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INVESTIGATION OF THE MECHANICAL BEHAVIOR OF EPOXY COMPOSITES FILLED WITH BAGASSE ASH AND PISTACHIO SHELL ASH: A COMPARATIVE STUDY

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Abstract:
In recent years, there has been a considerable increase in interest in the use of natural fillers in polymer composites because of their potential to improve mechanical qualities while preserving environmental sustainability. This study investigates the potential of utilizing agricultural waste, specifically Bagasse Ash (BA) and Pistachio Shell Ash (PA), as fillers in epoxy composites to enhance mechanical properties and support sustainable material development. Composites were prepared with varying weight percentages (2% to 10%) of BA and PA using an open mold technique. Mechanical properties, including tensile, flexural, and impact strength, were assessed to determine the effect of filler content. Results indicate that BA composites generally outperformed PA composites in tensile and flexural strength, with maximum tensile strength recorded at 6% filler content for both BA (19.16 MPa) and PA (11.49 MPa). The analysis shows that increasing filler content beyond the optimal level leads to decreased mechanical performance due to agglomeration and void formation. The enhanced mechanical properties of these composites suggest their suitability for applications in lightweight structural components, offering an eco-friendly alternative to conventional synthetic fillers.

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1. INTRODUCTION

The use of natural fillers in polymer composites has gained significant attention in recent years due to their potential to enhance mechanical properties while maintaining environmental sustainability [1]. Two prominent reinforcement options that have garnered significant attention are ash particles and fiber micro-particles. Ash particles, derived from the combustion of various organic materials, possess a unique set of characteristics that make them a viable reinforcement choice. Conversely, fiber micro-particles, often extracted from natural or synthetic sources, offer their own distinct advantages as reinforcement in epoxy composites.

To assess the comparative performance of these two reinforcement options, it is necessary to delve into their respective properties and their influence on the resulting epoxy composite characteristics. Ash particles, with their inherent heterogeneity and irregular morphology, can contribute to improved interfacial bonding between the epoxy matrix and the reinforcement, leading to enhanced load transfer capabilities and overall mechanical performance. Fiber micro-particles, on the other hand, can provide enhanced tensile strength, stiffness, and impact resistance due to their unique

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fibrous structure and high aspect ratio. The selection of the optimal reinforcement, whether ash particles or fiber micro-particles, ultimately depends on the specific application requirements, the desired mechanical and thermal properties, and the cost-effectiveness of the fabrication process [2].

Numerous studies have been conducted to explore the comparative advantages of ash particles and fiber micro-particles as reinforcement in epoxy composites. Bharath and Basavarajappa, [3] explore the potential of bio-composites made from natural fibers as a sustainable alternative to synthetic materials. The review highlights the growing use of these bio-composites in various sectors, including construction, automotive, and aerospace. While quantitative data is limited, the study emphasizes the significant growth and potential of bio-composites in replacing synthetic fibers, driven by environmental concerns and the search for cost-effective materials. In an investigation by Jose et al. [4], the author provides a comprehensive review of using bio-waste particles like coconut shells and groundnut shells as reinforcements in polymer composites. The study highlights the advantages of these materials, such as low cost, biodegradability, and good thermal properties. However, it also acknowledges drawbacks like higher moisture absorption and lower impact strength compared to conventional reinforcements. On the other hand, Jain et al. [5] examined rice husk-epoxy composites, focusing on their mechanical properties and machining performance. Composites with 10 wt.% rice husk particles show the highest tensile strength, Young’s Modulus, and hardness. Increasing rice husk content improves impact energy but reduces tensile and compressive strengths due to poor bonding. Machinability tests indicate that weight percentage significantly affects thrust force and torque during drilling, with 10 wt.% composites performing best. Adding cenosphere to jute-epoxy composites can improve their mechanical properties, according to Nadh et al. [6]. A 5wt.% cenosphere addition increased strength and hardness, but a 10wt.% addition had a negative impact. This highlights the potential of using cenosphere as a reinforcing filler in these composites. Additionally, Laouchedi et al. [7] investigated the influence of incorporating Algerian clay in both raw and calcined forms on the properties of epoxy resin composites. The authors concluded that adding clay fillers, particularly those with finer particle sizes and at higher loading rates, enhances the mechanical properties of the composite, notably its rigidity while offering potential cost benefits. Also, Alshammari et al. [1] evaluated the use of different date palm components as reinforcing fillers in epoxy composites. Results showed that adding date palm fruit bunch stalk significantly improves the mechanical properties of the composite, including tensile, impact, and flexural strength. However, this also leads to increased water absorption and thickness swelling. The study suggests that date palm fruit bunch stalk is a promising sustainable material for developing high-performance composites. In contrast, Matykiewicz [8] investigated the enhancement of hybrid epoxy composites through the addition of powder fillers like carbon nanotubes, graphene, nano clay, silica, and natural fillers. The research focuses on composites reinforced with glass, carbon, or basalt fibers, analyzing how these powder fillers influence the mechanical and thermal properties of the resulting materials. The findings suggest improvements in strength, adhesion, and resistance, making these composites suitable for various industrial applications. The research presented by Devendra and Rangaswamy [9] investigates the impact of various filler materials on the mechanical properties of E-glass fiber-reinforced epoxy composites. The study fabricated composites with varying concentrations of fly ash, aluminum oxide, magnesium hydroxide, and hematite powder. Mechanical properties like ultimate tensile strength, impact strength, and hardness of the composites were evaluated, and the results indicate that incorporating 10% volume of magnesium hydroxide yielded the highest ultimate tensile strength and hardness, while fly ash fillers resulted in the greatest impact strength. Also, Reis et al. [10] investigated the impact of incorporating cork and rice husk ash micro-particles on the mechanical properties of polyester composites. The study found that while both fillers improved impact energy absorption, they reduced flexural strength and fracture toughness. Notably, rice husk ash outperformed cork powder in enhancing impact resistance and maintaining fracture toughness at higher filler contents. The research study by Nandiyanto et al. [11] investigates the impact of rice husk particle size on the performance of resin-based brake pads. The study found that smaller rice husk particles led to enhanced compressive strength, reduced wear rate, and a higher friction coefficient, indicating the potential of using rice husk as a sustainable alternative material for brake pad friction. The study conducted by Vivek and Kanthavel [12] examines the influence of bagasse ash and hybrid natural fibers on the properties of bio-composites. Researchers used a vacuum bag technique to create and analyze these composites, employing methods like X-ray spectroscopy, diffraction, thermogravimetric analysis, and microscopy. Results show that incorporating BGA and hybrid fibers significantly enhances the composites' mechanical strength (flexural, tensile, impact) and thermal stability. The study by Sumesh et al. [13] investigated the impact of incorporating banana, pineapple, and coconut fly ash fillers (1-4 wt.%) into sisal/pineapple fiber epoxy composites. Results showed improved tensile strength (23.78–33.79 MPa), flexural properties (up to 22.11% enhancement), and impact resistance (up to 21.77% enhancement) compared to composites without fillers. Microscopic analysis confirmed good bonding between the fillers and the matrix. The study presented by Raju and Kumarappa [14] investigates groundnut shell particles as a reinforcing material for epoxy composites. The authors found that incorporating groundnut shell particles enhanced the mechanical properties, with a maximum strength observed at 50 wt% filler content. Additionally, the thermal conductivity of the composites ranged from 0.07638 W/mK to 0.3487 W/mK. Rizal et al. [15] examine how oil palm boiler ash can be used as a reinforcing filler in epoxy composites. By adding OPBA at various sizes (50-150 µm) and weights (10-50 wt.%), the study found that 30 wt.% loading and 50 µm size yielded the best physical, mechanical, and thermal properties. The study concludes that OPBA has the potential to be a viable alternative to traditional silica-based fillers. Rizal et al. [16] investigated oil palm ash nanoparticles as reinforcement in epoxy composites. The addition of nanoparticles improved tensile strength, modulus, and impact strength, with optimal properties at 4% loading. The nanocomposites also showed enhanced thermal stability up to 435°C. Prasanthi and Rao [17] examine the impact of voids on the mechanical properties of nano and hybrid composites. Using micromechanical modeling via finite element methods, the study quantitively assesses changes in Young's modulus and Poisson's ratio. Findings reveal that void presence significantly affects the transverse modulus of hybrid composites, highlighting the importance of void consideration in material design for desired strength. The study presented by Eswar et al. [18] investigates the impact of nano-carbon powder reinforcement on the mechanical properties of sisal fiber composites. Through experimental testing and finite element analysis, the authors found that adding 9% carbon powder to the composite increased its modulus and critical crack length, resulting in a material comparable in strength to man-made composites.

