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Investigating the Impact of Pistacia Vera L. Bio-filler on the Mechanical Properties of a Synthetic Fiber/Epoxy Composite

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The rising demand for sustainable composites has propelled research into agricultural waste as eco-friendly fillers. This work assesses the possible use of Pistacia vera L. (pistachio) shell powder (PBF) as a bio-filler in glass fiber-reinforced epoxy (GFRE) composites, so evaluating its effect on mechanical properties over mass fractions from 0% to 2%. Using compression moulding, composites were created; ASTM criteria were used to test tensile, flexural, and impact strengths. The findings showed a subtle balance: tensile and impact strengths were highest at 1.0% PBF (314 MPa and 36.1 J/cm², respectively), whereas flexural strength steadily dropped with rising PBF content. Higher loadings (>1.0%) caused particle agglomeration and interfacial weaknesses, so compromising performance. Though thorough optimization is crucial to minimize trade-offs in flexural resistance, this work emphasizes the possibility of pistachio shells as partial substitutes for synthetic fillers.

Keywords: Epoxy; Pistacia vera L; bio-filler; glass fiber; composite

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In recent years, the need for sustainable and eco-friendly composite materials has increased, propelled by worldwide initiatives to diminish dependence on synthetic, non-renewable fillers in industrial applications [1, 2]. Synthetic fibres, including carbon, porcelain, nylon, polyester, rayon, acrylic, glass, and plastic fibres, have grown into vital elements in fiber-reinforced composite constructions in the past two decades [3]. The composite substrate serves as a durable constituent of the substance; nevertheless, its internal constituents, including reinforcing substances or fillers, significantly influence its general performance [4]. Improving particle adherence may augment material stiffness; nevertheless, including such additives into polymers could compromise the composite by introducing void pockets [5, 6].

Polymer composites, especially glass fiber-reinforced epoxy (GFRE) systems, have consistently prevailed in industries including aerospace, automotive, and construction owing to their superior strength-to-weight ratio, anti-corrosion properties, and design versatility [7, 8]. The environmental impact of traditional composites, together with increasing apprehensions over resource depletion, has generated interest in using bio-based fillers as substitutes for synthetic materials [6, 9]. This transition follows the principles of a circular economy, where agricultural byproducts, often regarded as waste, are repurposed to improve the practical utility of advanced materials. Bio-fillers sourced from agricultural leftovers, including coconut shell, eggshells, rice hulls, and walnut shell, have arisen as viable reinforcements, providing an effective compromise between performance and ecological benefits. These substances not only diminish dependence on non-renewable resources but also enhance the value of agricultural waste, in accordance with the principles of the circular economy. The influence of fillers on composites is contingent upon their form, dimensions, surface region, dimension ratio, and uniformity of dispersion within the composite framework [5, 10]. Besides specific benefits, numerous issues exist during the generation of small-sized powders from the bio materials [9, 11].

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Faiz Norrrahim et al. [12] demonstrated the use of bio-fillers made from cow bone to enhance stiffness, resilience, and thermal resistance, serving as an environmentally friendly substitute for artificial fillers in building materials. Kumar et al. [13] examined a hybrid epoxy composite supplemented with jute fibre and powdered eggshell bio-filler, revealing that the incorporation of 9% eggshell powder markedly improved tensile strength, flexural strength, and hardness relative to plain jute fibre composites. The findings confirm the feasibility of 9% eggshell powder in jute fiber-based epoxy composites as an environmentally friendly, exceptionally well composite for situations exposed to mechanical stresses. In another study [14], sugarcane bagasse ash, a byproduct of agriculture, was used as a filler to improve the properties of GFRE. The addition of 5 wt.% filler resulted in an 11% increase in tensile strength and a 4% increase in compressive strength, while 10 wt.% led to a remarkable 59% increase in flexural strength, supporting environmentally friendly material targets.

