Received: 24 October 2023 | Revised: 7 December 2023 | Accepted: 19 December 2023

DOI: 10.1002/pc.28088

RESEARCH ARTICLE

Polymer COMPOSITES WILEY

Elaeocarpus ganitrus (rudraksha) seeds as a potential sustainable reinforcement for polymer matrix composites

Agustinus Purna Irawan[1] | **Januar Parlaungan Siregar**[2,3] | **Tezara Cionita**[4] | **Deni Fajar Fitriyana**[5] | **Ahmad Alias**[2] | **Rusiyanto Rusiyanto**[5] | **Jamiluddin Jaafar**[6] | **Pungkas Prayitno**[7] | **Rifky Ismail**[8] | **Athanasius Priharyoto Bayuseno**[8] | **Ayub Ahmed Janvekar**[9]

[1]Faculty of Engineering, Universitas Tarumanagara, Jakarta, Indonesia

[2]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Pahang, Malaysia

[3]Automotive Engineering Center (AEC), Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Pahang, Malaysia

[4]Faculty of Engineering and Quantity Surveying, INTI International University, Nilai, Malaysia

[5]Department of Mechanical Engineering, Universitas Negeri Semarang, Kampus Sekaran, Gunungpati, Indonesia

[6]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Malaysia

[7]Department of Mechanical Engineering, Faculty of Engineering, Universitas Pamulang Serang, Banten, Indonesia

[8]Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University, Semarang, Indonesia

[9]School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India

Correspondence
Januar Parlaungan Siregar, Faculty of Mechanical and Automotive Engineering Technology, Universiti of Malaysia Pahang Al-Sultan Abdullah (UMPSA), Gambang 26300, Pahang, Malaysia.
Email: januar@umpsa.edu.my

Funding information
Universitas Tarumanagara under the

Abstract

Creating environmentally friendly materials like polymer matrix composites (PMCs) enhanced with natural fillers has grown in recent decades. It supports the United Nations sustainable development goals (SDGs) by reducing the reliance on non-renewable resources, minimizing waste generation, and promoting sustainable land and water management practices. This investigation assesses the viability of employing *Elaeocarpus ganitrus* (rudraksha) seeds as a filler (rudraksha seed filler [RSF] in environmentally sustainable composite materials. Various loading concentrations and sizes of RSFs were incorporated by hand lay-up into polymer epoxy resin (ER). The effect of filler on the mechanical properties of composites was observed. Thermal properties of RSF/epoxy composites were investigated using thermogravimetric analysis (TGA) and Fourier transform infrared (FTIR). The 10 wt% 100-mesh filler had the maximum tensile strength (TS) at 42.30 MPa and flexural strength (FS) at 87.4 MPa, surpassing other filler sizes and loading concentrations. Meanwhile, the highest impact properties have been achieved with 20 wt% of RSF with 0.436 J. The results of this study highlight the significant impact of filler type and concentration on the mechanical properties of the material. These findings offer valuable insights that may be applied to various industrial contexts. Furthermore, incorporating 10% up to 30 wt% RSF in epoxy composites has brought more thermal stability than virgin epoxy. It revealed that the RSFs possess higher decomposition temperatures than the epoxy matrix. RSF has a potential sustainable reinforcement in polymer composites and holds great promise for addressing environmental challenges and aligning with several SDGs.

Highlights

- Interest in eco-friendly materials, like polymer composites with natural reinforcements, has been increasing in recent decades.

Research International Collaboration, Grant/Award Number: 1831-Int-KSln-KLPPM/UNTAR/XI/2021

- Rudraksha sees filler is lightweight with low moisture, high carbon content, and some mineral elements.
- The addition of Rudraksha seed filler has enhanced the tensile, flexural, and impact properties of the composites.
- Rudraksha seed filler possess higher decomposition temperatures than the epoxy matrix.
- Rudraksha seed filler has a promising future as a sustainable friction material for automotive brake pads.

KEYWORDS

Elaeocarpus ganitrus, natural filler, rudraksha, sustainable development goals, sustainable materials

1 | INTRODUCTION

Polymer composites, composed of a polymer matrix and reinforcing fillers, are frequently utilized in the construction, packaging, consumer products, automotive, and aerospace industries, among other areas.[1,2] Due to their inherent characteristics, such as those of glass fiber and carbon fiber, common synthetic fillers have restrictions on their impact on the environment and the availability of resources. Moreover, investigating natural fillers as reinforcement in polymer composites has progressed in engineering and material science.[3,4] Examining the mechanical, thermal, and morphological characteristics of natural-filled composites, as well as improving processing methods to ensure even dispersion and effective load transfer inside the composite structure, have been the main study areas.[5,6]

Filler size and filler loading are two important variables that profoundly affect the characteristics and performance of polymer composites. For composite materials to be properly tailored to meet application requirements, it is essential to understand the mechanisms by which these constituents interact.[1,7,8] Furthermore, the size of the filler particles has an impact on the composite's mechanical properties. Fillers that are nanoscale in size have a high surface area-to-volume ratio, which improves molecular reinforcement. As a result, the composite has an increased modulus, stiffness, and tensile strength (TS). Micron-sized fillers can patch cracks in polymer matrixes, enhancing the material's mechanical characteristics and interfacial adhesion. Even though particles may not offer the same level of reinforcement, macro-sized fillers can provide the composite with certain mechanical properties like toughness or ductility.[7,9–11] Additionally, the amount of filler in the composite has a significant impact on its mechanical properties as well. The mechanical properties of the composite regularly become stronger since filler dispersion and reinforcement work well at lower filler loadings. Lower filler loadings effectively disseminate the fillers throughout the matrix, which increases stiffness and strength due to the particles' improved capacity to support loads. High filler loading, on the other hand, might induce agglomeration and insufficient interfacial bonding, reducing the material's strength and impact resistance.[12–14]

Numerous studies have been conducted to determine the effects of natural filler size and loading on the tensile properties of epoxy composites. The tensile properties of composites have been discovered to be significantly influenced by the size and loading of fillers. TS and tensile modulus (TM) generally rise as filler content does.[15,16] As filler loading rises, tensile strain tends to climb.[17] Additionally, the outcomes reveal that the sizing of the fillers can enhance the composites' mechanical properties.[18] It is important to consider, though, that there might be a point at which additional filler loading increases could lead to a decline in tensile properties.[19] Cionita and coworkers examined how filler affects the flexural properties of an epoxy resin (ER)-reinforced composite made of untreated palm kernel cake filler (UPKCF). The results suggest that the maximum flexural strength (FS) and flexural modulus (FM) peak at 30% filler content before dropping to a minimum at 40% filler content as the filler load concentration increases. With 40% filler loading, the UPKCF/ER composites in FS and FM were lowered by 39% and 23%, respectively. This can be caused by deterioration in the interfacial adhesion between the hydrophobic epoxy matrix polymer and the hydrophilic UPKCF.[1]

An investigation carried out by Verma et al. (2020) explores the potential of pyrolyzed carbon black, obtained from used tires, as a filler in epoxy resin composites. The study focuses particularly on the utilization of carbon black in coating materials. The primary aim of this research endeavor is to examine the effects of varying

proportions of carbon infill on the composites' physical, mechanical, and thermal properties. The evaluation of the composites' mechanical properties was conducted through a variety of experiments. Note that the UTS and percentage elongation were determined to be the tensile properties. As a result of the addition of carbon black infill, the UTS increased, according to the study's findings. This observation implies that the enhanced strength can be attributed to the reinforcing effect of the carbon particles. The implementation of carbon black infill led to a progressive increase in the compression parameters, such as the ultimate compressive strength and strain at failure. As the quantity of filler increased, the flexural properties, particularly the flexural strength and flexural modulus, demonstrated a decreasing trend. Additionally, a decrease in both impact energy and intensity was noted in correlation with the increase in filler concentration. With an increase in filler quantity, the hardness of the composites demonstrated a progressive rise. The mechanical properties exhibited by these composites provide significant insights regarding the potential applications and performance attributes of coating materials.[20]

On the other hand, Marichelvam et al. (2021) investigate the automotive application of a hybrid palm sheath and sugarcane fiber-reinforced ER composite. The objective of the research was to evaluate the performance of the composite material and ascertain the most effective composition for fabricating a dashboard to decrease the weight of the vehicle and improve its fuel economy. The mechanical properties testing findings revealed that the composite material possessing the most favorable mechanical properties was the one consisting of palm and bagasse fiber in a weight proportion of 60:40. In particular, the material exhibited the following characteristics: TS of 19.80 MPa, Young's modulus of 0.953 GPa, an FS of 28.79 MPa, an impact strength of 2 kJ/m^2, and a hardness value of 38.02 HD. Based on these findings, the optimal sample for the construction of an automobile dashboard was determined.[21]

In 2022, Chandrika et al. investigated the impact strength of sugarcane bagasse ash, madar fiber, and ER composites. Impact energy increased by 22.28% as a result of the 7 wt% increase in the filler material. Furthermore, the impact strength of the madar fiber/ER composites made of sugarcane bagasse ash was 22.28% greater than that of clean madar fiber/ER composites, measuring 17.5 kJ/m^2 at 7 wt% filler loading. Researchers discovered that composites comprised of madar fiber, ER, and sugarcane bagasse ash could absorb much energy while preventing crack development. Note that ER, madar fibers, and sugarcane bagasse ash were combined to create composites. Since the filler was spread evenly throughout the matrix and the surfaces adhered effectively to one another, these composites exhibited a higher impact strength. Hence, the impact strength was decreased due to facile energy absorption and crack avoidance.[22]