In past research, it was evident that the introduction of natural fillers into epoxy resins has been investigated as a means of reducing the reliance on more expensive and less sustainable synthetic fillers, such as carbon and ceramic materials [19].

Also, recent studies emphasize the significance of natural fillers in reducing waste and pollution while enhancing the sustainability of composite materials. The integration of agricultural waste fillers into polymer matrices decreases landfill waste, lowers carbon emissions, and aligns with the goals of a circular economy. By reducing dependence on synthetic, non-renewable materials, this approach aids in resource conservation and benefits ecosystems overall. Economically, agricultural waste fillers serve as cost-effective alternatives to traditional fillers, which are often expensive and derived from limited resources. Additionally, using such byproducts provides supplementary income for farmers by transforming otherwise discarded waste into valuable revenue streams, further supporting agricultural economies [20].

Bagasse ash (BA) is a byproduct generated from the combustion of processed sugarcane in industrial boilers. This ash serves as a critical fuel source, primarily used for steam generation in electricity cogeneration, meeting up to 90% of industrial energy demands. Comprising over 70% inorganic material, bagasse ash is predominantly rich in silica, which makes it valuable for applications in the construction industry. BA, as a natural filler, has shown promise in improving the performance of metal matrix composites [21,22]. Pistachio shell powder is a readily available filler for polymer composites; however, it remains relatively unexplored in research. When shells are burned to produce ash, the resulting filler offers enhanced thermal stability, improved mechanical strength, and greater resistance to combustion compared to untreated shell powder. Rich in silica, calcium, and potassium, shell ash significantly strengthens the structural integrity and thermal resilience of composites. Studies indicate that using ash fillers, such as peanut shell ash or fly ash, can enhance flame resistance, rigidity, and dimensional stability, making them ideal for high-performance engineering applications. Additionally, ash fillers support sustainable waste management and contribute to eco-friendly material solutions in manufacturing [23,24].

In the present study, different weight ratios of Bagasse Ash (BA) and Pistachio Shell Ash (PA) particles were utilized as fillers, with epoxy serving as the matrix material. The composite materials were fabricated using the open molding technique. This investigation aims to evaluate the effects of varying the composition and distribution of these natural fillers on the overall performance of the composite materials. Fractured surface morphology was examined using scanning electron microscopy (SEM) to identify the failure mechanisms of the composites.

2. METHODOLOGY

2.1 Materials Used

In this investigation, Bagasse Ash (BA) and Pistachio Shell Ash (PA) were used as fillers, while epoxy resin served as the matrix material in the composites. The epoxy resin Araldilite LY556, Aradur HY951 was procured from M/s. Vaishnav Composites, Hyderabad.

Bagasse waste was collected from local juice shops and sun-dried for 72 hours to remove moisture content completely. Subsequently, it was burned in open air, as illustrated in Fig. 1.

Fig. 1. Bagasse Waste turned into ash

The burnt bagasse was collected and ground into a powdered form. The powder particles were then reduced to smaller microparticles using a ball milling apparatus at a speed of 300 rpm for a duration of 3 hours. The milled powder was subsequently heated to 200°C in a muffle furnace for 2 hours to completely remove any remaining moisture from the particles, as shown in Fig. 2.

Fig. 2. Bagasse Ash (BA)

The pistachio shells are separated from the pistachio nuts and dried in sunlight for 72 hours to remove moisture content. To convert the pistachio shells into ash, they are placed in a crucible and heated in an electric arc furnace at 200°C for 4 hours, as shown in Fig. 3.

Fig. 3. Burning of Pista Shells in Electric Arc Furnace

The burnt pistachio shell residue was collected and ground into a fine powder. The powder particles were then further reduced to smaller microparticles using a ball milling apparatus at 300 rpm for 3 hours. The milled powder was subsequently heated to 200°C in a muffle furnace for 2 hours to ensure the complete removal of any residual moisture from the particles.

2.2 Method of Fabrication

To fabricate the composite specimens, an open mold of size 300 mm x 300 mm was used, as illustrated in Fig. 4. The epoxy resin and hardener were mixed in a 10:1 ratio, along with the filler material particles according to the designated weight percentages presented in Table 1.

Table 1. Details of the composite fabricated for the experimental investigation

S.No.	Composite Code	% Weight of Filler	% Weight of Epoxy
1	BA2	0.02	0.98
2	BA4	0.04	0.96
3	BA6	0.06	0.94
4	BA8	0.08	0.92
5	BA10	0.10	0.90
6	PA2	0.02	0.98
7	PA4	0.04	0.96
8	PA6	0.06	0.94
9	PA8	0.08	0.92
10	PA10	0.10	0.90

The mixture was thoroughly blended using a mechanical stirrer to prevent agglomeration. The mixture was then poured into the open mold, and to eliminate air bubbles, hot air was passed over the surface of the mold. The mold was left undisturbed for 24 hours to allow the epoxy resin to cure fully.

Fig. 4. Open Mold Setup at M/s. Vaishnav Composites

2.3 Density of Composites

The theoretical density of composite materials is derived using the rule of mixtures shown in Eq. 1 [25]:

$$\rho_{ct} = \frac{1}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}}, \tag{1}$$

where are: w represents the weight fraction of the filler (w_f) and the epoxy matrix (w_m). The density of the composite (g/cc) is indicated as ρ_{ct}, while the densities of filler material and epoxy matrix are represented as ρ_f and ρ_m, respectively.

The experimental density values of the composites were determined using a specific gravity tester, following the ASTM D 792 test procedure. The test specimen was first weighed in its dry condition, and its weight (w_d) was recorded. Next, the sinker was immersed in a medium, and its weight (w_s.) was determined. Subsequently, the specimen was placed on the sinker, and the combined weight of the specimen and sinker, fully immersed in the water, was recorded as w_{sw}. The specific gravity (SG) and experimental density of the composite (ρ_{ce}, in g/cc) were then calculated using the following Eq. 2 and Eq. 3, respectively [24].

$$SG = \frac{w_d}{[(w_d + w_{sw}) - w_s]}, \tag{2}$$

$$\rho_{ce} = SG \times 0.9976. \tag{3}$$

The void content in the composite was determined using the ASTM D 2734-70 standard. The volume fraction of the voids (V_v) is given by the Eq. 4.

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}}. \tag{4}$$

2.4 Characterization of Powder Particles

In the characterization of powder particles, the objective is to determine the size distribution of the powder particles and the elemental analysis through SEM and EDS.