The shell of Pistacia vera L. (pistachio), a prevalent farming byproduct, is a potential but inadequately investigated alternate for bio-filler applications. This lignocellulosic substance, abundant in lignin and cellulose, possesses intrinsic hardness and thermal endurance characteristics that may enhance the brittle qualities of epoxy resins [15]. Initial investigations [16] into pistachio shell powder-reinforced epoxy systems demonstrated improved flexural and tensile strength, as well as hardness, at low filler loadings (<2%) with uniform dispersion and absence of agglomeration, confirming their viability as sustainable reinforcements for the matrix. At the same time, studies on hybrid systems like the combination of bio-fillers with synthetic fibres, such as glass, are still quite scarce, even though they hold the promise of enhancing the advantages of both elements. Ogah et al. [17] developed epoxy composites that were reinforced with bambara nut shell powder as a bio-filler. They found that the mechanical properties, including tensile, flexural, and impact strength, reached their highest levels at 15 wt.% of the bio-filler inclusion. Additionally, as the filler content increased, both hardness and thermal transitions improved. However, it was noted that moisture absorption raised and thermal stability decreased at greater loadings. The best performance at 15 wt.% bio-filler showcased its promise for achieving a good balance between mechanical and physical properties in sustainable composites.

The earlier studies proved that the incorporation of the appropriate bio-fillers in small mass fractions in the synthetic fiber-reinforced epoxy composites would enhance the mechanical behaviour of the material to a greater extent [18, 19]. On the other hand, the increased loading the bio-fillings might have resulted in the deterioration of the properties owing to the conglomeration of the particles within the epoxy matrix, which would result in the weakening of the matrix material. However, there are still significant gaps in our understanding regarding the way Pistacia vera L. shell bio-filler (PBF) affects the mechanical behaviour of GFRE composites, especially when considering a wide range of mass fractions. The current body of research mainly centres on synthetic-filler systems and varying filler loadings, which means the importance of bio-fillers, the relationship between the bio-filler concentration and fibre-matrix interaction, and the mechanisms of composite failure have not been thoroughly explored. Additionally, the impacts of particle size of pistachio shell powder with epoxy are not well understood, which hinders the optimisation of these hybrid composites.

This study systematically investigates the impact of Pistacia vera L. shell powder (PBF) at mass fractions ranging from 0 % to 2% on the tensile, flexural, and impact properties of glass fibre/epoxy composites. This work evaluates interfacial adhesion, filler dispersion, and the trade-offs between bio-filler content and mechanical performance. By correlating bio-filler loading with property changes, this work aims to identify optimal formulations that leverage environmental and mechanical advantages. The findings will advance sustainable composite design, offering insights into agricultural waste valorisation and eco-material innovation for industrial applications.

Figure 1. Bio-filler (a) Shells of Pistacia vera L. (b) Powdered PBF.

EXPERIMENTAL

Chemicals and Materials

Primarily, the epoxy resin and polyamidoamine (PAMAM) hardening media were purchased from the local vendors. The pistachios were procured from the near-by dry fruit shop and the shells were removed from the nuts for further processing. Next, the removed shells were sun-dried for two days to remove the moisture and any impurities present in the shells. After drying, the shells were finely ground to be the powder with the help of a mechanical ball mill. The ground PBF were then sieved to obtain the powder of uniform size and to remove any unwanted foreign materials. The pistachio shells, and PBF powder are illustrated in Figure 1.

The field emission scanning electron image (FESEM) of the powdered PBF was taken to identify the nature the particles. The FESEM displayed that the form of the particles was coarse and with uniform dimensions. Further, the particles are in rodlike structure, owing to the fibre content. The shape of the particles is randomly distributed and looks like the flakes as illustrated in Figure 2.

The particle size of the obtained PBF powder was assessed using a particle size analyzer. The results are presented in Figure 3. The results from the particle size analyzer confirmed that the major size of the PBF particles were found to be existed between the band of 126 – 150 µm and 151 – 175 µm. It can be understood that the average particle size of the PBF powder was around 150 µm. The distribution percentage of PBF powder was sparse around the above-mentioned bands. Further, it confirmed that the powder was very fine for being applied with the epoxy composite.

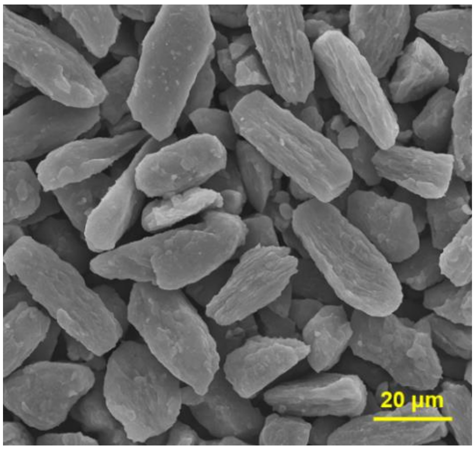

Figure 2. FESEM image of PBF powder.

