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DEVELOPMENT AND CHARACTERIZATION OF HYBRID POLYPROPYLENE COMPOSITES REINFORCED WITH CALOTROPIS GIGANTEA FIBER AND FLY ASH FOR ENHANCED MECHANICAL PROPERTIES

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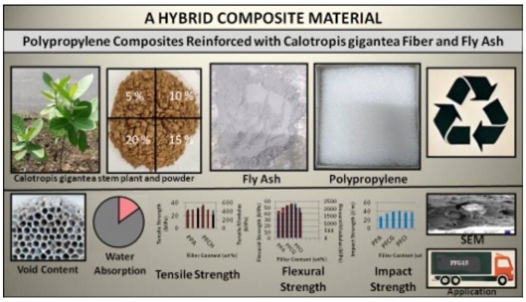
Graphical abstract



Abstract

Calotropis gigantea is a common weed found in several Asian countries, currently lacks industrial application and economic support to the region despite its excellent mechanical properties. This research focuses on the development and characterization of a novel hybrid composite material, incorporating Calotropis gigantea stem (CGS) fiber and fly ash (FA) as reinforcement materials within a polypropylene (PP) matrix at varying the weight percent of CGS fiber powder content at 5 weight percent, 10 weight percent, 15 weight percent, and 20 weight percent while maintaining a constant 10 weight percent fly ash content. The physical properties, including density, void content and water absorption and mechanical properties, including tensile strength, flexural strength, and impact resistance, were evaluated, demonstrating that the introduction of CGS fiber and fly ash significantly enhances the mechanical properties of the composites. The stress-strain curves and load-deflection behaviours were recorded. The maximum tensile strength, flexural strength and impact resistance was observed at 10 weight percent of CGS fiber and 10 weight percent of fly ash content. Furthermore, morphological studies using scanning electron microscopy (SEM) offered insights into the microstructural features, illustrating a well-integrated fiber-matrix interface and confirmed uniform distribution of reinforcements. This study introduces a sustainable approach to composite development by leveraging the mechanical benefits of CGS fiber and the cost-effectiveness of fly ash, offering a promising alternative for high-performance, environmentally friendly and to produce lighter weight composite materials.

Keywords: Calotropis gigantea fiber, Fly Ash, Polypropylene, Tensile Strength, Flexural strength, Impact strength, Scanning Electron Microscopy

1.0 INTRODUCTION

Natural fibers offer several advantages, including low cost, abundance, and renewability. Research has shown that natural fiber composites can achieve comparable mechanical properties to traditional composites while offering environmental benefits. In recent years, Rajmohan *et al.,* (2021) expressed that the development of composite materials has attracted considerable attention due to the growing demand for materials with enhanced mechanical and thermal properties [1]. Palanikumar *et al.,* (2016) stated that the traditional composites often rely on synthetic fibers, which can be costly and environmentally unfriendly [2]. Hanan *et al.,* (2018) reported that consequently, there has been a growing interest in exploring natural fibers as sustainable alternatives [3]. Natural fibers like jute, sisal, and hemp, have been extensively studied for their potential to reinforce polymer matrices. In this research, focused on the development of composites made from Calotropis gigantea fiber and fly ash as reinforcement in polymer matrix.

Calotropis gigantea, a plant known for its robust fibers, provides an eco-friendly reinforcement alternative. Vinod *et al.,* (2017) reported that the Calotropis gigantea is a common weed found in several Asian countries, including India, Indonesia, China, Malaysia, Pakistan, and Thailand [4]. Ashori *et al.*, (2009) and Huang *et al.,* (2016) indicated that the CGS fiber constitutes of higher percentage of hemicelluloses, cellulose and lignin which are more responsible for increase in strength [5, 6]. Vinod *et al.,* (2017) developed composite made from Calotropis gigantea stem powder, jute fibers, glass fiber, and epoxy resin, using the hand lay-up method, demonstrated enhanced tensile, flexural, compression, hardness, impact, and thermal properties when incorporating 10 weight percent of the Calotropis gigantea filler compared to 5 weight percent [4]. Singh *et al.,* (2015) studied that the Calotropis gigantea possesses toxic properties that can lead to symptoms such as diarrhea, vomiting, dilated pupils, and even death [7]. Ramesh *et al.,* (2020) prepared composite of Calotropis gigantea fiber with epoxy resin at different orientation and exhibited maximum strength in flexural, tensile, and impact test at 0° fiber orientation also thermal stability more than 600℃ [8]. Raja et al., (2023) fabricated hybrid composite material with Calotropis gigantean fiber reinforced with bran nano used as a filler blended epoxy resin, the inclusion of chopped Calotropis gigantea fibers resulted in an average improvement of 60% in tensile strength, flexural strength, and impact energy also bran nanofiller improved thermal stability [9]. K. Tamil Mannan *et al.,* (2022) prepared hybrid composite CG fiber reinforced (10,15,20,25 and 30 wt%) with Lime and Silicon nitide (5 wt%) as a filler, with epoxy resin as matrix, exhibited better mechanical properties compared to the composite without fillers [10]. Sahu *et al.,* (2023) developed composite material of CG bast fiber as a reinforcement material with epoxy resin as matrix, optimum mechanical properties were found at 20 wt% of fiber loading [11].