A Particle Size Analyzer (PSA) is a critical tool for determining the size distribution of particles in materials like powders, suspensions, and emulsions. Its primary objective is to provide accurate measurements of particle sizes within a sample, crucial for understanding material behaviour in various applications. The process begins with sample preparation, which ensures accurate and reliable results. Initially, a solution was prepared using the 5mg of powder sample and dispersed in water to prevent agglomeration and skewing of the particle size distribution data. The solution was then subjected to an Ultrasound sonication process for a duration of 180 seconds to ensure the uniform dispersion of the particles in the solution. The sample is then introduced into the PSA for measurement, typically using the laser diffraction technique. In this technique, a laser beam is passed through the dispersed sample, and the particles scatter the light in different directions depending on their size. This method allows for the determination of parameters like the median particle size (D50), finer (D10), and coarser (D90) particle sizes. The test was carried out at KELVN Labs, Hyderabad, using a Microtrac S3500 particle size analyzer. The elemental analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) was conducted in Annamalai University, Chidambaram.

2.5 Tensile Test

The tensile test specimen was prepared in accordance with ASTM D 638, as shown in the specimen drawing in Fig. 5. The tensile test was conducted at Prasad V Potluri Siddhartha Institute of Technology in Vijayawada using the Universal Testing Machine (DXT) at a loading rate of 10 mm per minute. Five specimens were tested for each weight percentage of filler material, and the average tensile strength was calculated.

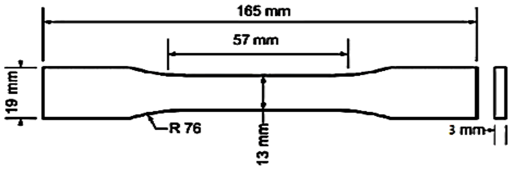

Fig. 5. Tensile Testing Specimen as per ASTM D638 Standards

2.6 Flexural Test

The aforementioned Universal Testing Machine (UTM) was used for the flexural test, following the ASTM D 792 standards (Fig. 6) for specimen preparation and testing procedures. Specimens measuring 130 mm in length and 12.7 mm in width were cut with a span-to-depth ratio of 16:1 and loaded onto a three-point bending setup. A 10 kN load cell was employed, and the test was conducted at a loading rate of 2 mm/min. For each weight percentage of filler material, five specimens were tested, and the average result was reported.

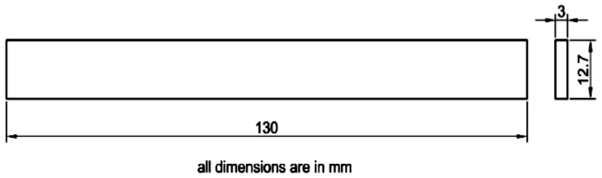

Fig. 6. Flexural Testing Specimen as per ASTM D790 Standards

2.7 Impact Test

The Izod impact test procedure was followed to determine the impact strength of the fabricated composite material. A V-notch cutter was used to prepare the specimens according to the ASTM D-256 standard, as shown in Fig. 7. For each weight percentage of filler material, five specimens were prepared, and the average impact strength of these specimens was recorded.

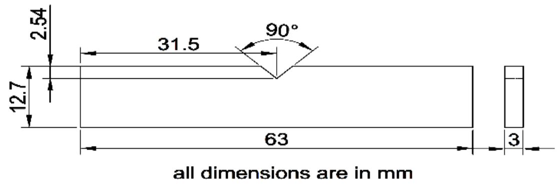

Fig. 7. Impact Testing Specimen as per ASTM D790 Standards

3. RESULTS AND DISCUSSION

3.1 Ash Particle Characterization

The size of the filler particle may impact the mechanical properties of the composite significantly. The particle size distribution curve of the bagasse ash filler is depicted in Fig. 8, and the details of the particle distribution are furnished in Table 2.

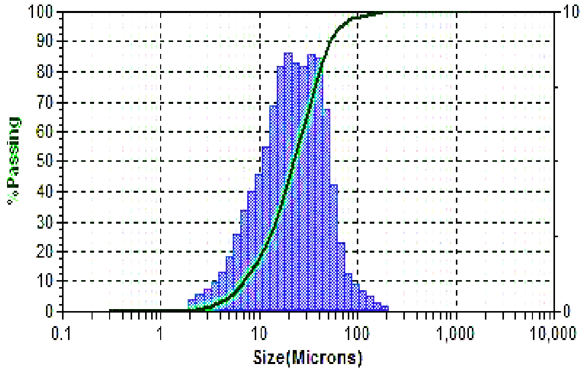

Fig. 8. Particle Distribution of BA filler material

Table 2. Particle Distribution (%) of BA filler material

% Tile	Size (µm)
10	6.58
20	8.59
30	11.03
40	14.18
50	17.00
60	19.33
70	21.51
80	23.91
90	27.37
95	30.87

The results depict that the particle size varies from 6.58 µm to 30.87 µm. The average particle size is considered for the experiment, i.e., 17.00 µm. Additionally, the graphs show that the particles are uniformly distributed in the tested sample.

The particle size distribution curve of the pistachio shell ash filler is depicted in Fig. 9, and the details of the particle distribution are furnished in Table 3.

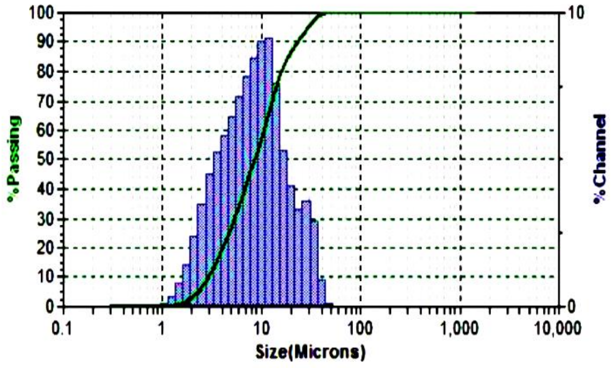

Fig. 9. Particle Distribution of PA filler material

Table 3. Particle Distribution (%) of PA filler material

% Tile	Size (µm)
10	2.92
20	4.09
30	5.42
40	6.89
50	8.54
60	10.40
70	12.55
80	15.67
90	22.97
95	29.52

The results depict that the particle size varies from 2.915 µm to 29.52 µm. The average particle size is considered for the experiment, i.e., 8.54 µm. Additionally, the graphs show that the particles are uniformly distributed in the tested sample.

The powder samples of BA and PA were examined under scanning electron microscopy (SEM) for examination of particle shape, and Energy-dispersive X-ray spectroscopy (EDS) was used to determine the elements that are present in the particles. The same was depicted in Fig. 10a, 10b (BA filler particles) and in Fig. 11a, 11b (PA filler particles). The elements in BA and PA, discovered through the EDS were depicted in Table 4 and 5 respectively.