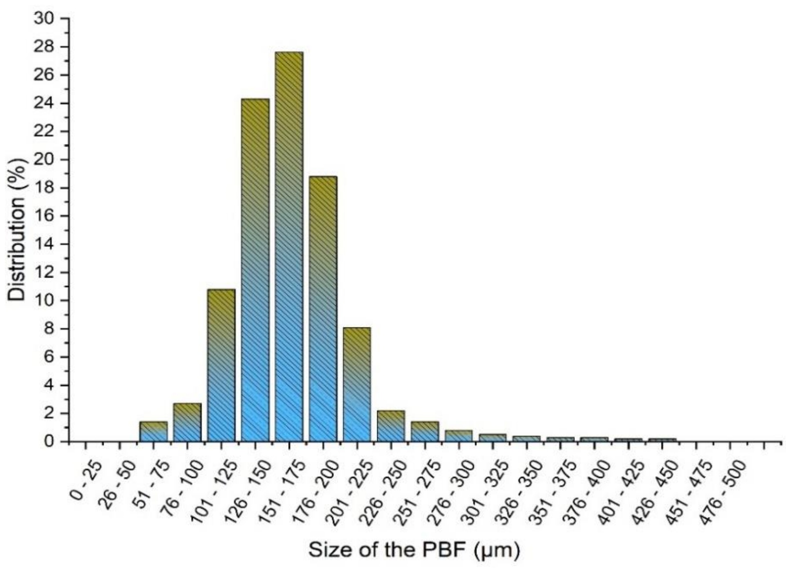

Figure 3. Particle size distribution of PBF powder.

Table 1. Chemical composition of the composite.

Sample No.	Bio-filler mass%	Epoxy mass%
1	0	100
2	0.5	99.5
3	1.0	99
4	1.5	98.5
5	2.0	98

Fabrication of Composite

The powdered Pistacia vera L. shell bio-filler (PBF) had been employed as a reinforcement in the matrix consist of epoxy resin. For this purpose, the ultrasonicator had been deployed to prepare the epoxy-powdered PBF mixture at different mass fractions as presented in Table 1. The polyamidoamine (PAMAM) hardening substance had been used with the epoxy in the ratio of 1:10 to ensure the smooth curing of the epoxy composite. The required glass fiber/epoxy composite plates with varying mass of PBF powder were fabricated by utilizing a hot-pressing compression molding machine. At a 10:1 ratio, the epoxy was blended with hardener. The commercial grade paraffin was used as the removing agent during the fabrication of the composite plates. The fabricated plates were cut into required dimensions as per the ASTM standards to perform the mechanical characterization of the composite plates.

RESULTS AND DISCUSSION

The mechanical characteristics of the prepared composites with varying PBF powder composition was assessed and the results are presented. The three key properties of the GFRE composites, namely, tensile strength, flexural strength and impact strength, were measured with bio-fillers. All the three tests were conducted on three samples each and then average values were taken for further analysis.

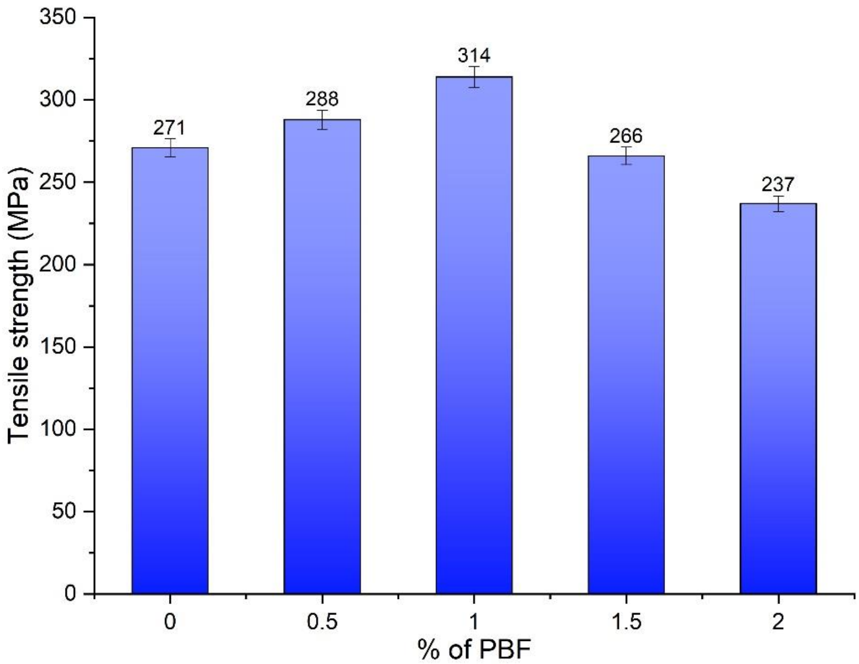

Figure 4. Tensile strength with increased PBF fractions.