Fly ash, a by-product of coal combustion in power plants, is a desirable filler material because of its affordability, wide availability, and pozzolanic characteristics. The incorporation of fly ash into composites has been shown to improve thermal stability, reduce manufacturing costs, and contribute to waste management efforts by utilizing industrial by-products. Accordance with Sharma *et al.,* (2021) incorporating up to 10 weight percent of fly ash in glass fiber reinforced composite materials enhances both tensile and flexural strength [12]. Ou *et al.,* (2016) observed the physical and mechanical properties of basalt fiber reinforced epoxy composites containing fly ash. And found that as the percentage of fly ash increased, so did the void content within the composites. Notably, the basalt-epoxy composite with 10 weight percent fly ash resulted excellent mechanical properties compared with the others [13]. Satheesh *et al.,* (2014) predicted that the mechanical behaviour of composites is increased with the addition of 10 weight percent fly ash and fiber [14]. Raghavendra *et al.,* (2014) reported that the maximum tensile strength was achieved in jute-glass fiber-reinforced epoxy hybrid composites by the addition of 10 weight percent fly ash as filler [15]. Tambrallimath *et al.,* (2022) reported that composites reinforced with fly ash in an acrylonitrile butadiene styrene matrix showed an increase in tensile strength by 28.19 weight percent and 36.13 weight percent at 5 weight percent and 10 weight percent fly ash respectively, while the roughness of surface reduced by 9.64 weight percent and 14.6 weight percent at these same concentrations [16]. Sim *et al.,* (2020) found that fly ash-reinforced epoxy composites exhibited increased tensile strength with volume up to 30 weight percent fly ash for particle sizes of 90 µm and smaller, while compressive strength consistently increased with higher fly ash volume percentages [17]. Raghunandan *et al.,* (2022) reported that Fly ash has the great potential to serve as a sustainable reinforcement for the development of biocomposites, offering an alternative to conventional composites [18].

Khan *et al.,* (2019) demonstrated that jute fiber reinforced polypropylene composites resulted to improved tensile and flexural strength compared with pure polypropylene, highlighting the utilization of natural fibers in enhancing composite performance [19]. Chow *et al.,* (2007) explored sisal fiber-reinforced composites and investigated that with the addition of sisal fibers significantly enhanced the impact resistance and thermal stability of the composites [20]. Saleem *et al.,* (2020) investigated hybrid composites using bast fibers with glass, carbon, and basalt fibers, demonstrating enhanced mechanical properties and lower environmental impact in comparison to conventional composites [21].

The novelty of this study lies in the hybrid reinforcement of polypropylene (PP) using CGS fiber and fly ash, aimed at enhancing mechanical performance and sustainability. CGS fiber, a natural lignocellulosic material, provides tensile strength and structural reinforcement, while fly ash, an industrial byproduct, contributes to improved dimensional stability and thermal resistance. Based on previous research findings, the fly ash content kept at 10 weight percent while CGS fiber were varied at 5 weight percent, 10 weight percent, 15 weight percent, and 20 weight percent to evaluate its influence on composite behaviour. The hybrid composite materials were fabricated through melt blending and injection molding to ensure uniform dispersion and interfacial interaction. This composite is designed to exploit the synergistic effects of fibrous and particulate fillers, offering a technically sound and environmentally responsible approach to developing value added polymer composite.

The aim of this experiment was to create high-strength and sustainable hybrid composite materials for use in industrial product manufacturing by investigating the effects of incorporating fly ash, and CGS fiber reinforced with polymer matrix. The resulting hybrid composites were tested for mechanical characteristics such as tensile, flexural, and impact resistance. Morphological characteristics were examined using scanning electron microscopy (SEM).

2.0 MATERIALS AND METHODOLOGY

2.1 Materials Used

- Polypropylene: The materials were supplied by Khushi Entreprises, Nashik, India. A widely used thermoplastic polymer characterized by its low cost, chemical resistance, ease of processing and good mechanical properties. Commercial grade polypropylene with a melt flow index suitable for composite fabrication. It serves as the base material in which the reinforcements are embedded.
- Calotropis gigantea stem fiber powder: The materials were supplied Shivay Herbals and Healthcare, 341, Katewa Nagar, New Sanganer Road, Shyam Nagar, Jaipur (Rajasthan), India. Since it is a widely found weed plant, it can be effectively utilized as a filler material in polymer composites.
- Fly Ash**:** The materials were supplied by Nexoos Con and Chem, Navi Mumbai, Maharashtra, India. Fly ash, a waste product generated from coal-burning thermal power plants was obtained and utilized as a filler substance in composites. Its inclusion aims to enhance thermal stability and contribute to cost-effectiveness.

The CGS fiber powder and fly ash were dried and preheated in an oven at 60°C for duration of 2 hours prior to processing to removal of any remaining moisture. The blending was carried out in a twin-screw extruder at 180°C to 230°C, and test specimens were created by injection moulding the extruded strands after they had been pelletized at Institute of Chemical Technology, Mumbai, Maharashtra, India. The properties of the material are shown in Table 1.