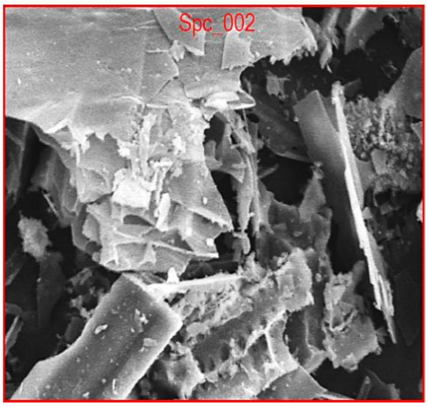

Fig. 10a. SEM Image of BA Filler Material

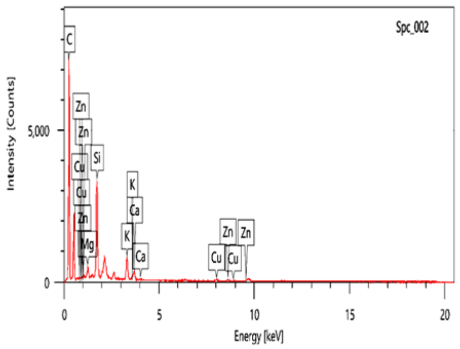

Fig. 10b. EDS of BA Filler

Table 4. Elemental Composition in BA particles

Element	% Wt.
C	83.48
Mg	0.93
Si	8.14
K	3.67
Ca	1.47
Cu	1.27
Zn	1.04

Fig. 11a. SEM Image of PA Filler Material

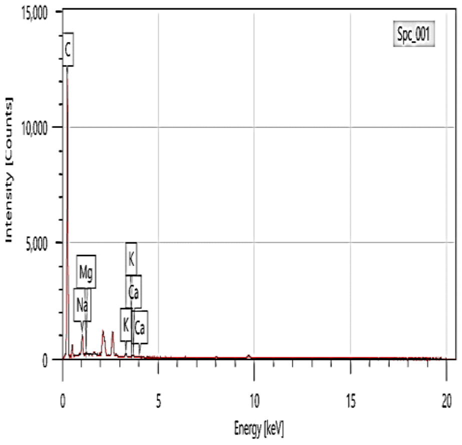

Fig. 11b. EDS of PA Filler

Table 5. Elemental Composition in PA particles

Element	% Wt.
C	94.16
Na	4.19
Mg	0.24
K	0.83
Ca	0.58

In the investigation conducted by Pappu and Thakur [2], it was evident that the consequences of high carbon content in agro-waste ash filler material on the mechanical properties of epoxy composites are a delicate balance, requiring careful consideration of the filler characteristics, matrix-filler interactions, and optimized processing conditions to maximize the composite's performance. Additionally, the presence of silicon in the agro waste ash fillers has been shown to improve the thermal stability and heat resistance of the composite, making it more suitable for applications that require exposure to elevated temperatures.

3.2 Density

The bulk density of the bagasse ash and pistachio shell ash is found to be 0.216 g/cc and 0.408 g/cc, respectively. The density of the composites with different weight percentages of filler materials BA and PA are illustrated in Fig. 12a and Fig. 12b, and the data is presented in Table 6 and Table 7. It was clearly evident from Fig. 12a and Fig. 12b that the density of the composites was decreased with an increase in filler content. When compared with composites with BA as a filler material, the composites with PA as a filler material have recorded lower densities. This means that PA-filled (PA10) epoxy composites are lighter in weight, and, when compared with pure epoxy, they are 26.08% less in weight. Additionally, the BA-filled (BA10) composite is 17.35% lighter in weight when compared with pure epoxy composite.

Table 6. Densities and percentage voids BA/Epoxy filled composites at various weight percentages

S.No.	Composite Code	Density (g/cc)		Percentage Voids
		ρ_{th}	ρ_{exp}	
1	BA2	1.13	1.08	4.54
2	BA4	1.11	1.03	7.43
3	BA6	1.09	1.03	6.30
4	BA8	1.08	0.99	8.30
5	BA10	1.06	0.98	7.72

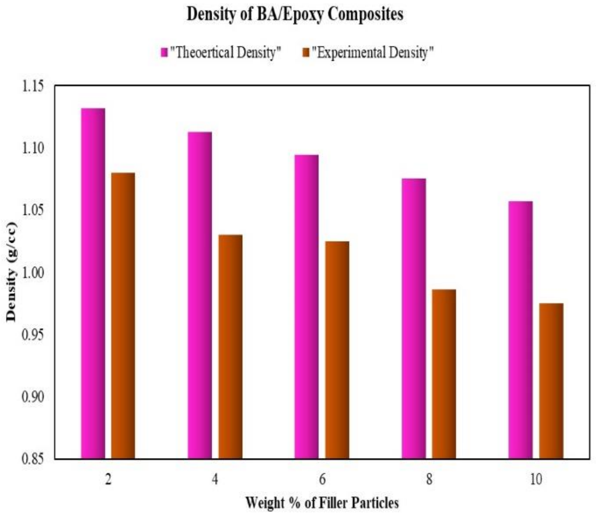

Fig. 12a. Density Variation of BA/Epoxy Composites

Table 7. Densities and percentage voids PA/Epoxy filled composites at various weight percentages

S.No.	Composite Code	Density (g/cc)		% Void
		ρ_{th}	ρ_{exp}	
1	PA2	1.11	1.08	2.67
2	PA4	1.07	0.99	8.12
3	PA6	1.04	0.91	12.43
4	PA8	1.00	0.89	10.95
5	PA10	0.97	0.85	12.34

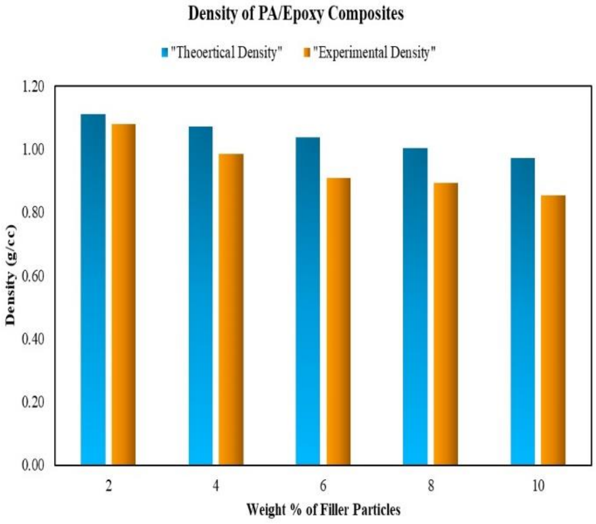

Fig. 12b. Density Variation of PA/Epoxy Composites

Void content in the composite significantly affects its performance when it is prone to loading conditions. The void content in the composite was calculated using Eq. 4. The percentage void content in the epoxy-filled composites is depicted in Table 8, and a comparative graph between the BA and PA epoxy composites with variation in void content is shown in Fig. 12c.

Table 8. Percentage Void Content of the BA/Epoxy and PA / Epoxy Composites

S.No.	Percentage Weight of Filler	Percentage Voids	
		BA / Epoxy	PA / Epoxy
1	2	4.54	2.67
2	4	7.43	8.12
3	6	6.30	12.43
4	8	8.30	10.95
5	10	7.72	12.34

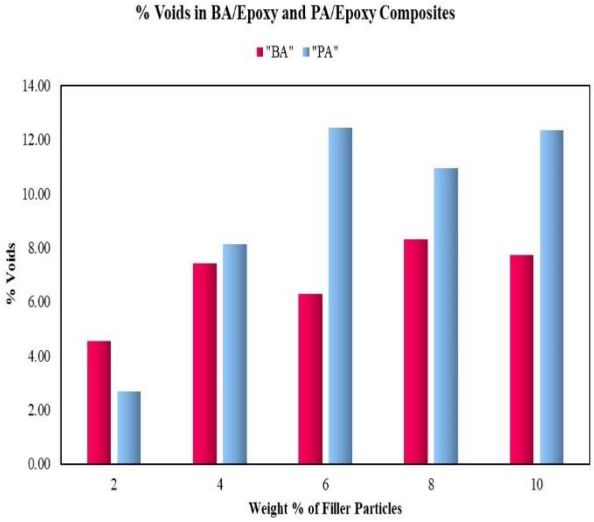

Fig. 12c. % Void Content Variation of BA/Epoxy and PA/Epoxy Composites

It was observed that from table 6 and Fig. 12c, the highest void content is present in the PA6 (12.43%) and PA8 (12.34%) composite; on the other hand, the lower values are recorded with PA2 (2.67%) and BA2 (4.54%).