The filler loading in polymer composites significantly impacts thermal behaviors, as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) demonstrate. With increased filler content, thermal stability improves since the fillers serve as heat sinks, dispersing heat and delaying degradation. Furthermore, including fillers reduces polymer chain mobility, resulting in a slower TGA degradation rate.[23–25] Some fillers can encourage char formation, providing a protective layer during breakdown. Filler loading influences the glass transition temperature (T_g) in DSC, increasing it due to reduced chain motion. Furthermore, fillers influence crystallization behaviors by supplying nucleation sites, modifying crystallinity, and influencing the latent heat of crystallization. Thus, understanding these mechanisms is critical for modifying thermal behaviors in polymer composites for various applications requiring increased thermal stability and specific thermal transitions.[7,23,26–28]

Jawaid and colleagues investigated the thermal properties of oil palm empty fruit bunch (OPEFB) composites with varied weight fractions of jute fibers. Decomposition of the hybrid composite (OPEFB/jute) started at a higher temperature (263–286°C) than that of the OPEFB composite alone (260°C), and the final degradation temperature ranges from 433 to 463°C. The final decomposition temperature of the composite is increased by hybridizing OPEFB with jute fibers.[29] Additionally, the thermal stability of the OPEFB composite improves with increasing jute fiber loading. This is due to jute's significantly superior heat stability compared to OPEFB fibers. As a result of the alkali-treated jute fiber (ATJF) polymer composites' thermal properties from Sajin et al. (2022), the weight loss of the composite occurs between 220 and 330°C due to degradation of the reinforcement material, notably cellulose, and hemicelluloses in ATJF. In contrast, the weight loss occurs at 100°C due to water evaporation from the specimen. In the alkali-treated jute fiber composite (ATJFC) sample, the peak between 340 and 450°C indicates isophthalic polyester (IP) is degrading. In contrast, the weight loss above 460°C indicates that lignin degrades in the ATJF sample. Note that the ATJFC specimen's thermal stability above the processing temperature is indicated by the peak of the DTG curve.[30]

According to the literature mentioned above, the type, size, loading, surface treatment, and compatibility of the fillers with the polymer matrix may all affect the filler loading's mechanical and thermal properties. The primary objective of this study is to analyze the impact of filler size and filler loading on the mechanical and thermal characteristics of epoxy composites that are

FIGURE 1 Process of rudraksha seeds to rudraksha fillers.

reinforced with a rudraksha seed filler (RSF). Knowledge regarding the properties and practical implementations of rudraksha as a reinforcing agent in polymer composites is noticeably limited. Hence, the scarcity of information highlights the necessity for additional investigation to delve into and clarify the potential of rudraksha to augment the characteristics of polymer composites. The present work encompasses a thorough investigation of the mechanical and thermal characteristics while also introducing a novel use of rudraksha fillers for enhancing the mechanical properties of polymer composites. The incorporation of rudraksha fillers is closely linked to many sustainable development goals (SDGs), underscoring the need for sustainable material development and responsible business practices. The exploration and utilization of rudraksha seeds in an innovative setting hold the potential for researchers and industries to actively contribute toward a future that is both ecologically mindful and socially responsible.

2 | EXPERIMENTAL SETUP

2.1 | Material

Elaeocarpus ganitrus, a species of plant that belongs to the *Elaeocarpaceae* family, is frequently referred to as a rudraksha. Numerous genera and approximately 350 species are spread over Southeast Asia, India, Indonesia, Nepal, China, Fiji, New Zealand, Hawaii, Malaysia, Madagascar, Australia, and New Guinea.[31] Rudraksha seeds were purchased from a supplier in Semarang, Indonesia. The processing of rudraksha seeds into rudraksha fillers is displayed in Figure 1. Consequently, the seeds were cleaned and rinsed with distilled water before being crushed. Subsequently, the filler was sieved using a sieve shaker with mesh sizes ranging from 30, 50, and 100.

In order to produce the polymer matrix utilized as a binder for the rudraksha filler, it was mixed with the epoxy hardener (651) product from Hexion, United States, in a weight ratio of 3:1. The epoxy and hardener were purchased from IZE Solution in Kuala Lumpur, Malaysia. Epikote 828 resin had a viscosity of 12–14 Pa.s at 25°C, a specific gravity of 1.16 at 25°C, a cure duration of 20–24 hours, and a transparent white color.

TABLE 1 Composition of rudraksha filler, epoxy, and hardener.

	Weight composition, wt%		
Materials	**RSF10/ER**	**RSF20/ER**	**RSF30/ER**
Rudraksha filler	10	20	30
Epoxy resin	152	144	136
Hardener	38	36	34

Abbreviations: ER, epoxy resin; RSF, rudraksha seed filler.

2.2 | Fabrication of specimen test

The RSF (RSH 30-mesh, 50-mesh, and 100-mesh) with constant loading at 10 wt.%, epoxies, and hardener were blended to produce varying filler sizes for the research study on the influence of filler sizes in epoxy polymer composites. At 100-mesh, filler loadings of 10 wt% (RSF10), 20 wt% (RSF20), and 30 wt% of RSF (RSF30) were employed. Table 1 summarizes the filler, hardener, and epoxy weights for each batch, which had a total weight of 200 g.

In order to maintain homogeneity and avoid bubble formation, the hardener was gradually added to the ER in a 3:1 ratio. The mixture was then agitated with a wooden stick. The liquid still had a few tiny bubbles despite efforts to reduce them. Subsequently, the mixture was stirred for 5 minutes while the filler was gradually added in two to three rotations. Prior to pouring the composite mixture into the mold, air bubbles were removed by vacuuming the mixture for 5 minutes at room temperature (25°C). A homemade funnel built from polyvinyl chloride (PVC) paper cone was used to pour the composite material into the mold to distribute it evenly. The

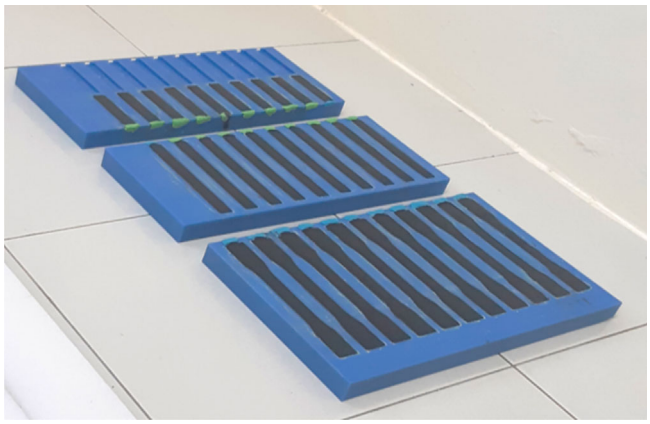


FIGURE 2 Composite specimen test.

composite was then allowed to cure for at least 24 hours at room temperature (Figure 2).

2.3 | Characterization of rudraksha filler

RSF emerges as a new potential filler material for Polymer Matrix Composites (PMCs), and detailed information on its properties is still limited. In the present study, moisture analysis, mass density measurement, x-ray diffraction (XRD) analysis, elemental analysis (EA) with a CHNS(O) analyzer, and inductively coupled plasma mass spectrometry (ICP-MS) were used to evaluate the important properties of RSF.

A moisture analyzer brand AND MX-50, which consists of a weighing and halogen heating device, were used to determine the moisture content using the loss on drying method. 5 g of RSF were weighed and dried at 105°C. The equipment will record the weight loss of moisture until it detects that the weight has remained constant, at which point it will stop automatically. The process takes between 10 and 15 minutes. For this experiment, five measurements with statistical averages were analyzed.

Rudraksha seeds were weighed in air and distilled water to determine their mass density in accordance with ASTM D792 standard.[32] A densimeter (Alfa Mirage model MD-300S) was used for this experiment. The measured density was a statistical average value from ten readings. The XRD was used to extract the physical, chemical, and structural properties of the material. Consequently, RSF was analyzed using a Bruker D8 Advance with Ni-filtered Cu-K, radiation (1 = 0.154 18 nrn), 40 kV, and 40 mA. The present method was carried out following procedures similar to those of the previous experiment.[33]

EA is an analytical chemistry technique used to evaluate the elemental composition of chemical compounds and their mixtures. The Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), and Oxygen (O) compositions were determined using the Vario Macro CHNS analyzer. In the present work, the oxygen intake pressure should be between 2.0 and 2.2 bar, and the helium intake pressure should be between 1200 and 1250 bar. The helium flow rate should be 600 mL/min, and the melt-flow controller (MFC)–thermal conductivity detector (TCD) should also be 600 mL/min. Control combustion tube 1150 and reduction tube 850 were used in the experiment, together with their respective functional software. In this experiment, three samples were weighed and packed in a foil tin. Finally, insert the packing sample on the vario macro cube elementar autosampler. Then, configure the technique based on the type of sample and run the experiment until it is complete.

In this study, it was proposed to measure Sodium (Na), Magnesium (M), Aluminum (Al), Calcium (Ca), Beryllium (Be), and other elements in rudraksha seed with an ICP-MS (ICP-MS 7500, Agilent, US). The procedure for such a technique is similar to that reported by Olalere et al.[34] A calibration method was developed using a multi-element standard solution. Five concentrations (0–50 ppm) of the standard solution and a blank of 2% nitric acid (HNO_3) were used to generate a calibration curve. The liquid sample was loaded into the ICP-MS nebulizer and spray chamber. The material was dried, evaporated, atomized, and ionized inside a plasma chamber with several heating zones. The elemental composition of the material was evaluated by turning the specimens into excited atoms with positively charged ions.

2.4 | Mechanical testing

According to the American Society for Testing and Materials (ASTM D638-14),[35] the type 1 tensile test specimen was produced with dimensions of 165 mm overall length and 19 mm width. Instron 3369, a universal testing device with a 50 kN capacity and a crosshead speed of 2 mm/min, was used in this experiment. Note that the flexural testing utilized the same instruments and methods. According to ASTM D790-15,[36] 127 mm × 12.7 mm × 3 mm flexural specimens were produced. According to ASTM D256-10,[37] the Izod impact test requires a specimen with dimensions of 64 mm × 12.7 mm × 3 mm. For each measurable parameter, a total of seven replicate specimens were evaluated.