Table 1 Properties of the material used for the composite

Material	Supplier	Melt Flow Index	Density g/cm^3	Melting Temp. ℃	Shape	References
Calotropis gigantea stem fiber powder	Shivay Herbals and Healthcare	—	1.67	220℃	Spherical	[18] (2023)
Polypropylene	Khushi Enterprises	230℃, 2-50 g/10 min	0.90	180	Granules	
Fly Ash	Nexoos Con & Chem	—	2.0	230	Spherical	

2.2 Material and Specimen Preparation

2.2.1 *Description of Calotropis gigantea Stem Fiber Powder Preparation*

The CGS fiber powder used in this study was procured directly from the supplier. According to the supplier and reported by Vinod et al. (2017), the CGS fiber powder is prepared by manually extracting the fibrous layer in its raw state from a weed plant (Figure 1a). The stems of Calotropis gigantea are harvested and sun-dried to eliminate moisture. Afterward, the dried stems are chopped into smaller pieces and ground into a fine powder to a mesh size of 100–150 [4]. The CGS fiber powder were preheated, before being incorporated into the polymer matrix to produce the hybrid composite (Figure 1b). Ashori et al. (2009) reported that the CGS fiber constitutes of higher percentage of holocellulose (mixture of hemicelluloses and cellulose) and lignin are 76%, and 18% respectively and other constituents are 6% [5].

Figure 1 (a) Calotropis gigantea stem plant

Figure 1 (b) Calotropis gigantea stem fiber powder

2.2.2 *Dry Blending*

Composites were prepared with varying weight percentages of CGS fiber powder at 5 weight percent, 10 weight percent, 15 weight percent, and 20 weight percent, while maintaining a constant 10 weight percent of fly ash reinforcement materials within a polypropylene (PP) matrix. The filler material fiber and fly ash were heated in an oven at 60°C for a duration of 2 hours to remove any remaining moisture and then left to cool down to room temperature (Sajith, 2019 and Wickramaarachchi *et al.,* 2021) [22, 23]. Mixing was done with a mechanical stirrer in various proportions of filler material for 10 minutes to ensure even distribution of the mixture. The particulate compositions of composite taken for mechanical test are shown in Table 2. The optimal mixture was achieved with 20 weight percent of CGS fiber. Exceeding this percentage leads to difficulties in mixing due to aggregation, resulting in an imperfect blend.

Table 2 Calotropis gigantea stem fiber, fly ash reinforced polymer matrix developed composites compositions

Composition of Composites	Polypropylene weight percent	Fly Ash weight percent	CGS fiber powder weight percent
PPA	100	-	-
PFB	90	10	-
PFCG	85	10	5
PFCH	80	10	10
PFCI	75	10	15
PFCJ	70	10	20

2.2.3 *The Melt Compounding*

The melt compounding of filler reinforced polymer matrix was carried out on synchronous twin screw extruder having 16 mm screw size, L/D ratio of 38:1 and screw rpm 60. The temperatures of the extruder zones for melt compounding are given in Table 3. The extruded composite material was pelletized on pelletizer. The rpm of the pelletizer machine was maintained in the range of 60-80 rpm.

Table 3 Temperatures of the extruder zones for melt compounding

	Zone1	Zone2	Zone3	Zone4	Die
Temperature (°C)	180	190	200	215	230

2.2.4 *Injection Molding*

An injection mold was employed to create test specimens for various mechanical properties. The mold, equipped with dies for tensile, flexural, and impact test specimens, was used to produce specimens accordance with ASTM standards for tensile, impact, and flexural testing. The temperatures of the injection molding machine for specimens are presented in Table 4. The specimen of composites taken for tensile, flexural and impact test are represented in Figure 2.

Table 4 Temperature of injection molding machine

Temperature	Zone1	Zone2	Zone3	Zone4	CoolingOil
Set value	260°C	255°C	230°C	230°C	55°C
Actual value	96°C	99°C	142°C	108°C	45°C

Figure 2(a) **Figure 2(b)** **Figure 2(c)**

Figure 2(a) Composite specimen for tensile test, (b) Composite specimen for flexural test, (c) Composite specimen for impact test

2.3 Physical And Mechanical Properties

The composite's physical properties were analysed for density, void content, and water absorption. For density measurement Archimedes principle was used, whereas for determination of void content ASTM D2734 was used. The behaviour of water absorption of the composite was evaluated as ASTM D570 standard. To calculate the tensile strength of each composite, five specimens were tested accordance with ASTM D638 Type I standards and guidelines. The specimens were tested for fracture using a universal testing machine (UTM) at Institute of Chemical Technology, Mumbai, Maharashtra, India, Serial No. 0512 on auto mode with a jaw speed set to 50 mm/min, travel limit 800 mm and load limit of 0-500 kg was used as shown in Figure 3(a). To determine flexural strength of each composite, five specimens were tested according to ASTM D790 standards. The test was conducted using a UTM at Shri Bhagubhai Mafatlal Polytechnic, Department of Plastic Engineering, Mumbai, Maharashtra, India, Serial No. 0229 under three point loading conditions on auto mode with a jaw speed set to 10 mm/min, travel limit 20 mm and load limit of 0-220 kg was used as shown in Figure 3(b). To determine impact resistance of each composite, five specimens using the IZOD impact test were tested accordance with ASTM D256 standards by using pendulum type with 2.7 J striker at Institute of Chemical Technology, Mumbai, Maharashtra, India Figure 3(c). For each specimen, the average results from five repetitions were reported.