The tensile test samples were produced according to ASTM D3039. During the tests, the specimen was secured in the jaws of the universal testing machine for axial loading. The samples used for the flexural test have been organized in accordance with ASTM D790 requirements. The sustained spacing was 16 times more than the depth of the samples in the three-point bending experiment. The mean depth of the samples was 0.278 cm. The amount of energy consumed by an element prior to fracture upon collision with a high-velocity object is referred to as impact strength. This study used the Charpy impact test in accordance with ASTM A370.

Figure 4 illustrates the tensile strength of the composite with different mass fractions of the bio-filler. It can be understood that the tensile strength was progressively enhanced with rising PBF content until 1.0% of PBF in composite. It has reached to the peak value of 314 MPa at 1.0% PBF content. Beyond this point, the strength dropped significantly to about 237 MPa at 2% PBF. It can also be referred from Table 2. This drop implies that although little bio-filler inclusion could slightly improve stress distribution, more concentrations probably introduce discontinuities in the matrix, which may also be caused by the agglomeration of the particles at higher mass fractions. Though they are organic in origin, the bio-filler particles might be stress concentrators because of poor interfacial bonding with the epoxy resin. Agglomeration of PBF at higher mass fractions may also aggravate microstructural flaws, therefore impairing load-transfer performance.

Figure 5 displays the variations in flexural strength of the composites with increased loading of the PBF. Unlike the tensile strength of the composite, it was found with a significant drop in strength as PBF content rose. The composite recorded a maximum value of flexural strength of 168 MPa without loading the PBF. However, it was then dropped almost linearly to 97 MPa at 2% PBF. Matrix-fiber interfacial integrity greatly influences flexural failure mechanisms in fiber-reinforced composites. Compared to the hydrophobic epoxy matrix, the bio-filler's hydrophilic character may produce weak interfacial zones that lower bending stress resistance. These weak areas at higher PBF loadings probably spread fractures more easily, therefore hastening failure under flexural loads.

Table 2. Tensile strength of the samples.

Sample No.	Bio-filler mass%	Tensile strength (MPa)
1	0	271
2	0.5	288
3	1.0	314
4	1.5	266
5	2.0	237

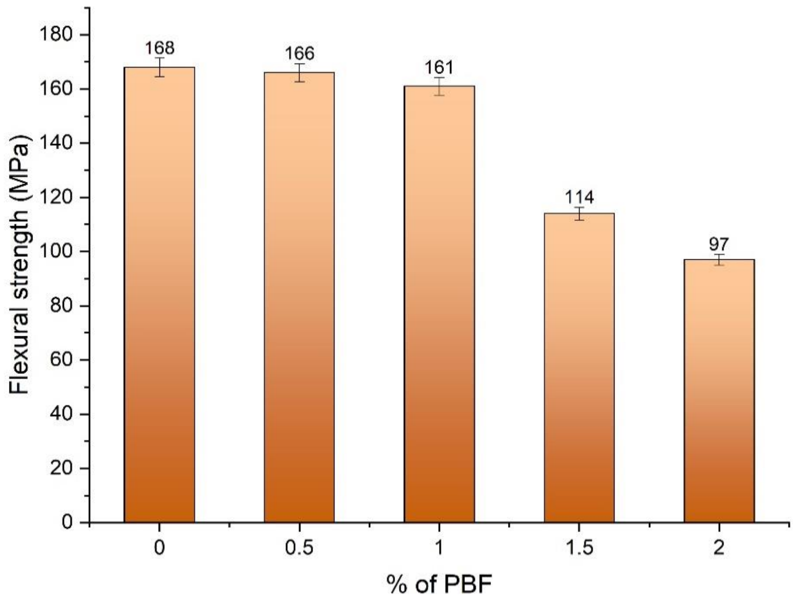

Figure 5. Flexural strength with increased PBF fractions.