2.5 | Scanning electron microscopy

Using a Hitachi TM3030 Plus scanning electron microscope (Hitachi, Tokyo, Japan), the tensile fractures of RSF/ER composites were investigated. Double electrically conductive carbon adhesive tapes were employed to mount the samples

on the mounting holder for assessments. The samples were initially sputter-coated with a thin palladium coating to prevent surface charge before being mounted on a scanning electron microscopy (SEM) holder. After that, the samples were analyzed under a microscope with 2 K and 5 K times magnification and a 10 kV acceleration tension.

2.6 | Thermogravimetric analyzer

The Hitachi STA7200 thermogravimetric analyzer (Hitachi, Fukuoka, Japan) was used to assess the thermal stability of ER, RSF, and composite fillers. Each sample comprised 10 mg of powdered material put into an alumina crucible before being heated under strict control in the furnace. The temperature was raised during the experiment at a constant rate of 10°C/min while nitrogen gas flowed at 20 mL/min. Thermal analysis was conducted in the temperature range of 30 to 900°C.

2.7 | Fourier transform infrared spectroscopy

The epoxy and RSF composite samples were run through Thermo Fischer's Nicolet iS50 Fourier Transform Infrared (FTIR) spectroscopic analyzer to investigate the possibilities of forming chemical bonds between the two components. Studies that could be identified in the scientific literature suggest that the IR spectrometer should be set between 4000 and 400 cm^{-1} [1].

3 | RESULTS AND DISCUSSION

3.1 | Properties of rudraksha

The mechanical and chemical properties of the RSF, such as moisture content, density, XRD, EA, and ICP-MS, are tabulated in Table 2. The percentage of moisture in the RSF used in this study is around 7.7%. According to earlier studies, fibers made from natural sources typically have moisture contents ranging between 7% and 15%.[38,39] It is critical to determine the natural fillers' moisture content before the candidate material is incorporated with epoxy polymer resin to preserve the composite material's performance and effectiveness. Deranged moisture content in the fillers is known to potentially deteriorate the binding efficacy, affecting the composite's material mechanical properties. Additionally, the presence of excess moisture may also interfere with the curing process, affecting the material's consistency in its size and structural stability. Furthermore, excessive water molecules may cause cosmetic damage to the material to an extent, inherently degrading its presentation aesthetically. It is required to dry the filler material at approximately 105°C for 24 hours to ensure that its moisture level is within acceptable range before the mixing can take place.[40,41]

TABLE 2 Result of rudraksha analysis.

Type of analysis	Unit value	Results
Moisture content	%	7.7 (± 0.2)
Density	g/cm^3	1.052
XRD	–	Carbolite/Carbon (C)
		Hydrogen (H_2)
		Nitrogen (N)
		Oxygen (O_2)
Elemental analysis	%	Carbon (C): 48.46
		Hydrogen (H_2): 6.37
		Nitrogen (N): 0.54
		Sulphur (S): 0.08
		Oxygen (O_2): 44.5
ICP-MS	Parts per million (ppm)	Sodium (Na): 11.86
		Magnesium (Mg): 99.87
		Aluminium (Al): 33.43
		Potassium (K): 216.13
		Calcium (Ca): 627.48
		Other materials: Not detected (less than 0.1)

Abbreviations: ICP-MS, inductively coupled plasma mass spectrometry; XRD, x-ray diffraction.

From analytical data, the rudraksha filler has been reported to have a density of approximately 1.052 g/cm^3. Most natural fibers are known to have mass densities between 1.2 and 1.51 g/cm^3.[42] As such, against that of hemp, jute, coir, banana, sisal, kenaf, ramie, pineapple, and cotton fibers, rudraksha has a relatively lighter mass occupying the same volumetric space. This indicates that the RSF has the potential to be used as a lightweight material in the reinforcement of polymers.

Figure 3 illustrates XRD analysis tracing rudraksha chemical elements such as C, H, N, and O. The XRD patterns of activated carbon from rudraksha seeds were mapped to match those of amorphous carbon. They both had two similar broad peaks in the weak diffraction 2 theta range of approximately 23° and 34° (after comparison with the JCPDS 00–050-0926 card). Therefore, the results from the present investigation are consistent with those data reported by other studies that rudraksha

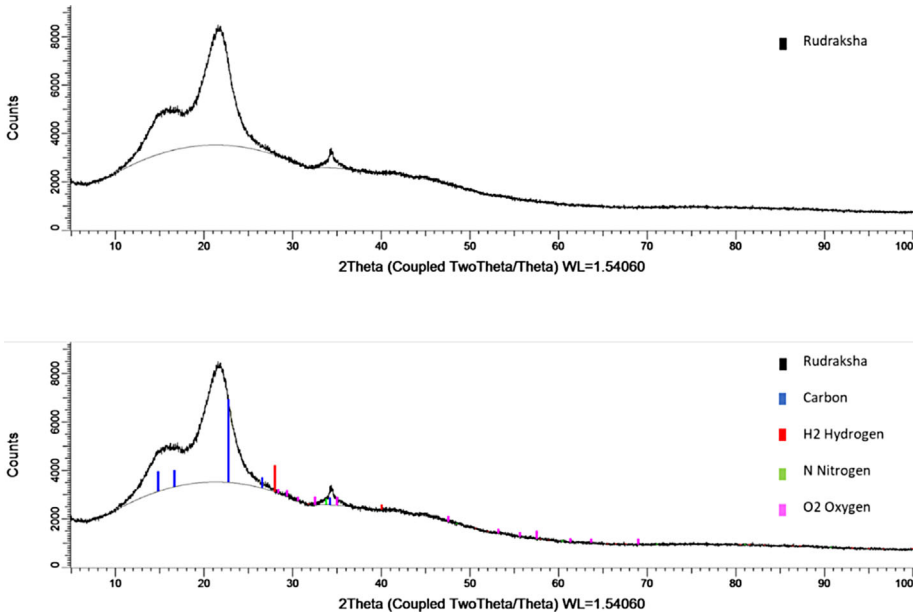


FIGURE 3 X-ray diffraction (XRD) traces of rudraksha.

samples have been found to be broadly peaking at two diffraction angles of 25° and 43° (weak), respectively. This, in turn, suggestively posits the presence of an amorphous carbon element rather than the crystalline carbon.[43]

Additionally, the XRD results supported an EA that determined the rudraksha's composition to be C (48.46%), H_2 (6.37%), N (0.54%), S (0.08%), and O_2 (44.5%). According to data reported by Gupta (2018), rudraksha has a chemical composition of 50.031% C, 0.95% N, 17.897% H, and 30.53% O.[44] This study demonstrated that the chemical compositions of C, H, N, and S are found to be slightly lower than the prior data. In another study, the effects of rudraksha with three, four, and five Mukhi were observed. The findings showed that the content of C and H increased with the introduction of Mukhi rudraksha.[45] It is noticeable that the origin, type, species, and environment all have an impact on the chemical composition of rudraksha. It is noticeable that the origin, type, species, and environment all have an impact on the chemical composition of rudraksha. Additionally, the findings of the research indicate that rudraksha seeds have significant amounts of carbon and can be classified as carbonaceous materials.

Using an ICP-MS analysis, five different minerals, including sodium, magnesium, aluminum, potassium, and calcium, can be traced in rudraksha. Chlorine, copper, nickel, cobalt, and iron are also commonly found in lower concentrations (less than 0.1 ppm).[46] Previous research demonstrates that researching the characteristics of rudraksha has the potential for the development of new treatments and medical applications.[47,48]

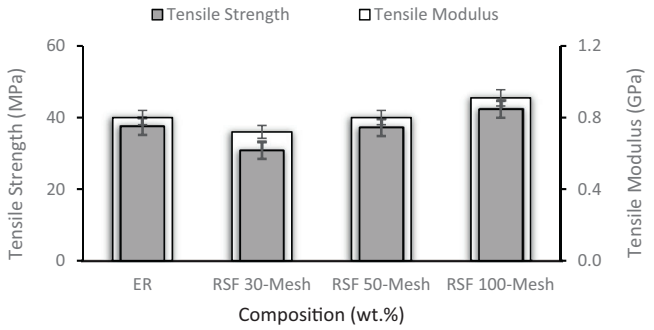


FIGURE 4 Influence filler sizes on tensile properties of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

As reported by the analysis, rudraksha emerges as a significant potential in somewhat broad applications, particularly in the field of polymer composites, owing to its desirable mechanical and chemical characteristics, for instance, the low moisture and high carbon contents, lightweight and the compositional presence of some mineral elements.

3.2 | Tensile properties

Figure 4 illustrates the mechanical properties of TS and TM in polymer composites impacted differently when different filler sizes, such as 30-mesh, 50-mesh, and 100-mesh, were tested. According to the findings, out of the three filler sizes tested, the composite with small particles of 100-mesh had the highest TS with 42.30 MPa. This result can be explained by the larger surface area and effective load transmission of the smaller particles.

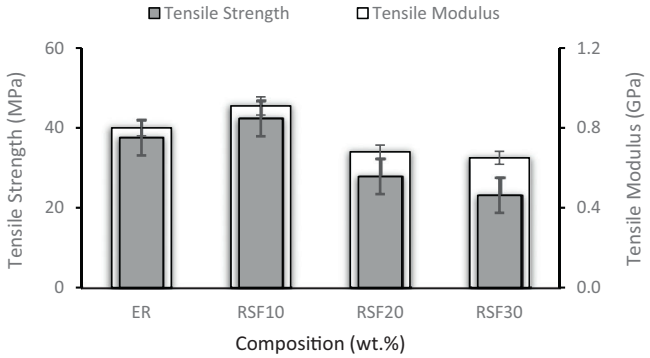


FIGURE 5 Influence filler loading tensile properties of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

This results in improved stress distribution and a reinforced polymer matrix. Note that 30-mesh and 50-mesh were bigger particles with lesser TSs of 30.80 MPa and 37.20 MPa, respectively. This might result from ineffective filler-matrix interactions, agglomeration, or void formation, which leads to stress concentration and reduced overall mechanical properties.[49,50] The composite with 100-mesh fine particles displayed the highest TM (0.91 GPa), similar to TS. Moreover, a composite's stiffness and modulus were raised as a result of the small particles' efficient restriction of polymer chain mobility. In contrast, the coarser fillers (30-mesh and 50-mesh) demonstrated lower TM due to their diminished capacity to limit polymer chain motion and less efficient reinforcing.[51,52] In summary, the comprehensive examination of various filler sizes inside polymer composites yields a nuanced comprehension of the intricate relationship between particle size and mechanical properties. The increased mechanical capabilities seen in the composite containing 100-mesh small particles underscore the significance of optimizing filler qualities in polymer composites. This finding holds potential for use in diverse engineering and structural applications.