From the above results, it is evident that, as filler content increased, the experimental density decreased for both composites, while void content increased more significantly in PA composites. This is attributed to the smaller average particle size of PA (8.54 µm) compared to BA (17 µm), promoting agglomeration and air entrapment during fabrication. Both fillers have a high carbon content, contributing to their lower density compared to the epoxy. While the minor elements present in both ash types (Si, K, Ca, Mg, Zn in BA; Na, Mg, K, Ca in PA) can potentially influence mechanical properties through interactions with the epoxy matrix. The higher void content in PA composites, resulting from smaller particle sizes, is the primary factor driving their lower overall density compared to BA composites.

According to Jang et al. [26], voids within composites disrupt effective load transfer between fibers and the matrix, leading to uneven stress distribution and a greater tendency for failure. These voids not only diminish the composite's load-bearing capacity but also weaken the bond at the fiber-matrix interface and create pathways for moisture entry. Consequently, the presence of voids promotes crack initiation and accelerates material degradation, thereby reducing the composite's overall strength, durability, and mechanical performance.

The techniques for reducing voids in fiber-reinforced composites are also applicable to epoxy composites that contain fillers. Using low-viscosity resins aids in effectively wetting the filler particles and limits air entrapment. Surface treatments on fillers, such as applying a coupling agent, enhance wettability and help reduce void formation. Additionally, controlling the size and distribution of filler particles minimizes empty spaces within the composite. Techniques such as vacuum mixing, degassing, centrifugal and pressure casting, and optimized curing cycles are beneficial for reducing voids. In filler-only composites, carefully adjusting filler loading and ensuring uniform dispersion is essential for achieving target properties and limiting void content. The specific approach depends on the filler type, its concentration, and the performance goals of the composite [27].

3.3 Tensile Strength

The tensile test results of the epoxy composites were demonstrated in the below Fig. 13a, 13b, 13c and 13d. The impact of filler content in the epoxy composites has shown a positive trend in the increase of strength in the epoxy composites. It is evident from Fig. 13a and 13b that the tensile load and tensile strength followed a similar trend. In the case of BA-filled epoxy composite, the maximum tensile strength is obtained for BA6 composite (19.16 MPa) and lowest for BA8 (13.74 MPa); on the other hand, for PA composites, the highest tensile strength was recorded for PA6 (11.49 MPa) and lowest for PA8 (8.54 MPa). When compared with BA6 composite, the tensile strength and load-carrying capacity of BA2, BA4, BA8 and BA10 composites are 3.20 %, 20.96 %, 30.72% and 25.60% lower, respectively. Likewise, when compared with PA6 composite, the tensile strength and load-carrying capacity of PA2, PA4, PA8 and PA10 are 19.76%, 17.74%, 25.73% and 13.87% lower, respectively.

The standard deviation of tensile strength in both Bagasse Ash (BA) and Pistachio Shell Ash (PA) composites provides insight into the consistency of these materials under tensile loads. In the case of BA, the standard deviation values are relatively moderate, with BA6 showing the highest tensile strength with a standard deviation of 1.13 MPa. This moderate variance suggests that BA fillers provide relatively stable reinforcement, allowing for a fairly uniform tensile response across different samples, especially at the 6% filler level, where agglomeration effects are minimized. In contrast, PA composites show higher standard deviation values (PA2 with 3.24 MPa), indicating more variability in tensile performance. This larger variability could stem from differences in filler dispersion, with PA composites more prone to inconsistent particle distribution, leading to weaker areas within the matrix.

The standard deviation of tensile load reflects similar trends as observed in tensile strength. BA composites display consistent load-bearing capacity with moderate standard deviations, with BA4 and BA6 exhibiting lower standard deviations (7.08 and 7.34 kg, respectively), indicating stable reinforcement at these filler levels. PA composites, however, demonstrate greater variance in load capacity, as seen with PA2 (21.15 kg) and PA8 (17.52 kg). This high deviation in PA composites might result from the less cohesive bonding between PA particles and the epoxy matrix, resulting in inconsistent stress distribution and higher susceptibility to premature failure.

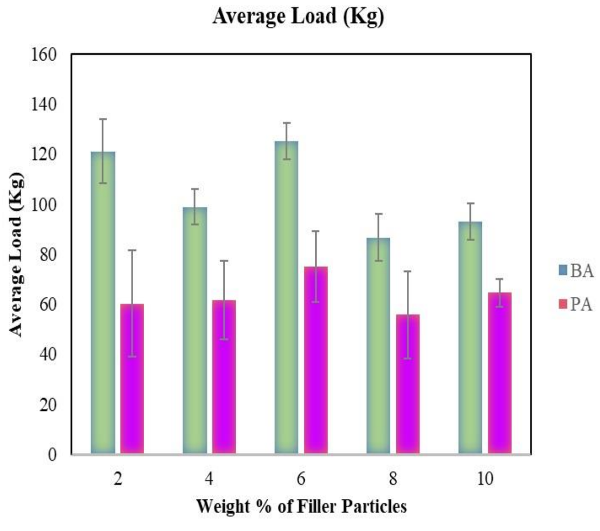

Fig. 13a. Tensile Load of BA/Epoxy and PA/Epoxy Composites

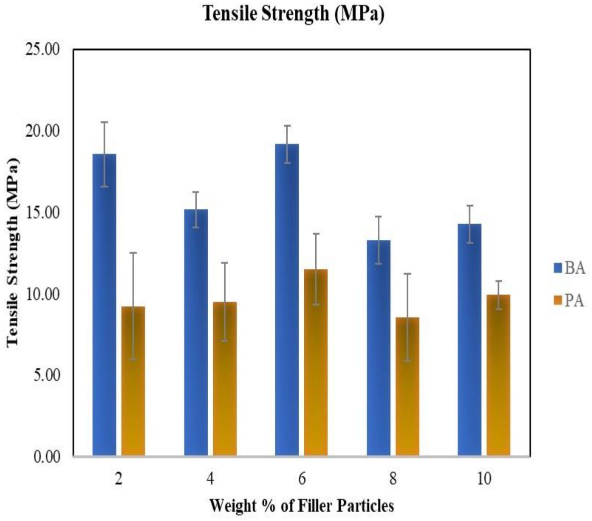

Fig. 13b. Tensile Strength of BA/Epoxy and PA/Epoxy Composites

Fig. 13c represents the tensile modulus of the composite. Tensile modulus is recorded higher with BA2 (60.68 MPa), and in the case of PA composites, the highest tensile modulus is observed with PA6 (35.39 MPa). On the other hand, the lowest tensile modulus is observed with composite BA8 (32.86 MPa) for BA/epoxy composite and for PA2 and PA8 (27.11 MPa) in the case of PA/epoxy composites. It was also observed that when compared with BA2, the composites BA4, BA6, BA8, and BA10 have 25.00%, 20.83%, 45.83% and 37.50% lower tensile moduli. Likewise, when compared with PA2 and PA8 composites, the tensile moduli of PA2, PA4, and PA10 are 21.43%, 14.29%, and 21.43% lower, respectively.

The tensile modulus standard deviation is notably lower in BA composites than in PA composites, reinforcing the observation that BA fillers contribute to a more consistent elastic response under load. For instance, BA2 shows a deviation of 9.46 MPa, whereas PA composites, such as PA6 (9.46 MPa) and PA4 (12.89 MPa), show slightly higher variability. The lower standard deviations in BA composites indicate that BA fillers help stabilize the matrix elasticity, resulting in a predictable stiffness increase that is beneficial in applications where controlled deformation is critical.