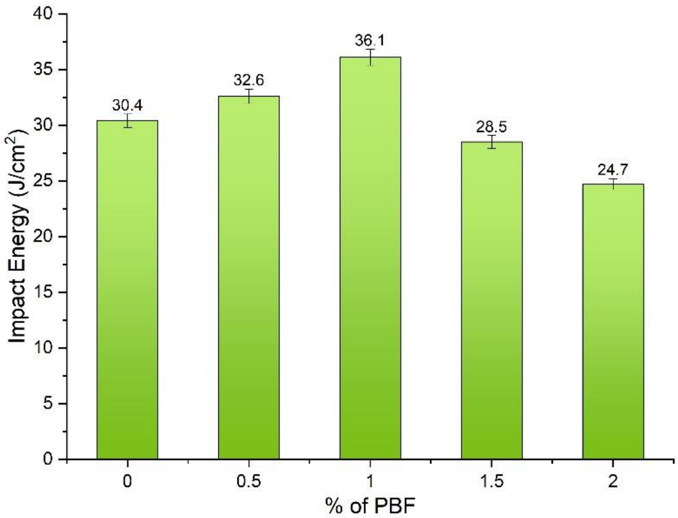

Figure 6. Impact strength with increased PBF fractions.

Table 3. Impact strength of the samples

Sample No.	Bio-filler mass%	Impact strength (J/cm^2)
1	0	30.4
2	0.5	32.6
3	1.0	36.1
4	1.5	28.5
5	2.0	24.7

The impact strength of the composite has followed a similar trend as like tensile strength as shown in Figure 6. The maximum impact strength was recorded as 36.1 J/cm^2 at 1.0% of PBF, further rise in PBF concentration greatly compromised impact resistance, a vital characteristic for structural uses. The impact strength was determined as 24.7 J/cm^2 at 2% PBF, which is 18.75% lesser than the impact strength of the pure epoxy composite as given in Table 3. Impact energy absorption in composites is determined by the material's capacity to dissipate energy through mechanisms including fiber pull-out, matrix deformation, and crack deflection. The brittle character of the bio-filler and weak matrix adhesion probably limited these energy-dissipating routes at their higher mass fractions, therefore increasing the likelihood of catastrophic fracture of the composite under fast loads.

The results proved the capability of the bio-filler to enhance the tensile and impact properties of the GFRE. However, the addition of the bio-fillers has the negative effect on the flexural properties of the GFRE, which need to investigated in a deeper manner. Although PBF has environmental benefits, its polar surface chemistry is very different from the non-polar epoxy resin, which results poor interfacial bonding. This discrepancy would have lowered the flexural characteristics of the composite performance by encouraging debonding under mechanical stress. Moreover, particle agglomeration at greater loadings (more than 1.0% PBF) intensifies heterogeneity by producing localized stress concentrations that accelerate failure.

Curiously, the slight improvement or stability in characteristics at very low PBF fractions (less than or equal to 1.0%) suggests a possible "sweet spot" where the bio-filler could serve as a secondary reinforcement without overloading the matrix. This is consistent with research on hybrid composites, which show that small filler additions increase strength by bridging microcracks. Beyond this limit, the disadvantages of bad adhesion and agglomeration take center stage.

CONCLUSION

This study demonstrates the potential of pistachio shell bio-filler (PBF) to enhance the sustainability and mechanical performance of GFRE composites. Also, this study promotes eco-material innovation by valorising agricultural waste, so providing a model for sustainable composite design in sectors aiming to lower synthetic filler dependency without sacrificing important qualities. The following are the key outcomes:

- PBF at 1.0% mass fraction outperformed unfilled composites in tensile and impact strengths by 15.86% and 18.75%, respectively, suggesting efficient stress distribution and microcrack bridging.

- PBF addition, on the other hand, caused a linear drop in flexural strength, falling 42.26% at 2% loading, probably because of hydrophilic-hydrophobic mismatches and weak interfacial bonding. Beyond 1.0% PBF, the drop in properties emphasises the difficulties of matrix heterogeneity and particle agglomeration under greater loadings.

- These findings highlight that, given optimal dispersion and adhesion, even small bio-filler inclusion can align mechanical performance with circular economy ideas.

- Future research should investigate hybrid filler strategies to balance flexural trade-offs and surface treatments to improve PBF-epoxy compatibility.

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