The tensile properties of ER reinforced using RSF at different weight concentrations are illustrated in Figure 5. The graph shows virgin ER has a TS and TM of 37.5 MPa and 0.8 GPa, respectively. The TS and TM of ER were increased to 42.30 MPa and 0.91 GPa, respectively, by adding 10 wt.% of RSF. The RSF raises the TS and TM materials by about 12.8%, respectively. Additionally, the epoxy matrix can act as reinforcement with the use of fillers. RSF can enhance load transfer to the filler particles embedded in an epoxy matrix. During loading, stresses are dispersed throughout the composite, and infill particles can help with both distribution and absorption. As a result, the composite's TS may be improved, and the distribution and absorption of stresses during loading may be improved. This may also decrease the incidence of microcracks and cavities inside the composite. Due to the composite's improved resistance to deformation and failure under applied forces, this can boost TS.

Figure 5 portrays that the TS and TM of composites decrease when the filler concentration rises from 10% to 30%. The TS and TM of the composites are decreased to 23.10 MPa and 0.65 GPa, respectively, when the maximum RSF content of 30% is reached. The possibility that adding filler could lower TS and TM must be considered while designing and optimizing composite materials. Hence, understanding the root causes of this issue and observing the possible mitigation or balance measures are crucial. An increase in the filler content of composites can cause a decrease in their tensile characteristics as a result of the production of agglomerates and clumps of filler particles.[53,54] Moreover, high filler concentrations can cause the particles to over-compact, reducing the area of the matrix-filler interface and impairing interfacial bonding. This could decrease the stiffness and strength of the filler particles by reducing the load transfer from the matrix to them.[20]

On the other hand, Shakuntala et al. explored how filler loading affected the mechanical properties of an epoxy composite reinforced with wood apple shells. Composites' TS increased from 5% to 15% of filler content. However, it deteriorated when the filler level was increased to 20%. Therefore, the author concludes that a high filler content makes it difficult for the polymer to reach the fillers' contracting gaps, resulting in inadequate coverage and reduced stress transfer across the filler-resin interface.[14]

Table 3 compares several filler types investigated in earlier studies and employed in ER. The maximum improvement in TS and TM in composites depends on the filler material concentration, with a weight of 30% being the highest filler loading. However, this study discovered that an RSF10 concentration significantly improved TS and TM. The TS and TM values discovered in this investigation are within the acceptable range suggested by earlier studies. Thus, the TS and TM values can be affected by the type of filler, the matrix, and the proportion between the filler and the matrix.[20,21]

SEM analysis is a useful tool for examining the microstructure of composites and how filler dispersion affects the mechanical properties of the composite, particularly its TS. Figure 6 displays the fracture surface of RSF loaded with ER at 1000× and 5000× magnifications. The distribution of 10% filler within ER is depicted in Figure 6A,B. The amount of porosity and voids in the composite can serve as areas where tension can build up and eventually fail. Therefore, a good filler dispersion can also assist in lowering these characteristics. Furthermore,

TABLE 3 Comparison of tensile properties with previous studies.

Filler and matrix	Corresponding filler content (wt%)	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Coconut shell–epoxy	20	30.60	0.85	55
Wood apple shell–epoxy	15	45.60	—	14
Ipamoea–epoxy	30	23.75	7.20	56
Orange peel–epoxy	20	25.85	—	57
RSF–epoxy	**10**	**42.30**	**0.91**	**Current study**

Abbreviation: RSF, rudraksha seed filler.

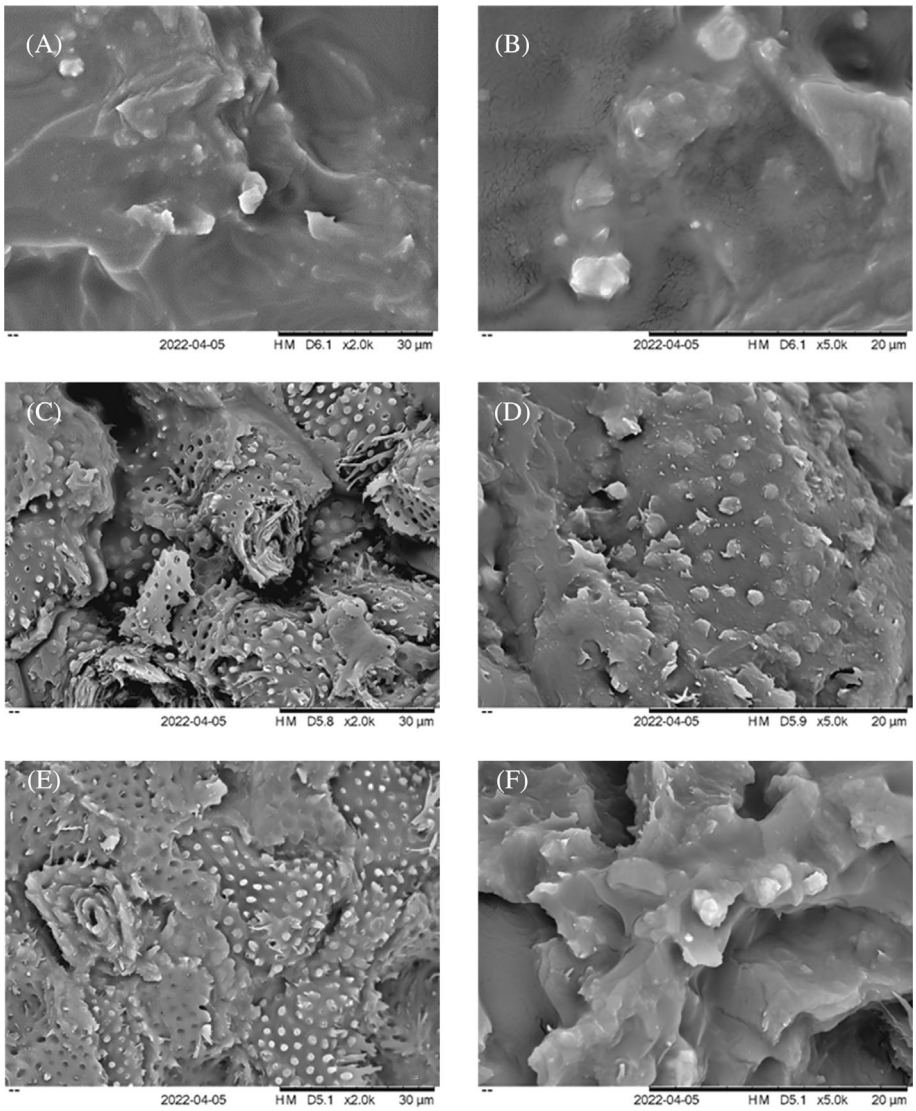


FIGURE 6 Scanning electron microscopy (SEM) images of the tensile fractured surface of rudraksha seed filler (RSF)/epoxy resin (ER) composites; A-B 10 wt%; C-D 20 wt% and E-F 30 wt% of filler.

a more uniform stress distribution throughout the composite and higher TS results from achieving homogeneous dispersion of fillers, lowering the likelihood of voids and porosity appearing.[58–62] A proper filler dispersion in the epoxy matrix can increase the composite's TS by enhancing load transfer to the filler particles. The RSF10 discovered in the TS and TM samples is supported by this investigation.

Figure 6C–F depict the SEM image of the higher filler concentrations (20 and 30 wt%). When filler

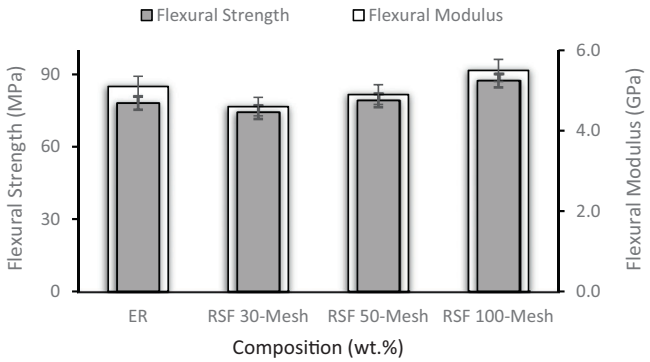


FIGURE 7 Influence filler sizes on flexural properties of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

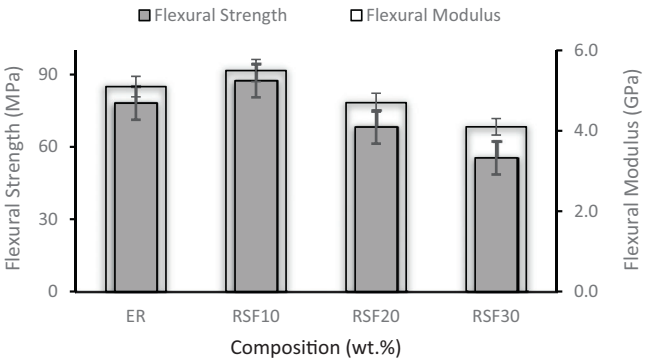


FIGURE 8 Influence filler loadings on flexural properties of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

concentrations in epoxy are raised, particle distribution can become more difficult. Since the mixture has more filler, it could be more difficult to distribute the particles uniformly throughout the matrix. As a result, filler particle agglomeration may happen, resulting in some composite sections having a higher particle concentration than others.[63–65]