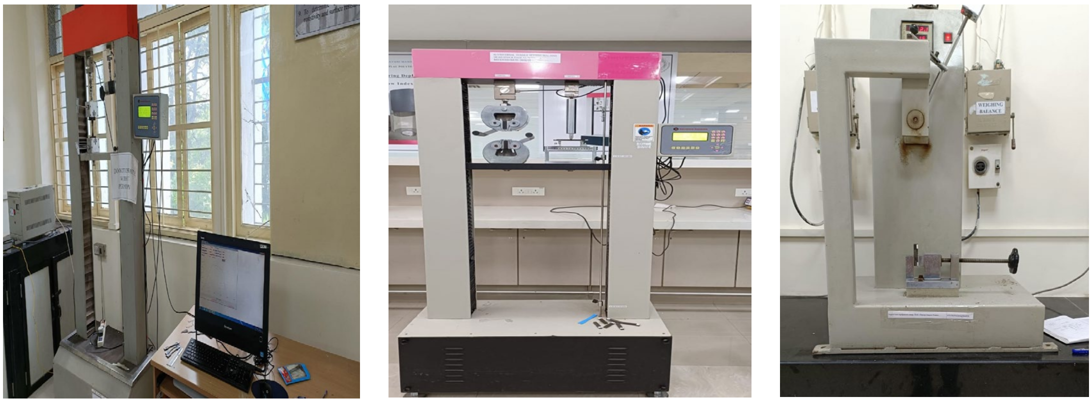


Figure 3(a) **Figure 3**(b) **Figure 3**(c)

Figure 3(a) UTM for Tensile (b) UTM for Flexural test (c) Izod Impact test for Impact resistance

2.4 Morphological Properties

Morphological analysis was conducted in accordance with ASTM D3171 using a Metrological Image Analyzer, model Zeiss Gemini 300 FESEM, Indian Institute of Technology, Mumbai, Maharashtra, India as shown in Figure 4. The Zeiss Gemini SEM 300 was a high-performance, variable-pressure Scanning Electron Microscope (SEM) equipped with a Schottky-type field emission gun and multiple detectors. These included in-lens and Everhart-Thornley secondary electron detectors, a variable-pressure secondary electron detector, an in-lens backscattered electron detector, and a multi-quadrant solid-state backscattered electron detector. The system was also equipped with Oxford EDS and EBSD detectors. To maintain hydrocarbon-free imaging, it utilized an oil-free vacuum system. Additionally, the SEM was equipped with an in situ reactive oxygen specimen cleaning system to ensure a clean imaging environment. The Atlas 5 software was available for large-scale mapping. The fractured specimen's surfaces had examined the microstructure of the composites, focusing on the interface between the fiber and matrix and the dispersion of reinforcement materials by SEM.

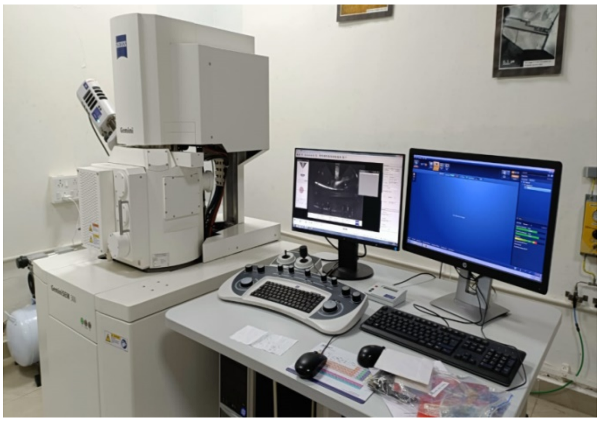


Figure 4 Scanning Electron Microscope

3.0 RESULT AND DISCUSSION

The experimental values of the tensile test, flexural test, and impact test conducted on the hybrid composite shown by scatter diagram, using Microsoft Excel to calculate the result of addition of the filler material as it effects on tensile strength, and impact strength. The results of the investigation of physical and mechanical properties are summarized in the following sections.

3.1 Physical Properties of the Composite

The assessed values of the physical properties of the hybrid composites, based on their composition, are presented in Table 5.