The standard deviation in % elongation is generally low across both BA and PA composites, suggesting relatively stable ductility characteristics. BA composites display slight variability in elongation, with deviations ranging from 0.13 to 0.20 for BA6 and BA8, respectively. However, PA composites show slightly higher deviations (e.g., PA2 at 0.35), which could reflect less uniform filler-matrix interactions, leading to inconsistencies in elongation at break. Lower elongation variability in BA composites aligns with their overall stability in tensile properties, indicating better filler dispersion and matrix compatibility.

This aligns with the general trend in filled polymer composites, where excessive filler content can have detrimental effects.

Comparing this study with Ogah et al. [28], which used Bambara nut shell fiber, reveals a similar trend of increasing tensile strength up to an optimal filler loading followed by a decrease. However, in the article by Ogah et al. [29], the optimal loading (15 wt%) is significantly higher than in this study (6 wt%). This difference is likely due to the varying nature of the fillers and their interaction with the epoxy matrix. Bambara nut shell fiber may have better interfacial adhesion or dispersion, allowing for higher filler loadings before agglomeration dominates.

Similar to castor bean shell-filled epoxy composites discussed in [29], this study also observed an optimal filler loading at 6%wt of Bagasse Ash (BA) for maximum tensile strength and modulus. The decrease in properties beyond this point is attributed to inefficient dispersion and agglomeration, highlighting the importance of controlling filler dispersion.

While Umarfarooq et al. [30] focus on hybrid nanoparticle reinforcements in epoxy-PLA composites, the concept of optimizing filler loading is relevant. It was also shown that specific combinations and concentrations of hybrid nanoparticles can significantly improve tensile strength, reinforcing the importance of controlling filler characteristics and dispersion for optimal performance.

Sienkiewicz and Czub's [22] study on epoxy composite properties reveals that natural fillers can improve mechanical performance. They found that silanized fillers showed better properties than unmodified ones. The study also highlighted the importance of filler size and morphology in influencing dispersion and bonding. It also suggested that natural fillers could contribute to the curing process.

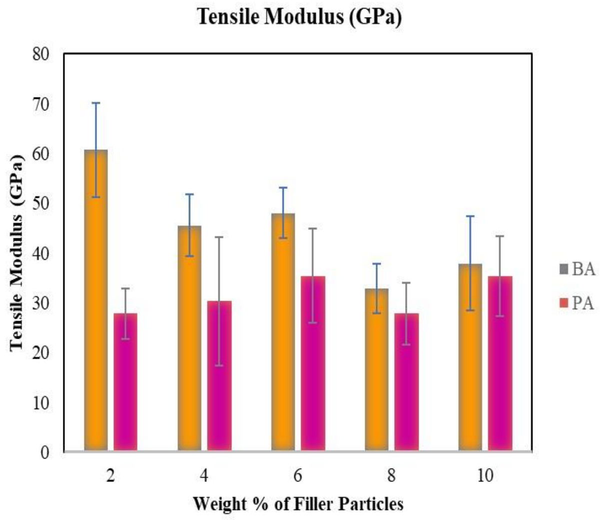

Fig. 13c. Tensile Modulus of BA/Epoxy and PA/Epoxy Composites

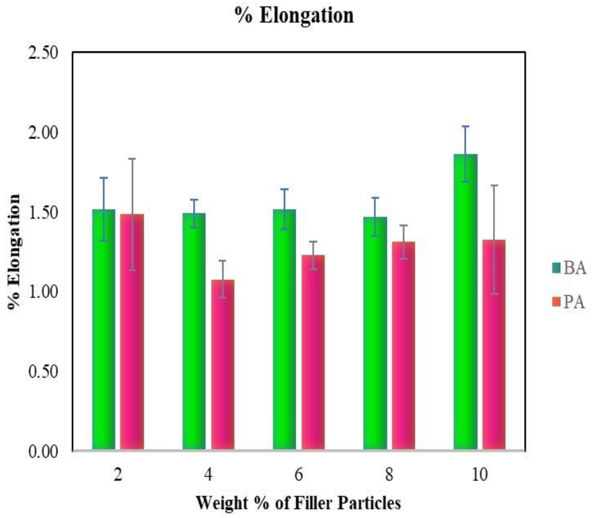

Fig. 13d. % Elongation of BA/Epoxy and PA/Epoxy Composites

The SEM micrographs of the fractured surfaces of the tensile specimens were demonstrated in Fig. 14a, 14b and 14c for BA/Epoxy composite and in Fig. 15a, 15b and 15c for PA/Epoxy composites.

SEM images clearly show agglomeration of BA and PA fillers, acting as stress concentrators and initiating cracks. This aligns with Sharma et al. [31], which found that larger CLP filler particles in epoxy composites led to increased void content and decreased mechanical properties due to agglomeration. Similarly, Rodriguez et al. [32] highlight the importance of filler morphology and dispersion in dental resin composites, noting that non-aggregated nanofillers contribute to better mechanical properties compared to larger, irregularly shaped particles. Mohan and Kanny [33], while focusing on nano-sized eggshell particles, also emphasizes the importance of uniform dispersion, with agglomeration at higher loadings leading to decreased elongation. Saravanakumaar et al. [34] discuss the impact of filler size and distribution on natural fiber-polymer composites, reinforcing the idea that agglomeration negatively affects mechanical performance.

The presence of stream-like cracks emanating from the agglomerates further confirms their role as stress concentration points. These cracks propagate through the matrix, ultimately leading to failure.

Voids and air bubbles, visible in the SEM images, are another significant factor contributing to the reduced mechanical properties. These imperfections weaken the material by reducing the effective load-bearing area.

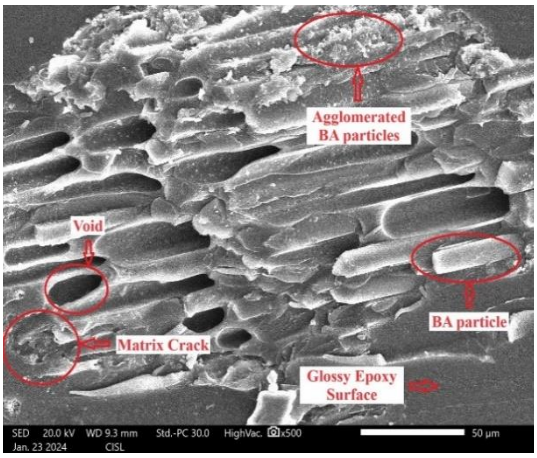

Fig. 14a. SEM micrographs of fractured tensile tested bagasse ash epoxy composite specimens at 500x magnification

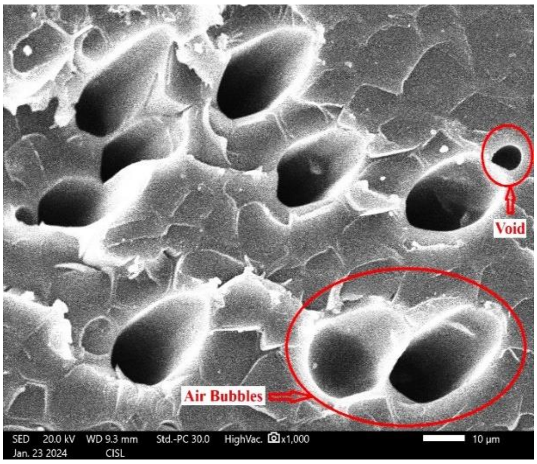

Fig. 14b. SEM micrographs of fractured tensile tested bagasse ash epoxy composite specimens at 1000x magnification