3.3 | Flexural properties

Figure 7 demonstrates the influence of several RSF mesh sizes, specifically 30-mesh, 50-mesh, and 100-mesh. ER has an FS of 78.1 MPa and an FM of 5.1 GPa. TS and TM are marginally reduced when RSF 30 and RSF 50-mesh are added. Surprisingly, adding RSF 100-mesh enhanced TS and TM to 87.4 MPa and 5.5 GPa, respectively. The increase in RSF 100-mesh over RSF 30-mesh is around 18% and 19.5% for TS and TM, respectively. This finding can be due to the smaller particles' greater surface area and improved filler-matrix interaction. The finer particles bridged the gaps in the polymer matrix, resulting in more efficient load transfer and increased resistance to bending forces.[8,63] Conversely, composites with coarser fillers (30-mesh and 50-mesh) had lower FS, which could be attributed to the existence of voids, agglomeration, reduced interfacial adhesion, and limited load-bearing capability.[66,67]

Additionally, the fine particle composite (100-mesh) had the highest FM. The finer particles significantly reduced the mobility of the polymer chains, resulting in improved stiffness and rigidity in the composite material. Composites with coarser fillers (30-mesh and 50-mesh), on the other hand, have a lower FM, indicating an inferior resistance to deformation under bending forces.[29,68]

Figure 8 illustrates that the amount of filler in a composite affects its mechanical properties, including its FS and FM. This investigation determined that, compared to filler concentrations of RSF20 and RSF30, RSF10 improved these attributes the most. One explanation for this outcome can be the impact of filler loading on the interfacial bonding between the filler and the matrix. According to earlier studies, excessive filler loading can cause agglomeration and reduced interfacial area between the filler and the matrix, leading to a weaker interface and diminished mechanical properties.[69–71] On the other hand, a lower filler loading enables a more uniform dispersion of the filler particles in the matrix, producing a stronger interface and improved mechanical properties. This finding is consistent with earlier research that evaluated the eggshell filler affected the tensile and flexural characteristics of glass fiber-reinforced polymer composites. Moreover, the increased filler loading causes a decrease in FS and FM. When eggshell filler, ranging from 10% to 40%, is applied, the slope of the flexural stress and strain curve is drastically reduced. This indicates that the modulus falls off as the filler content rises. Compared to samples with 25% and 40% eggshell filler, the composite sample with 10% can tolerate more bending stress.[72]

The results of this study suggest that the most significant improvements in FS and FM can be obtained in composites with a moderate filler concentration, such as 10 wt%. This study demonstrates the importance of modifying the filler concentration in composite materials for improved mechanical properties. This is consistent with previous research regarding the effect of filler development on mechanical properties. According to most researchers, the sizes and loads of filler can considerably affect the flexural properties of epoxy composites.[11,19,69,73]

3.4 | Impact strength

As displayed in Figure 9A, the effects of three filler sizes in polymer composites of 30-mesh, 50-mesh, and

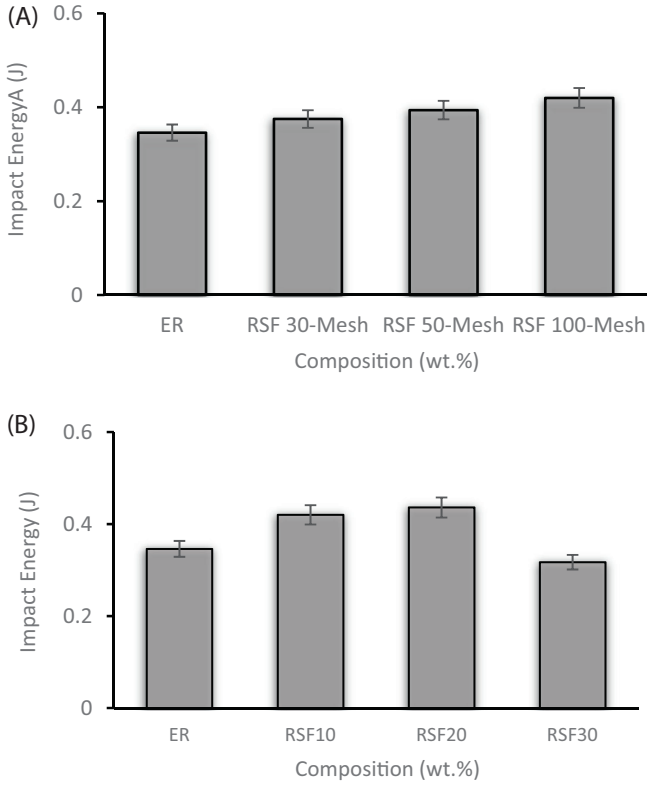


FIGURE 9 (A) Influence filler sizes and (B) filler loadings on the impact strength of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

100-mesh revealed some interesting things about how the impact strength behaved. Furthermore, Figure 9B illustrates that investigating the effect of various filler loadings (10 wt%, 20 wt%, and 30 wt%) provided a better understanding of the composite's reaction to altering filler content. It is clear that the composite with 100-mesh filler particles had the highest impact strength of the three filler sizes tested, measuring 0.420 J, followed by those with 50-mesh and 30-mesh filler particles, measuring 0.394 J and 0.375 J, respectively. There are several important reasons why the fine particle type, specifically the 100-mesh RSF, has better impact performance. To begin with, the increased surface area of tiny particles facilitates enhanced stress distribution inside the composite material under impact loading conditions. The enhanced surface area facilitates enhanced contact with the epoxy matrix, promoting more effective load transmission and dispersion of stress. Additionally, the fact that small particles are less likely to stick together than larger ones means that the RSF is spread out more evenly in the epoxy matrix, which improves its resistance to impact. The enhanced toughness of materials can be attributed to the reduced dimensions of fine particles, which enable them to efficiently absorb and disperse impact energy, hence impeding the spread of cracks. Fine particles may also have a stronger reinforcing effect on the epoxy matrix because of their smaller size. This makes the matrix stronger and more resilient when it is hit. The occurrence of fewer voids during the curing process, which is linked to the presence of small particles, results in a composite structure that is more compact and uniform. This, in turn, contributes to improved impact performance. In conclusion, better compatibility between the tiny particles and the epoxy matrix leads to stronger adhesion at the filler-matrix interface. This makes it easier to create a cohesive and integrated structure that improves the resistance to impact.[74,75]

Filler loading of RSF in polymer composites substantially impacted impact strength. Surprisingly, the composite with an RSF 20 wt% filler loading attained the highest impact strength (0.436 J) among the evaluated loadings (RSF 10 wt%, RSF 20 wt%, and RSF 30 wt%). This indicates the presence of optimal filler content, which results in the greatest impact resistance. Lower loadings (10 wt%) may not offer adequate reinforcement, whereas larger loadings (30 wt%) may cause agglomeration or reduced interfacial adhesion, lowering impact strength.[76,77] The best impact performance was achieved with fine particles (100-mesh) and a 20% filler loading. This indicates how important filler size and loading are for getting the desired impact resistance in the composite.[1,78–80]

Previous researchers investigated how filler loading affected the impact strength of epoxy composites reinforced with natural filler. The researchers discovered that, up until a certain point, increasing filler loading initially improved impact strength. However, after that point, it lowered impact strength.[23,69,81,82] Researchers explained this behavior by explaining that the matrix changed from ductile to brittle at greater filler loadings, which caused an impact strength reduction.[78,83,84] Moreover, the findings of this investigation indicate that composite materials with the greatest impact strength can be produced with a modest filler concentration, such as 20 wt%. Therefore, this study demonstrates how crucial it is to adjust the filler concentration in composite materials to provide the optimum mechanical properties, which is consistent with earlier research on how filler loading influences impact strength.[3,4]

The results of this investigation challenge accepted theories regarding the relationship between filler size and impact strength in polymer composites. The fact that fine particles outperformed coarse particles in impact resistance demonstrates how different filler size ranges might contribute to various mechanical behaviors and energy-dissipating mechanisms.[19,73,85] Hence, these findings significantly affect the composite material design, especially where impact resistance is an important consideration.

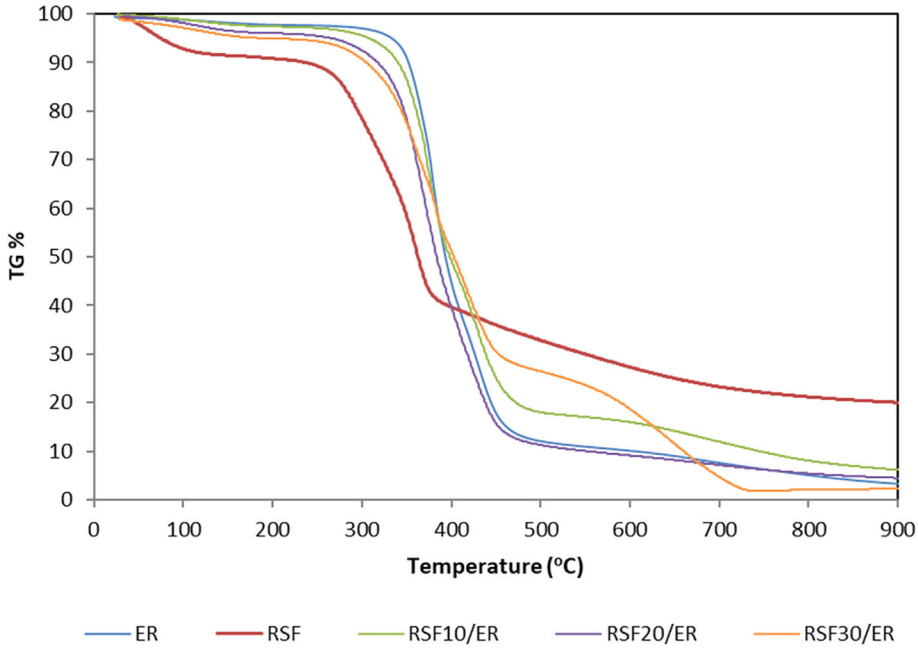


FIGURE 10 TGA curves of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

Furthermore, the significance of proper optimization is highlighted by finding the best filler loading (20 wt%) for the highest impact strength. This will help provide the mechanical properties that are required.