Table 5 Mean values and Standard Deviations (SD) for physical properties of the composite

Composition of Composites	PPA	PFB	PFCG	PFCH	PFCI	PFCJ
Density (g/cm^3)	0.90 ± 0.23	1.076 ± 0.45	1.082 ± 0.56	1.188 ± 0.63	1.053 ± 0.11	1.004 ± 0.32
Void content (%)	0.16 ± 0.015	0.18 ± 0.011	0.14 ± 0.052	0.12 ± 0.021	0.17 ± 0.025	0.23 ± 0.111
Water absorption (%)	0.10 ± 0.017	0.13 ± 0.021	0.15 ± 0.042	0.16 ± 0.034	0.19 ± 0.025	0.25 ± 0.021

The density of the tested composites varied slightly, ranging from 0.90 to 1.188 gm/cubic cm. The PFCH composite specimen had the lowest density, while the PFCJ specimen had the highest. The findings suggest that density values decreased as the content of CGS fibers increased. Additionally, it was measured that an increase in fiber content resulted in a higher void content in the composites. This increase in void content could be attributed to the structural interspaces caused by the higher fiber concentration. The composite PFB containing fly ash, showed the lowest void content at 0.18%, while the composite PFCJ, which included CGS fibers, showed the highest void content at 0.23%. Additionally, the water absorption capacity of the composites gets enlarged as fiber loading increases. This greater water uptake can be directly linked to the hygroscopic nature of the natural fibers used (Saw *et al.,* 2014) [24]. Furthermore, the structural interspaces caused by increased fiber content also contributed to higher water absorption. The hybrid composite with 20 weight percent CGS fiber loading demonstrated the highest water uptake at 0.25%, whereas the composite with 5 weight percent CGS had the lowest at 0.15%.

3.2 Mechanical Properties of the Composite

The assessed values of the mechanical properties of the hybrid composites, based on their composition, are presented in Table 6.

Table 6 Mean values and Standard Deviations (SD) for mechanical properties of the composite

Composition of Composites	PPA	PFB	PFGC	PFGD	PFGE	PFGF
Ultimate Tensile Strength (MPa) ± SD	25.71 ± 0.29	26.26 ± 0.62	30.59 ± 1.00	33.70 ± 0.54	21.58 ± 0.23	20.48. ± 2.03
Tensile Modulus (MPa) ± SD	421.21 ± 0.35	431.41 ± 0.88	438.00 ± 0.95	540.81 ± 0.10	424.48 ± 0.65	418.42 ± 0.05
Elongation at Yield (%)	20.94	11.02	11.45	11.01	11.17	10.20
Flexural Strength (MPa) ± SD	45.32 ± 0.25	50.66 ± 1.38	54.03 ± 2.45	56.13 ± 6.05	50.06 ± 2.15	42.05 ± 3.01
Flexural Modulus (MPa) ± SD	1624.07 ± 0.04	1710.05 ± 1.04	2165.25 ± 3.24	2323.57 ± 5.62	2367.87 ± 13.43	2045.36 ± 2.56
Impact resistance (J/m) ± SD	26.73 ± 0.16	34.37 ± 0.09	38.71 ± 0.04	39.06 ± 0.11	37.32 ± 0.10	36.45 ± 0.08

3.2.1 Tensile Strength and Tensile Modulus

The ultimate tensile strengths of the developed hybrid composites are summarized in Table 6. The neat polypropylene (PPA) demonstrated a tensile strength of 25.71 MPa. In contrast, the hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ showed improved tensile strengths of 26.26 MPa, 30.59 MPa, 33.70 MPa, 21.58 MPa, and 20.48 MPa, respectively, when compared to PPA (Figure 5). The tensile modulus of neat polypropylene (PPA) was recorded at 421.21 MPa. The hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ exhibited increased tensile moduli of 431.41 MPa, 438.00 MPa, 540.81 MPa, 424.48 MPa, and 418.42 MPa, respectively, compared to PPA (Figure 5). Additionally, the neat polypropylene (PPA) displayed an elongation of 20.94%. However, the hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ showed reduced elongations of 11.02%, 11.45%, 11.01%, 11.17%, and 10.20%, respectively, relative to PPA.

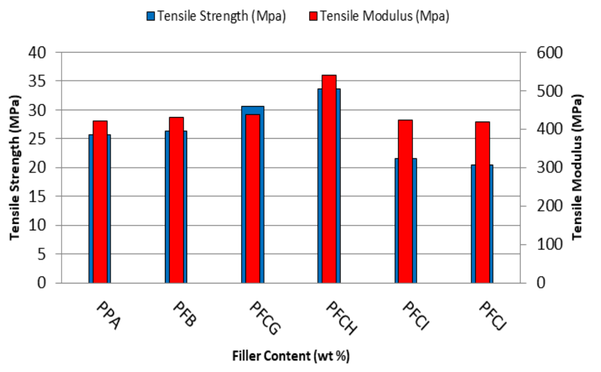


Figure 5 Tensile strength and Tensile modulus of the hybrid composite

Additionally, the CGS fiber at 10 weight percent, exhibited a higher tensile strength and 10 weight percent exhibited a higher tensile modulus compared with other composition. The tensile properties of natural fiber contribute to improving the tensile strength of composites, whereas the addition of any filler can either positively or negatively affect the tensile strength, depending on the quantity used (Cazan *et al.,* 2021) [25]. To attain optimal tensile strength in composites, it is preferable to use a lower amount of filler (Shrikavad *et al.,* 2014) [26]. Comparable results were observed in the study, where the combination of 10 weight percent fly ash with 10 weight percent CGS fiber proved to be the most effective composition (Figure 6). The addition of more than 10 weight percent of CGS fiber made the composite material more brittle, the composite lost its toughness and show reduced tensile strength and tensile modulus.