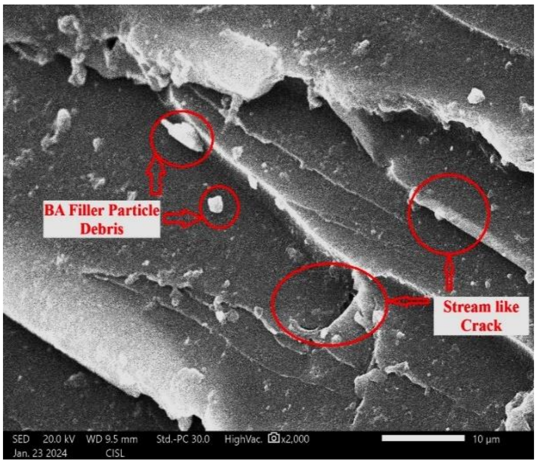

Fig. 14c. SEM micrographs of fractured tensile tested bagasse ash epoxy composite specimens at 2000x magnification

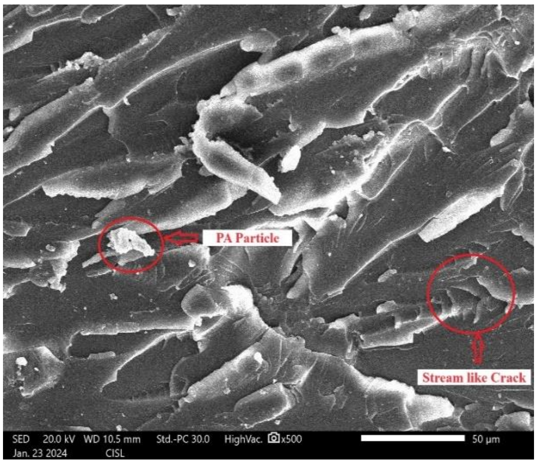

Fig. 15a. SEM micrographs of fractured tensile tested pistachio ash epoxy composite specimens at 500x magnification

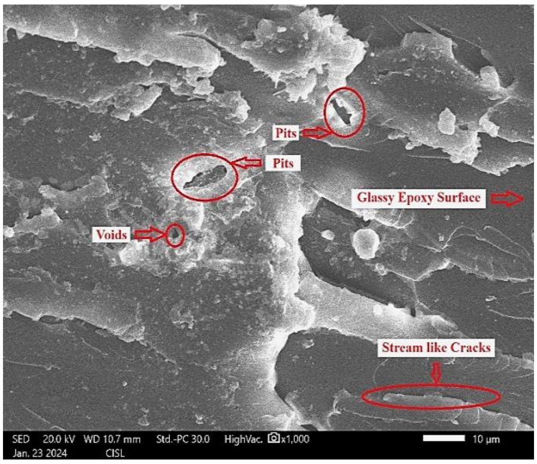

Fig. 15b. SEM micrographs of fractured tensile tested pistachio ash epoxy composite specimens at 1000x magnification

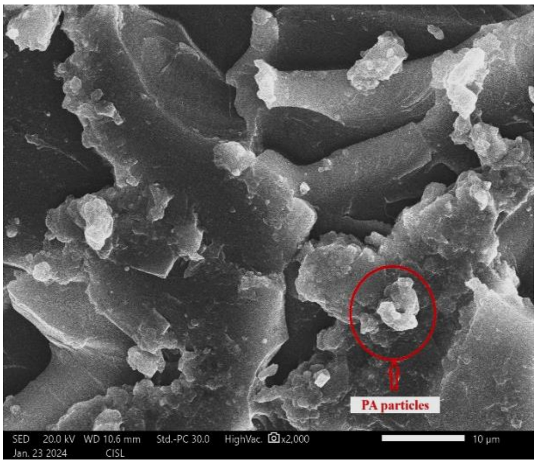

Fig. 15c. SEM micrographs of fractured tensile tested pistachio shell ash epoxy composite specimens at 2000x magnification

3.4 Flexural Strength

The flexural test results for different weight percentages of epoxy composites were depicted in Fig. 16a and Fig. 16b. From the experiments, it can be noted that the BA/epoxy composites performed superiorly to PA/epoxy composites. It was evident that from Fig. 16a, the BA2 composite gained higher flexural strength (137.58 MPa), and in the case of PA/epoxy composites, PA2 and PA10 (115.72 MPa) achieved the highest flexural strength. When compared to the BA2 composites, the composites BA4, BA6, BA8 and BA10 are 35.71%, 31.78%, 43.93% and 5.61% lower in flexural strength. In a similar way, when compared with the PA2 composite, the composites PA4, PA3, PA8 and PA10 have 61.11%, 55.56% and 5.56% lesser flexural strengths. However, a similar behaviour of flexural strength was observed by Ozsoy et al. [35] and they found that the presence of filler with rigid behaviour may be the reason.

The flexural strength standard deviations for BA composites are relatively moderate, with BA2 exhibiting the lowest deviation (18.45 MPa), indicating stable reinforcement under flexural stress at this filler level. As filler content increases, deviations in BA composites become more pronounced, such as in BA10 (27.70 MPa), suggesting a higher tendency for agglomeration and potential void formation at elevated filler concentrations. This trend indicates that an optimal filler loading exists, beyond which structural uniformity decreases, thus increasing variability. PA composites, in contrast, display significantly higher deviations, such as PA2 at 35.68 MPa. This higher variability suggests that PA fillers may not reinforce the matrix as consistently as BA fillers, possibly due to weaker interfacial bonding and less predictable distribution within the matrix.

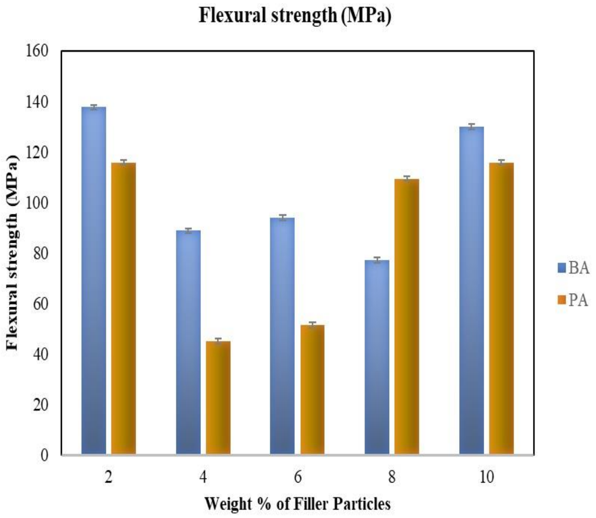

Fig. 16a. Flexural Strength of BA/Epoxy and PA/Epoxy Composites

Subsequently, Fig. 16b demonstrates the trend for flexural modulus of the composites with different fillers and weight percentages. The BA2 composite gained a higher flexural modulus (564.69 MPa), and in the case of PA/epoxy composites, PA2 and PA10 (518.56 MPa) achieved the highest flexural modulus. When compared to the BA2 composites, the composites BA4, BA6, BA8 and BA10 are 35.71%, 31.78%, 43.93% and 5.61% lower in flexural strength. In a similar way, when compared with PA2 and PA10 composite, the composites PA4, PA6, and PA8 have 27.64%, 18.89% and 12.40% lesser flexural modulus.