3.5 | Thermogravimetric analysis

Natural filler-reinforced polymer composites are rising in importance in various industries due to their controlled features and superior performances compared to virgin polymers. Fillers included in polymer matrices can substantially impact the resulting composites' thermal properties, making them appropriate for applications requiring greater thermal stability. Additionally, TGA is used in this work to explore the thermal stability of polymer composites with varying filler loadings (RSF 10 wt%, RSF 20 wt%, and RSF 30 wt%) at a constant 100-mesh size. Figures 10 and 11 display the TGA and corresponding derivative thermogravimetric (DTG) derivative curves. The virgin ER experiences an initial weight loss of 1.2% at 100°C, significantly less than the pure RSF, which experiences a weight loss of 7.13%. The evaporation of the water in the RSF fills the cause of this variation.[86,87] It is clear from analyzing the filler incorporation in the epoxy composite that RSF10 wt% exhibits the least weight loss compared to the other two loading levels. Note that the weight loss for RSF10 is specifically 1.14%, whereas weight losses for RSF20 and RSF30 are 1.9% and 2.7%, respectively. These results reveal that weight loss decreases with filler loading, with RSF10 wt% demonstrating the best thermal stability among the three loading levels. Therefore, these findings also agree with those observed by other researchers, who reported that the increase in filler content decreased the thermal stability of the composites.[1,88]

The TGA curve demonstrates that at the highest temperature of 900°C, the char residue for ER was 3.7%. However, the char residue for RSF was substantially higher at 20.03%. This result demonstrates the RSF's significant char-forming capabilities. A big char layer that forms during thermal breakdown indicates that RSF has outstanding thermal stability, as evidenced by the high char residue. Moreover, the char residue of composites containing RSF10 is 10.79%, 4.5% for composites containing RSF20, and 2.33% for composites having RSF30. The findings indicated that a moderate filler content facilitates the formation of a significant char layer during thermal degradation. This is considering that, compared to the composites with the other two loadings, those with RSF10 had greater char residue. Here, the 30 wt% of filler composites had the least char residue. A large amount of filler could prevent a consistent char structure from forming. A perfect filler loading may maximize the char-forming capacity, as evidenced by the composites with RSF20 indicating an intermediate char residue. Furthermore, previous studies have proposed that a lower filler loading can improve the thermal stability of the matrix by slowing down thermal deterioration and increasing char generation during combustion. Conversely, high filler loading may induce matrix deterioration and lower thermal stability values.[86,89] Hence, these findings have significance for developing polymer composite materials for high-temperature applications where maintaining structural integrity and fire resistance meet critical requirements.

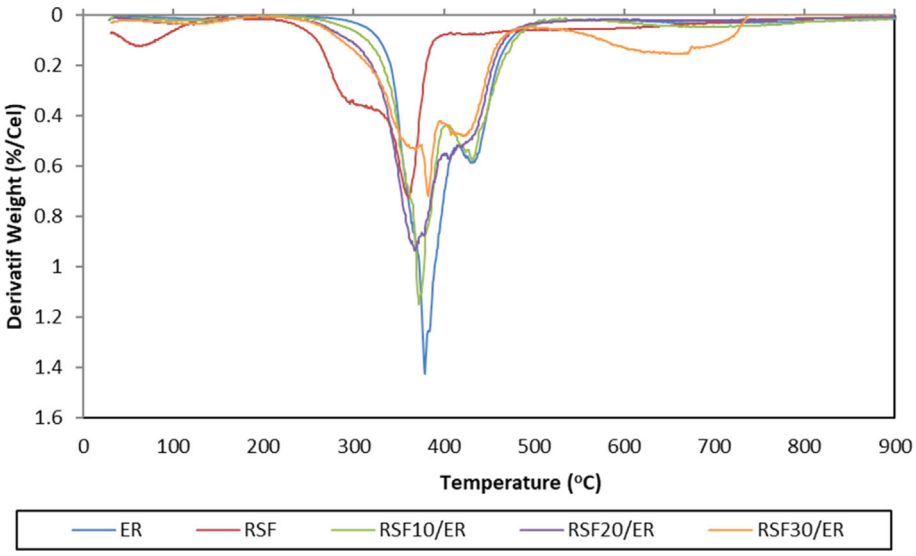


FIGURE 11 DTG curves of rudraksha seed filler (RSF)/epoxy resin (ER) composites.

Figure 11 illustrates the second stage of weight loss of the composite materials, between 200 and 600°C, which was implicated in the chemical composition breakdown in RSF/ER composites. According to Viswanathan et al. (2021), the composition of rudraksha contains 50.031% carbon, 0.95% nitrogen, 17.897% hydrogen, and 30.53% oxygen.[90] T_{max} is the temperature at which maximal weight loss occurs during degradation and is connected to the maximum decomposition temperature, both of which are essential indicators of the thermal stability of the materials.[1,91,92] The maximum decomposition temperatures of virgin epoxy and pure RSF were 370°C and 353°C, respectively. Meanwhile, the deterioration peak of RSF10, RSF20, and RSF30 occurred at temperatures of 372.56°C, 375.10°C, and 383.20°C. From the analyzed data obtained, it can be concluded that adding filler has increased the thermal stability of the composites.

3.6 | Fourier-transform infrared spectroscopy

The utilization of Fourier-transform infrared (FTIR) spectroscopy, which can examine the hydrogen-bonded region between 3550 and 3200 cm^{-1} spectra sweep, as depicted in Figure 12, is crucial for identifying and characterizing chemical compounds. This spectral band focuses mostly on the stretching vibrations of the hydrogen-bonded functional groups, particularly the hydroxyl groups (OH), which are prevalent in various organic compounds. The OH stretch is a strong, broad band often detectable between 3400 and 3300 cm^{-1}, and it offers crucial underlying information on the hydrogen bonding environment and other functional groups in its surroundings. The

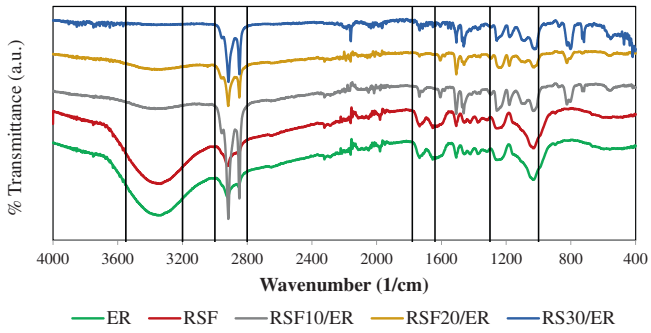


FIGURE 12 Fourier-transform infrared (FTIR) of epoxy, rudraksha filler, and composites.

finding agrees with the data reported in prior work on the utilization of natural filler in composite materials.[93,94] FTIR spectral analysis further reveals that alcohol groups with a broad and strong intensity (i.e., secondary CH—OH) also showed up at 3328.45 cm^{-1}.[44]

The stretching vibrations of C—H bonds in organic compounds, such as epoxies, are related to the region between 3000 cm^{-1} and 2800 cm^{-1} in an FTIR spectrum.[95] The characteristic peak of virgin epoxy is found at 2923 cm^{-1} and 2853 cm^{-1}, respectively. The peak levels of the spectrum for pure rudraksha filler were observed at 2916 cm^{-1} and 2853 cm^{-1}. Previous studies also reported that sharp and strong intensities of varying functional groups, including alkane, methyl, methylene, ethyl, and alkene, were found in a similar spectrum band to that of rudraksha, at 2925.28 cm^{-1} and 2854.35 cm^{-1}, respectively (Gupta, 2018). Identical characteristics were discovered for epoxy and rudraksha composites made with various concentration loadings. RSF10 has two peaks at 2916 and 2849 cm^{-1}, RSF20 has two peaks at 2918 and 2850 cm^{-1}, and RSF30 has two

peaks at 2916 and 2848 cm^{-1}, respectively. By analyzing the FTIR data across the 3000–2800 cm^{-1} spectral band, researchers would be able to further classify the many types of C—H bonds that are present, distinguishing aliphatic and aromatic compounds, and ultimately develop a new body of knowledge concerning the molecular structure and functional groups contained in rudraksha samples. Owing to its versatility, the spectra offer indispensable groundwork for the analysis of a variety of organic compounds, including hydrocarbons, polymers, and other organic functional groups, posing it as a crucial instrument in chemical inquiry and elaborative material characterizations.[96–98]

The carbonyl region, also known as the C═O stretching region, refers to the region of the FTIR spectrum between 1780 and 1640 cm^{-1}.[99] The information in this spectral band is crucial for understanding compounds with carbonyl functional groups, such as aldehydes, ketones, carboxylic acids, esters, and amides. Previous work has revealed that the pure rudraksha filler content of these functional groups can be identified in the region of the dominant spectrum corresponding to 1746.39 cm^{-1} (Gupta, 2018). The findings from the present work indicate that the spectrum of pure rudraksha filler and the mixture with ER reaches its peak performance level at 1735 cm^{-1}. The absorption peak of virgin epoxy detected at around 1653 cm-1 could represent various functional groups or their respective structural features. The Amide I band, which frequently occurs in the area of similar range and is especially pronounced in proteins as a result of the C═O stretching vibration of the peptide bond, is one critical explanation that may be relevant to this phenomenon as observed by authors.[100–102]

Respective wavenumbers of 1300 cm^{-1} and 1000 cm^{-1} indicate specific molecular vibrations and functional groups in the material being tested. The vibrations produced by C—H bending in alkanes or C—N stretching in amines fall within the range of 1300 cm^{-1}.[103] It showed that the peak wavenumber of epoxy was at 1253 and 1030 cm^{-1}, and that of rudraksha was at 1255 and 1030 cm^{-1}, respectively. At a wavenumber of 1240.54 cm^{-1}, a functional group discovered in rudraksha, such as carboxylic acids (COOH), can be identified. Additionally, this region can reveal the presence of specific functional groups, such as the amide III band in proteins. It could be an indicator of vibrations such as C—O stretching in carboxylic acids, esters, and anhydrides, as well as C—C and C—O bending in diverse compounds.[104–106] The inclusion of rudraksha as a filler in epoxy composites demonstrates a high-level wavenumber of RSF at 1255 and 1029 cm^{-1}, RSF20 at 1236 and 1030 cm^{-1}, and finally RSF30 at 1259 and 1020 cm^{-1}, respectively.