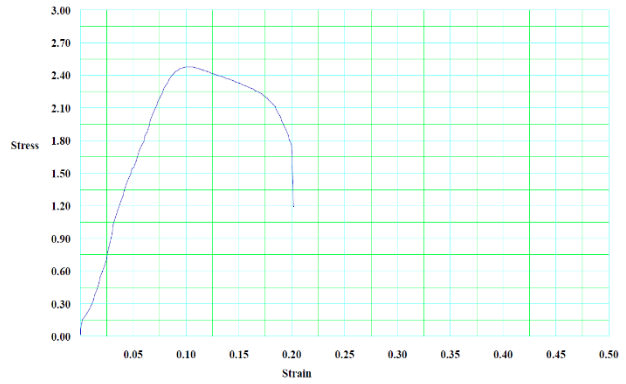


Figure 6 Tensile stress and strain curve of the composite PFCH

3.2.2 Flexural Strength and Flexural Modulus

The flexural strengths of the developed hybrid composites are presented in Table 5. The neat polypropylene exhibited a flexural strength of 45.32 MPa. In comparison, the hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ showed improved flexural strengths of 50.66 MPa, 54.03 MPa, 56.13 MPa, 50.06 MPa, and 42.05 MPa, respectively, relative to PPA (Figure 7). The flexural modulus of neat polypropylene (PPA) was recorded at 1624.07 MPa. The hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ exhibited increased flexural moduli of 1710.05 MPa, 2165.25 MPa, 2323.57 MPa, 2367.87 MPa, and 2045.36 MPa, respectively (Figure 7). This enhancement in stiffness can be attributed to the combined reinforcing effects of the natural fiber and inorganic filler. CGS fiber, rich in cellulose, provide high tensile stiffness due to their semicrystalline structure, while fly ash particles act as rigid fillers that restrict polymer chain mobility under flexural loading. The synergistic interaction between these two reinforcements improves stress transfer efficiency within the matrix, resulting in significantly higher flexural modulus values compared to neat polypropylene.

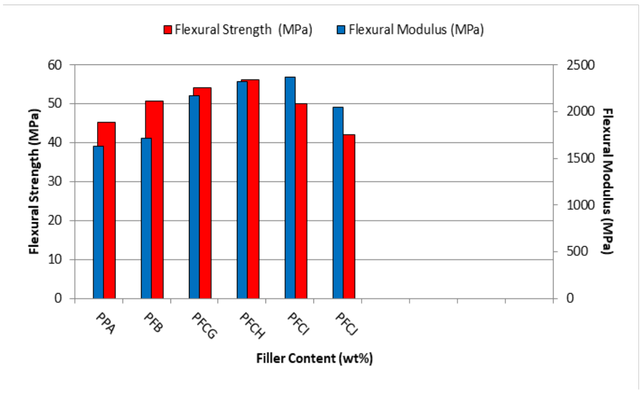


Figure 7 Flexural strength and Flexural modulus of the hybrid composite

The CGS fiber for 15 weight percent and 20 weight percent exhibited decreasing trend in flexural strength for PFCI and PFCJ, whereas for 10 weight percent of fiber exhibited increase in flexural strength and for 15 weight percent of fiber exhibited decrease in flexural strength. A similar observation has also been confirmed by the Ramesh et al., 2022, where increased filler content beyond an optimal level led to reduced mechanical performance due to poor dispersion and weak interfacial bonding [27]. The investigation reported that the highest flexural strength was observed at the lowest proportion of 10 weight percent CGS fiber, and it decreased with further increases in CGS fiber content. To achieve optimal flexural strength in hybrid composites, incorporating fly ash as filler is a better choice. Additionally, 10 weight percent of CGS fiber and 10 weight percent of fly ash was the optimal composition for achieving maximum flexural strength and flexural modulus among PFB, PFCG, PFCH, PFCI, and PFCJ (Figure 7).

3.2.3 Impact Strength

The impact strengths of the developed hybrid composites are shown in Table 6. The impact resistance of neat polypropylene was measured at 26.73 J/m. In comparison, the hybrid composites PFB, PFCG, PFCH, PFCI, and PFCJ demonstrated increased impact resistance values of 34.37 J/m, 38.71 J/m, 39.06 J/m, 37.32 J/m, and 36.45 J/m, respectively, compared to PPA (Figure 8).