In terms of flexural modulus, BA composites also exhibit more consistent results compared to PA composites. The standard deviation for BA2 (13.66 MPa) is lower than in PA composites (e.g., PA2 at 31.40 MPa), indicating that BA fillers enhance the rigidity of the epoxy matrix in a more uniform manner. As filler concentration increases, BA composites show some increase in deviation but remain relatively stable compared to PA composites. This stability in flexural modulus deviation suggests that BA fillers better integrate with the epoxy matrix, providing a more controlled increase in stiffness that benefits structural applications. PA composites, however, display higher variance, likely due to less uniform stress transfer, possibly caused by weak filler-matrix adhesion.

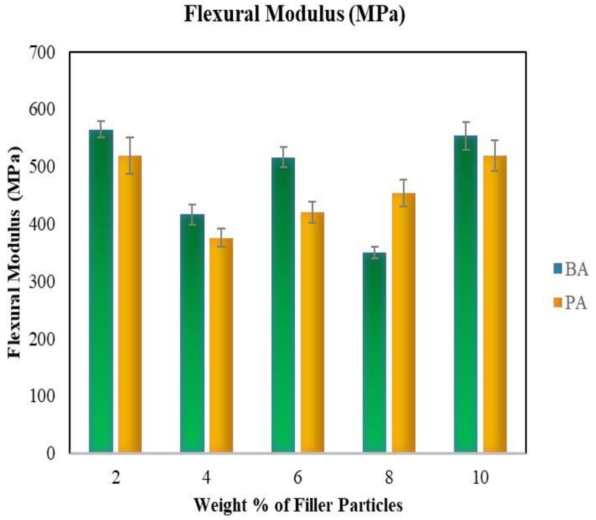

Fig. 16b. Flexural Modulus of BA/Epoxy and PA/Epoxy Composites

3.5 Impact Strength

The impact strength for different weight percentages of epoxy composites was depicted in Fig. 17. A similar trend was also observed from the impact strength that BA/epoxy composites performed superior to PA/epoxy composites. It can be noted that from Fig. 17, the BA4 composite gained a higher impact strength (1.98 kJ/m^2), and in the case of PA/epoxy composites, PA6 (1.76 kJ/m^2) had the highest impact strength. When compared to the BA4 composites, the composites BA2, BA6, BA8 and BA10 are 13.23%, 30.44%, 20.65% and 43.16% lower in impact strength. In a similar way, when compared with the PA6 composite, the composites PA2, PA4, PA8 and PA10 have 10.08%, 44.65%, 36.90%, and 29.67% lesser impact strengths.

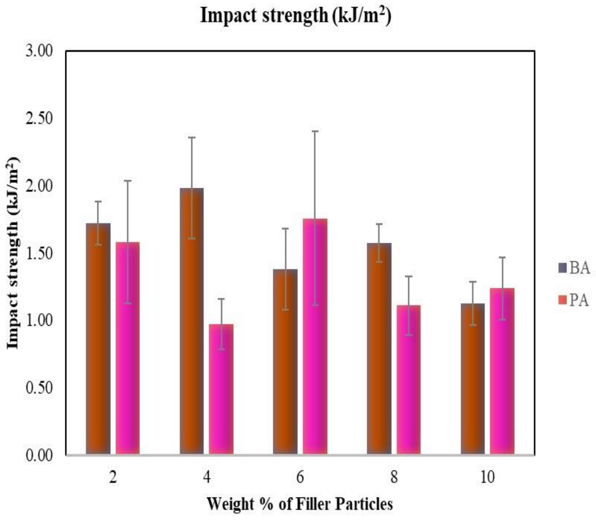

Fig. 17. Impact Strength of BA/Epoxy and PA/Epoxy Composites

The addition of bagasse ash particles led to an increase in the hardness and compressive strength of the composites, while the impact energy decreased as the weight percent of bagasse ash increased [36]. In contrast, the lower impact strength of the pistachio shell ash/epoxy composites may be due to the less effective load transfer between the pistachio shell ash particles and the epoxy matrix [37,38].

The impact strength standard deviations provide critical insights into the toughness and energy-absorbing capacity of the composites. BA composites show relatively lower deviations, especially at optimal filler levels, with BA4 having a standard deviation of 0.37 kJ/m². This lower variance indicates that BA fillers improve impact resistance consistently, likely due to their morphology and strong adhesion to the matrix, which promotes even stress distribution during impact loading.

PA composites, however, exhibit higher standard deviations in impact strength, as seen with PA6 (0.65 kJ/m²), suggesting less reliable performance under impact conditions. The higher variability in PA composites could be due to inconsistent filler dispersion or weaker interfacial bonding, resulting in uneven stress dissipation and a higher likelihood of fracture initiation at weaker sites. This variability in PA composites limits their predictability in high-impact applications, where uniform energy absorption is essential. Overall, the relatively stable standard deviations in BA composites make them more suitable for applications demanding reliable toughness and impact resistance.

4. CONCLUSION

This study demonstrates the potential of using agricultural byproducts like BA and PA as lightweight materials in polymer composites. These fillers not only enhance mechanical properties but also contribute to waste management and eco-friendly material production. Key findings indicate that BA composites generally exhibit superior mechanical properties compared to PA composites.

- BA fillers demonstrated superior performance due to their larger particle size, lower void content, and beneficial elemental composition (including silicon and minor elements like potassium and calcium). These characteristics contributed to more stable filler dispersion, enhanced filler-matrix bonding, and improved load transfer capabilities.

- PA fillers, despite their higher carbon content and lower density, exhibited challenges in achieving uniform dispersion. The finer particle size of PA led to higher agglomeration tendencies, resulting in increased void content and more significant variability in mechanical properties. This variability limits their reliability in load-bearing applications without further optimization in processing techniques or surface treatments.
- Tensile Strength of BA-filled composites peaks at 6 wt% filler loading, with BA6 achieving a maximum of 19.16 MPa, a 66.74% increase compared to PA-filled composites. This is due to increased agglomeration and void content, which impair stress transfer between the matrix and filler particles. The void content affects the composites' tensile performance, with higher content disrupting matrix continuity and leading to premature failure. BA composites have lower standard deviations, indicating more stable reinforcement, while PA composites display higher variability due to finer particle size, resulting in uneven stress distribution and a higher likelihood of localized failure.
- Flexural Strength of BA-filled composites is 18.87% higher when compared to PA composites at their optimal loadings. The flexural modulus, a measure of the composite's stiffness, also shows superior performance in BA composites, with the highest recorded at 564.69 MPa. The higher void content in BA composites, resulting from larger particle size, enhances stress distribution under bending loads. The void content also plays a significant role in determining the flexural performance of the composites. BA composites have lower variability in flexural strength, indicating more stable reinforcement and uniform stress distribution. However, higher variability in PA composites suggests less predictable performance under bending loads due to weaker interfacial bonding and inconsistent filler dispersion.
- BA-filled composites showed superior impact strength, with BA4 recording the highest value of 1.98 kJ/m². PA-filled composites had the maximum strength at PA6, with 1.76 kJ/m². An initial increase in strength was 4 wt% for BA and 6 wt% for PA. However, beyond this point, strength declined due to increased filler agglomeration and void content. Void content, a critical factor affecting composite performance, disrupted the load path, causing cracks. PA composites had higher void content, leading to reduced strength. BA composites showed consistency, with a standard deviation of 0.37 kJ/m², due to larger particle size and uniform energy absorption.
- Future studies should focus on optimizing filler content, developing hybrid composites, and evaluating thermal and environmental properties. Additionally, research should explore degradation and recycling processes and advanced processing techniques and assess the cost-effectiveness and sustainability of these and similar composite materials through life cycle assessments.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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