4 | CONCLUSIONS

Elaeocarpus ganitrus (rudraksha) seeds have been investigated as a potential sustainable reinforcement for PMCs, with promising findings. The mechanical and thermal properties of composites with various rudraksha filler sizes and loadings were successfully investigated in the study. Moreover, the results reveal that using small particles improved the mechanical properties of the composites significantly. Notably, when compared to other compositions, the insertion of RSF10 in the epoxy composite resulted in the greatest enhancement in mechanical properties and thermal stability. Finally, including rudraksha as a sustainable reinforcement for polymer composites, particularly with small particles at 10 wt%, demonstrates its promise for enhancing eco-friendly and high-performance materials. According to the findings of the exploration on thermal stability, RSF has a promising future as a sustainable friction material for automotive brake pads. This study adds to the pursuit of sustainable and responsible practices in the materials sector and progress towards several SDGs aimed at constructing a more ecologically conscious and socially responsible future.

AUTHOR CONTRIBUTIONS

The article reflects the collaborative efforts of Agustinus Purna Irawan, Januar Parlaungan Siregar, Tezara Cionita, Deni Fajar Fitriyana, Rusiyanto Rusiyanto, Jamiluddin Jaafar, Pungkas Prayitno, Rifky Ismail, Athanasius Priharyoto Bayuseno, and Ayub Ahmed Janvekar. Agustinus Purna Irawan led conceptualization and supervision, Januar Parlaungan Siregar handled the original draft and investigation, and Tezara Cionita contributed to methodology and investigation. Deni Fajar Fitriyana conducted formal analysis and data curation, while Rusiyanto Rusiyanto provided support in methodology and resources. Writing, review, and editing were undertaken by Jamiluddin Jaafar and Rifky Ismail, with validation. Pungkas Prayitno contributed to visualization and resources, and Athanasius Priharyoto Bayuseno and Ayub Ahmed Janvekar participated in formal analysis and validation. All authors have approved the published version of the article.

ACKNOWLEDGMENTS

The authors would like to acknowledge Universiti Malaysia Pahang Al-Sultan Abdullah for providing research data collection equipment and Universitas Tarumanagara for funding via Research International Collaboration Grant No: 1831-Int-KSln-KLPPM/UNTAR/XI/2021.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

We ensure that all data are contained within the article.

ORCID

Januar Parlaungan Siregar https://orcid.org/0000-0002-8130-1168

Jamiluddin Jaafar https://orcid.org/0000-0002-8306-2834

REFERENCES

1. Cionita T, Siregar JP, Shing WL, et al. The influence of filler loading and alkaline treatment on the mechanical properties of palm kernel cake filler reinforced epoxy composites. *Polymers (Basel)*. 2022;14(15):3063.
2. Akter M, Uddin MH, Anik HR. Plant fiber-reinforced polymer composites: a review on modification, fabrication, properties, and applications. *Polym Bull*. 2023;80:1-85.
3. Sienkiewicz N, Dominic M, Parameswaranpillai J. Natural fillers as potential modifying agents for epoxy composition: a review. *Polymers (Basel)*. 2022;14(2):265.
4. Jagadeesh P, Puttegowda M, Thyavihalli Girijappa YG, Rangappa SM, Siengchin S. Effect of natural filler materials on fiber reinforced hybrid polymer composites: an overview. *J Nat Fibers*. 2022;19(11):4132-4147.
5. Irawan AP, Fitriyana DF, Siregar JP, et al. Influence of varying concentrations of epoxy, rice husk, Al2O3, and Fe2O3 on the properties of brake friction materials prepared using hand layup method. *Polymers (Basel)*. 2023;15(12):2597.
6. Matykiewicz D. Hybrid epoxy composites with both powder and fiber filler: a review of mechanical and thermomechanical properties. *Materials*. 2020;13(8):1802.
7. Doumeng M, Berthet F, Delbé K, Marsan O, Denape J, Chabert F. Effect of size, concentration, and nature of fillers on crystallinity, thermal, and mechanical properties of polyetheretherketone composites. *J Appl Polym Sci*. 2022;139(5):51574.
8. Boey JY, Lee CK, Tay GS. Factors affecting mechanical properties of reinforced bioplastics: a review. *Polymers (Basel)*. 2022;14(18):3737.
9. Jenish I, Sahayaraj AF, Suresh V, et al. Analysis of the hybrid of mudar/snake grass fiber-reinforced epoxy with nano-silica filler composite for structural application. *Adv Mater Sci Eng*. 2022;2022(7805146):1-10.
10. Jasmee S, Omar G, Othaman SSC, Masripan NA, Hamid H. Interface thermal resistance and thermal conductivity of polymer composites at different types, shapes, and sizes of fillers: a review. *Polym Compos*. 2021;42(6):2629-2652.
11. Shinkai K, Taira Y, Suzuki S, Kawashima S, Suzuki M. Effect of filler size and filler loading on wear of experimental flowable resin composites. *J Appl Oral Sci*. 2018;26:e20160652.
12. Jawaid M, Khalil HPSA, Bakar AA, Hassan A, Dungani R. Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites. *J Compos Mater*. 2013;47(13):1633-1641.
13. Jaafar J, Siregar JP, Oumer AN, Hamdan MM, Tezara C, Salit MS. Experimental investigation on performance of short pineapple leaf fiber reinforced tapioca biopolymer composites. *Bioresources*. 2019;13(3):6341-6355. doi:10.15376/biores.13.3.6341-6355
14. Shakuntala O, Raghavendra G, Samir KA. Effect of filler loading on mechanical and tribological properties of wood apple shell reinforced epoxy composite. *Adv Mater Sci Eng*. 2014;2014(538651):1-9.
15. Shejkar SK, Agrawal B, Agrawal A. Effect of particle size on physical properties of epoxy composites filled with micro-size walnut shell particulates. *Mater Today Proc*. 2021;47:2657-2661.
16. Benjamin U, Hilary U. Tensile behaviour of oil bean pod shell and mahogany sawdust reinforced epoxy resin composite. *Int J Sci Technol Soc*. 2019;7(1):1.
17. Prosper EO, Uguru H. Effect of fillers loading on the mechanical properties of hardwood sawdust/oil bean shell reinforced epoxy hybrid composites. *Int J Sci Res Sci Eng Technol*. 2018;4(8):620-626.
18. Naik P, Pradhan S, Sahoo P, Acharya SK. Effect of filler loading on mechanical properties of natural carbon black reinforced polymer composites. *Mater Today Proc*. 2020;26:1892-1896.
19. Zafar MF, Siddiqui MA. Effect of filler loading and size on the mechanical and morphological behaviour of natural fibre-reinforced polystyrene composites. *Adv Mater Process Technol*. 2021;7(4):647-659.
20. Verma A, Baurai K, Sanjay MR, Siengchin S. Mechanical, microstructural, and thermal characterization insights of pyrolyzed carbon black from waste tires reinforced epoxy nanocomposites for coating application. *Polym Compos*. 2020;41(1):338-349.
21. Marichelvam MK, Manimaran P, Verma A, et al. A novel palm sheath and sugarcane bagasse fiber based hybrid composites for automotive applications: an experimental approach. *Polym Compos*. 2021;42(1):512-521.
22. Chandrika VS, Anamika A, Jeeva C, et al. Natural fiber incorporated polymer matrix composites for electronic circuit board applications. *Adv Mater Sci Eng*. 2022;2022:1-9.
23. Azwa ZN, Yousif BF, Manalo AC, Karunasena W. A review on the degradability of polymeric composites based on natural fibres. *Mater Des*. 2013;47:424-442.
24. Norkhairunnisa M, Farid B, Hua TC. Flame retardant nanofillers and its behavior in polymer nanocomposite. *Advanced Polymer Nanocomposites*. Elsevier; 2022:483-511.
25. Oosthuizen H, Jones L, Naseem S, Labuschagne F, Leuteritz A. Tailoring materials for their need: sustainable layered double hydroxide polymer composites. *J Polym Sci*. 2023;61(16):1749-1777.
26. Kumar S, Prasad L, Bijlwan PP, Yadav A. Thermogravimetric analysis of lignocellulosic leaf-based fiber-reinforced thermosets polymer composites: an overview. *Biomass Convers Biorefin*. 2022;12:1-26.
27. Thiagamani CM, Nagarajan R, Siengchin S. Natural fiber-reinforced composites. *Composites*. 2022;8:9.
28. Veerasimman A, Shanmugam V, Rajendran S, et al. Thermal properties of natural fiber sisal based hybrid composites–a brief review. *J Nat Fibers*. 2021;19:1-11.
29. Jawaid M, Khalil HPSA, Bakar AA. Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. *Mater Sci Eng A*. 2010;527(29–30):7944-7949.