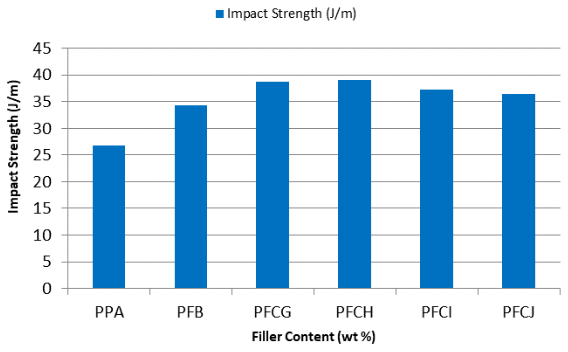
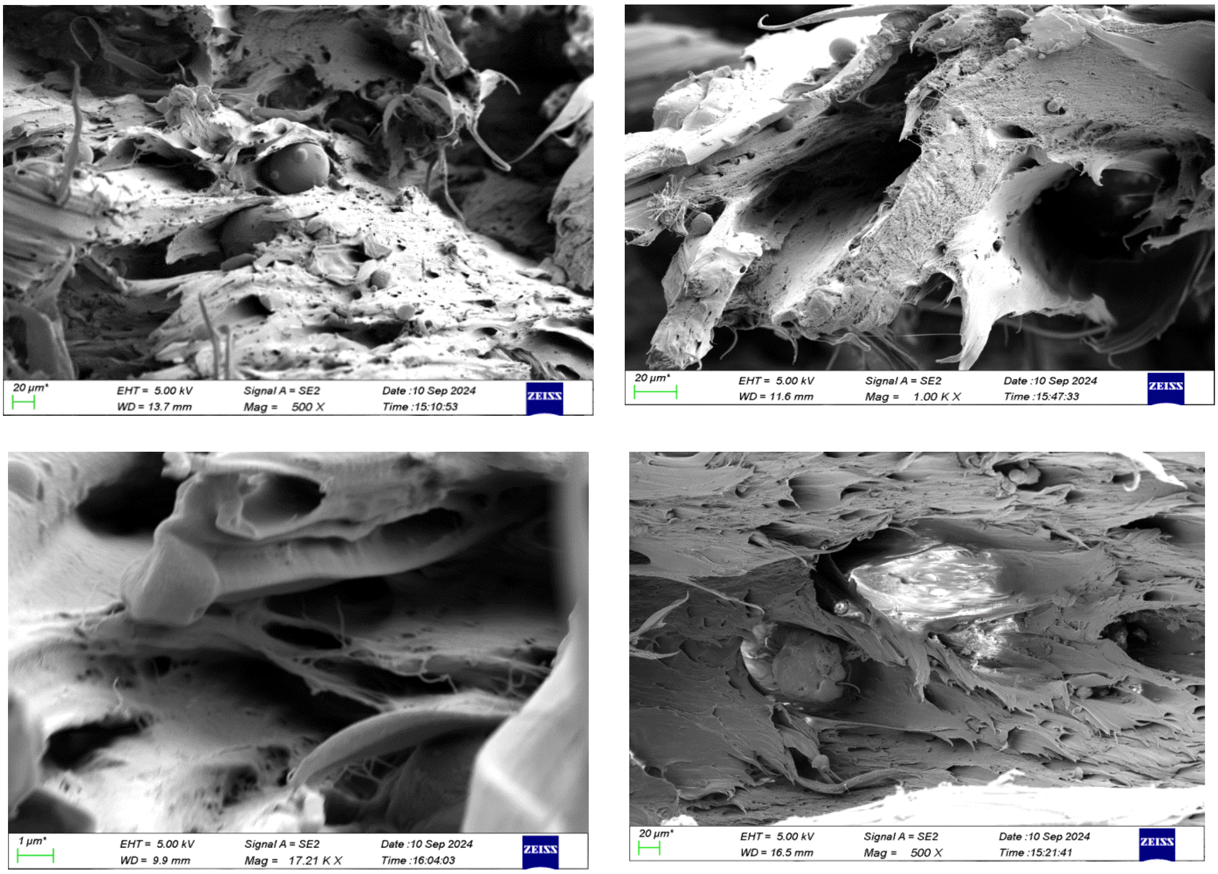


Figure 8 Impact resistance of the hybrid composite

The enhancement of impact resistance can be categorized as significant, average, and minimal with the affilation of fly ash, and CGS fiber, respectively. The impact characteristics of natural fiber were found to increase the impact resistance of composites (Faruk *et al.,* 2012, Kalauni *et al.,* 2023, Thomason *et al.,* 2018) [28, 29, 30]. The study emphasized that the optimal combination of fiber and filler content is essential for accomplish the greatest impact performance. Therefore 10 weight percent of CGS fiber and 10 weight percent of fly ash was the optimal composition for achieving maximum impact resistance among PFB, PFCG, PFCH, PFCI, and PFCJ (Figure 8).

