 18–30 MPa depending on fiber treatment and reinforcement loading [5], [6].

3.3. Impact strength analysis

Figure 4 shows the impact strength of hybrid composites reinforced with coconut coir fiber (CF) and pine fruit peel powder (SP). Overall, the results indicate that the impact resistance of the composites is affected by variations in fiber and filler content. Excessive reinforcement loading tends to reduce the composite's ability to absorb impact energy. For composites containing 5 vol.% CF, the highest impact strength was obtained with SP10, reaching 46.5 kJ/m^2. This result indicates that the composite structure is able to effectively dissipate impact energy through adequate matrix continuity and efficient stress transfer between the epoxy matrix and reinforcement. However, increasing the SP content to 20 and 30 vol.% reduced the impact strength to 30.4 kJ/m^2 and 28.8 kJ/m^2, respectively. This decrease is likely related to particle agglomeration and the formation of stress concentration sites, which can facilitate crack initiation and propagation under impact loading conditions. A similar trend was observed for the CF10 composite. Impact strength decreased from 43.2 kJ/m^2 in SP10 to 31.3 kJ/m^2 in SP30, while a moderate value of 36.7 kJ/m^2 was recorded in SP20. These results indicate that a balanced combination of fiber and filler can maintain adequate energy absorption capacity, while excessive filler loading can reduce composite toughness due to reduced matrix ductility and increased structural imperfections.

For composites containing 15 vol.% CF, impact strength ranged from 35.7 kJ/m^2 to 22.4 kJ/m^2, which is lower than that of composites CF5 and CF10. The decrease in impact strength at higher fiber loadings may be related to fiber agglomeration, inadequate fiber wetting, and increased void formation, although void density and content measurements were not performed in this study. These factors can reduce the quality of the interfacial bond and limit the composite's ability to absorb and transfer impact energy effectively [23], [24]. The results indicate that increasing the CF and SP content beyond the optimal level tends to reduce the impact strength. This behavior may be due to less uniform reinforcement dispersion, weaker interfacial interactions, and increasingly brittle nature of the composite at high reinforcement loads. Therefore, an appropriate balance between fiber and filler content is necessary to achieve a favorable combination of toughness and stiffness. The maximum impact strength of 46.5 kJ/m^2 obtained for CF5/SP10 is comparable to values reported for natural fiber-reinforced hybrid epoxy composites. These findings demonstrate the potential of combining coconut coir fiber and pine fruit peel powder to produce sustainable hybrid composites with good impact resistance and structural integrity.

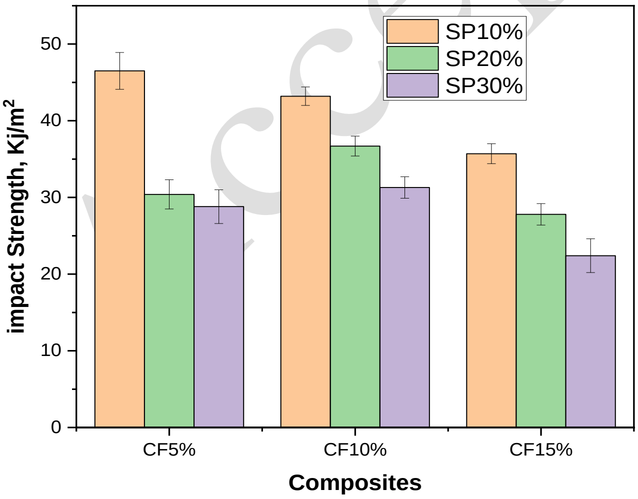

Figure 4. Impact strength of hybrid CF/SP composites epoxy

4. Conclusion

Hybrid composites reinforced with coconut coir fibers and pine fruit peel powder were successfully fabricated using an epoxy matrix. The highest tensile strength (25.61 MPa) and impact strength (46.5 kJ/m^2) were obtained for the CF5/SP10 composite, while the highest modulus of elasticity (1.46 GPa) was achieved by CF15/SP20. FTIR analysis identified the characteristic functional groups of cellulose, hemicellulose, lignin, and epoxy resin and suggested improved fiber–matrix compatibility following alkali treatment. The results indicate that the incorporation of coconut coir fibers and pine fruit peel powder can provide sustainable reinforcement for lightweight composite applications. Future studies should investigate density and void content, SEM morphology, alkali treatment concentration, particle size distribution, fiber orientation, and statistical reproducibility using a larger number of specimens to further clarify reinforcement interactions, failure mechanisms, and the long-term performance of the developed hybrid composites.

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Conflict of Interest - The authors declare that there are no conflicts of interest.

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