3.3 Scanning Electron Microscopy

The SEM analysis of the developed hybrid composite was conducted to investigate its microstructure. The SEM examination with different magnification (Figure 9) revealed a even distribution of filler particulates throughout all the hybrid composites. The results indicated a well-balanced mixture with effective incorporation of both filler particulates fly ash and CGS fiber. Nevertheless, the amount and type of filler had a significant effect on the findings related to mechanical strength (Wypych 2016) [31]. The presence of both CGS fiber and fly ash provided a symbiotic effect, improving the overall performance of the composites. Overall, the PFCI, and PFCJ hybrid composites displayed several voids content, water absorption, instances of fiber pull-out, and diminished adhesion at the fiber-pp interface. In contrast, the all hybrid composites PFCG, and PFCH demonstrated better adhesion bonding, reduced porosity, and fewer voids. Additionally, PFCG hybrid composites demonstrated excellent adhesion, effective void-filling, minimal porosity, and extensive fiber breaking without fiber detachment, resulting in enhanced mechanical strength of the composites. However, at higher filler loadings, fiber pull-out phenomena were observed, which may be attributed to insufficient interfacial bonding between the fiber and the polymer matrix. As the filler content increases, the matrix may become less effective in fully wetting and encapsulating each fiber, leading to poor adhesion at the interface. This weak interface reduces the efficiency of stress transfer during mechanical loading, causing fibers to be pulled out rather than fractured. Such behavior has been reported in similar systems (Cazan *et al.,* 2021) [25] and is commonly associated with agglomeration or fiber crowding that limit matrix penetrations and bonding. Thus, incorporating 10 weight percent fly ash with 5 weight percent CGS fiber in the hybrid composite (PFCG) proved to be an effective composition for achieving extensive fiber breaking and excellent adhesion between the polypropylene, fly ash and the CGS fiber.



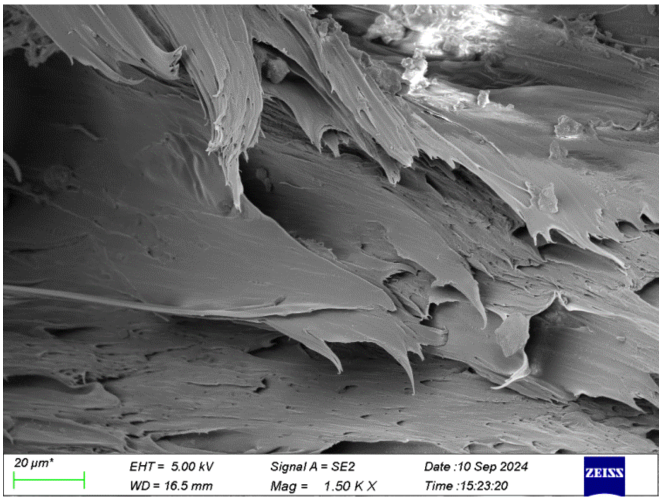


Figure 9 SEM images of the developed hybrid composite (a) PFB, (b) PFCG, (c) PFCH, (d) PFCI, and (e) PFCJ

3.4 Comparison With Other Work

The results of this study have been compared with those from another research. For tensile strength, the present study reported a value of 33.70 MPa, higher than the values of 33.52 MPa for the flax fiber composite (Kumar et al., 2009) [32], 22.46 MPa for the palmyra fiber composite (Kumar et al., 2009) [32], and less than the values of 37.57 MPa for the jute fiber composite (Brahma et al., 2009) [33]. For flexural strength, the present study reported a value of 56.13 MPa, higher than the values of 51.92 MPa for the flax fiber composite (Kumar et al., 2009) [32], and less than the values of 57.72 MPa for the palmyra fiber composite (Kumar et al., 2009) [32], and 58.85 MPa for the jute fiber composite (Brahma et al., 2009) [33]. Similarly, for impact strength, the current study showed a value of 39.06 J/m, compared to 29.4 J/m for both the flax and jute fiber composites (Kumar et al., and Brahma et al., 2009) [32, 33], and 19.6 J/m for the palmyra fiber composite (Satheesh et al., 2014) [14].

4.0 CONCLUSION

The results of the study on novel hybrid composites made from fly ash and Calotropis gigantea fiber are summarized as follows. Incorporating any type of filler particulates with Calotropis gigantea fiber into the polypropelene led to enhanced mechanical properties. In the study,

- The enhanced physical properties were achieved with 10 weight percent CGS fiber, more fiber added result in decreases density, increases void content and water absorption.
- The highest tensile strength, flexural strength and impact resistance of composite material with 10 weight percent fly ash combined with 10 weight percent CGS fiber were obtained 33.70 MPa, 56.13 MPa and 39.06 J/m respectively. The addition of more than 10 weight percent of CGS fiber made the composite material more brittle, the composite lost its toughness, and show reduced its mechanical properties.
- Incorporating 10 weight percent fly ash with 10 weight percent CGS provided excellent excellent adhesion between the polypropylene, and filler material. SEM analysis revealed that untreated CGS fiber had a larger aspect ratio, while all filler particulates were uniformly distributed within the composites. This even distribution contributed to a strong adhesive bond incorporating the fly ash, CGS fiber, and the polymer matrix.

Furthermore, incorporating fly ash filler particulates into cellulosic Calotrpois gigantea fiber-reinforced hybrid composites emerges as the most advantageous choice due to their superior mechanical properties, enhanced thermal stability, and reduced porosity. Consequently, natural fiber reinforced with polypropylene hold considerable potential for applications in various sectors, including automotive, aerospace, rockets, aircraft, railway coaches, and everyday products, thereby fostering sustainable environmental development.

5.0 FUTURE SCOPE

The use of additives with CGS fiber and fly ash-reinforced polypropylene has the potential to significantly expand the range of applications for these composites. Additives can improve mechanical, thermal, and environmental properties, enabling their use in more demanding industrial applications and leading to the development of smart, durable, and sustainable materials.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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