30. Sajin JB, Paul RC, Binoj JS, et al. Impact of fiber length on mechanical, morphological and thermal analysis of chemical treated jute fiber polymer composites for sustainable applications. *Curr Res Green Sustain Chem*. 2022;5:100241.
31. Lal P. Elaeocarpus sphaericus: a tree with curative powers: an overview. *Res J Med Plant*. 2013;7(1):23-31.
32. ASTM D792-20. Standard test methods for density and specific gravity (relative density) of plastics by displacement. ASTM International.
33. Azhar FH, Sazali N, Harun Z, Hussin R, Sazali N, Jamalludin R. Simple approach in measuring the synthesized zeolite from kaolin as nutrient retention for mung bean growth. *Emerg Adv Integr Technol*. 2022;3(2):52-59.
34. Olalere OA, Abdurahman NH, Mohd Yunus R, Alara OR. Data article on elemental and metabolomic-based alkaloidal composition in black pepper oleoresin using a positive ESI-mode LC-QToF and ICP-mass spectroscopy. *Data Brief*. 2018; 19:1627-1630.
35. ASTM D638-14. Standard test method for tensile properties of plastics. ASTM International.
36. ASTM D790-15. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. ASTM International.
37. ASTM D256-10. Test methods for determining the Izod pendulum impact resistance of plastics. ASTM International.
38. Fabien BE, Boris N, Ateba A. A literature review on natural fibers, its properties and influence of water absorption on mechanical properties of composites. *Int J Recent Adv Multidiscipl Res*. 2019;6(4):4790-4797.
39. Mahir FI, Keya KN, Sarker B, Nahiun KM, Khan RA. A brief review on natural fiber used as a replacement of synthetic fiber in polymer composites. *Mater Eng Res*. 2019;1(2):86-97.
40. Touil M, Lachheb A, Saadani R, Sanbi M, Talidi A, Rahmoune M. Experimental investigation on the combined effect of the water mixing ratio and the addition of spent coffee grounds on plaster's thermo-mechanical properties. *Therm Sci Eng Prog*. 2022;36:101488.
41. Pongsuwan C, Boonsuk P, Sermwittayawong D, Aiemcharoen P, Mayakun J, Kaewtatip K. Banana inflorescence waste fiber: an effective filler for starch-based bioplastics. *Ind Crops Prod*. 2022;180:114731.
42. Thyavihalli Girijappa YG, Mavinkere Rangappa S, Parameswaranpillai J, Siengchin S. Natural fibers as sustainable and renewable resource for development of eco-friendly composites: a comprehensive review. *Front Mater*. 2019;6:226.
43. Gurung V, Pokharel B, Adhikari S, Shrestha RM, Joshi RR. Characterization of activated carbon prepared from peach (prunus persica) seed stone by chemical activation with zinc chloride (ZnCl2). *Proc IOE Graduate Conf*. 2019;7:59-64.
44. Gupta SRN. Various types of rudraksha beads, their benefits and FTIR spectra. *Int J Res Biosci Agric Technol*. 2018;34-40.
45. Sharma S, Rai DV, Rastogi M. Compositional characteristics of rudraksha (Elaeocarpus Ganitrus Roxb.). *Plant Arch*. 2021; 21(1):627-634.
46. Jain S, Jatwa K, Sharma A, Mahajan SC, Jain V. A review on elaeocarpus sphaericus (Rudraksha). *PharmaTutor*. 2014;2(7): 83-91.
47. Dwivedi P, Narvi SS, Tewari RP. Rudraksha assisted generation of silver nanoparticles for integrated application in the biomedical landscape. *Int J Green Nanotechnol*. 2012;4(3): 248-261.
48. Sinha A, Manjhi J, Kumar V, Rai DV. Evaluation of antibacterial properties of silver nanoparticles prepared via green route using elaeocarpus ganitrus (rudraksha) beads extract. *J Bionanosci*. 2018;12(4):553-561.
49. Kuan HTN, Tan MY, Shen Y, Yahya MY. Mechanical properties of particulate organic natural filler-reinforced polymer composite: a review. *Compos Adv Mater*. 2021;30: 26349833211007504.
50. Ezenkwa OE, Hassan A, Samsudin SA. Mechanical properties of rice husk and rice husk ash filled maleated polymers compatibilized polypropylene composites. *J Appl Polym Sci*. 2022; 139(9):51702.
51. Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Development and characterization of sugar palm nanocrystalline cellulose reinforced sugar palm starch bionanocomposites. *Carbohydr Polym*. 2018;202:186-202.
52. John MJ, Anandjiwala RD. Recent developments in chemical modification and characterization of natural fiber-reinforced composites. *Polym Compos*. 2008;29(2):187-207.
53. Ramezanpour M, Pourabbas B. High-resolution 3D printing resin reinforced by polyurethane filler particles; physical and mechanical properties. *Polym Compos*. 2023;44:1-13.
54. Om Prakash M, Gujjala R, Panchal M, Ojha S. Mechanical characterization of arhar biomass based porous nano activated carbon polymer composites. *Polym Compos*. 2020;41(8): 3113-3123.
55. Bhaskar J, Singh VK. Physical and mechanical properties of coconut shell particle reinforced-epoxy composite. *J Mater Environ Sci*. 2013;4(2):227-232.
56. Basumatary KK, Acharya SK. Investigation into mechanical properties of Ipomoea carnea reinforced epoxy composite. *Int J Macromol Sci*. 2013;3(3):11-15.
57. Ojha S, Raghavendra G, Acharya SK. Fabrication and study of mechanical properties of orange peel reinforced polymer composite. *Cellulose*. 2012;13:6.
58. Latief FH, Chafidz A, Junaedi H, Alfozan A, Khan R. Effect of alumina contents on the physicomechanical properties of alumina reinforced polyester composites. *Adv Polym Technol*. 2019;2019:1-9.
59. Zhou Y, White E, Hosur M, Jeelani S. Effect of particle size and weight fraction on the flexural strength and failure mode of TiO2 particles reinforced epoxy. *Mater Lett*. 2010;64(7): 806-809.
60. González-López ME, Pérez-Fonseca AA, Cisneros-López EO, et al. Effect of maleated PLA on the properties of rotomolded PLA-agave fiber biocomposites. *J Polym Environ*. 2019;27:61-73.
61. Goh GD, Yap YL, Agarwala S, Yeong WY. Recent progress in additive manufacturing of fiber reinforced polymer composite. *Adv Mater Technol*. 2019;4(1):1800271.
62. Nilagiri Balasubramanian KB, Ramesh T. Role, effect, and influences of micro and nano-fillers on various properties of polymer matrix composites for microelectronics: a review. *Polym Adv Technol*. 2018;29(6):1568-1585.
63. Nurazzi NM, Norrrahim MNF, Sabaruddin FA, et al. Mechanical performance evaluation of bamboo fibre reinforced polymer composites and its applications: a review. *Funct Compos Struct*. 2022;4(1):015009.

64. López-Bañuelos RH, Moscoso FJ, Ortega-Gudiño P, Mendizabal E, Rodrigue D, González-Núñez R. Rotational molding of polyethylene composites based on agave fibers. *Polym Eng Sci*. 2012;52(12):2489-2497.
65. Petinakis E, Yu L, Edward G, Dean K, Liu H, Scully AD. Effect of matrix–particle interfacial adhesion on the mechanical properties of poly (lactic acid)/wood-flour micro-composites. *J Polym Environ*. 2009;17:83-94.
66. Jaafar CNA, Rizal MAM, Zainol I. Effect of kenaf alkalization treatment on morphological and mechanical properties of epoxy/silica/kenaf composite. *Int J Eng Technol*. 2018;7: 258-263.
67. Ramesh M, Rajeshkumar LN, Srinivasan N, Kumar DV, Balaji D. Influence of filler material on properties of fiber-reinforced polymer composites: a review. *e-Polymers*. 2022; 22(1):898-916.
68. Mohammed AA, Bachtiar D, Rejab MRM, Hasany SF, Siregar JP. Influence of different sugar palm fiber content on the tensile, flexural, impact, and physicochemical properties of eco-friendly thermoplastic polyurethane. *Theoretical Foundations Chem Eng*. 2019;53(3):454-462. doi:10.1134/S0040579519030072
69. Fu SY, Feng XQ, Lauke B, Mai YW. Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate–polymer composites. *Compos B Eng*. 2008;39(6):933-961.
70. Ganesan K, Kailasanathan C, Rajini N, et al. Assessment on hybrid jute/coir fibers reinforced polyester composite with hybrid fillers under different environmental conditions. *Construct Build Mater*. 2021;301:124117.
71. Ahad NA, Lum KS, Halim K. The effect of seashells as filler in epoxy composites. *Sci Lett*. 2023;17(2):119-129.
72. Muhammad AF, Abidin MSZ, Hassan MH, Mustafa Z, Anjang A. Effect of eggshell fillers on the tensile and flexural properties of glass fiber reinforced polymer composites. *Mater Today Proc*. 2022;66:2938-2942.
73. Aji IS, Zainudin ES, Khalina A, Sapuan SM, Khairul MD. Studying the effect of fiber size and fiber loading on the mechanical properties of hybridized kenaf/PALF-reinforced HDPE composite. *J Reinf Plast Compos*. 2011; 30(6):546-553.
74. Wong KJ, Low KO, Israr HA. Impact resistance of short bamboo fibre reinforced polyester concretes. *Proc Instit Mech Eng Part L: J Mater Design Appl*. 2017;231(8):683-692.
75. Hammajam AA, Nur IZ, Salit SM, Zulkeffle L. The effect of fiber sizes on mechanical properties of millet husk (pennisetum glaucum) fiber filled high density polyethylene composites. *Arid Zone J Eng Technol Environ*. 2020;16(1):37-47.
76. Das O, Babu K, Shanmugam V, et al. Natural and industrial wastes for sustainable and renewable polymer composites. *Renew Sustain Energy Rev*. 2022;158:112054.
77. Mustafa BS, Jamal GM, Abdullah OG. Enhancement of the hardness and impact strength of epoxy-based metal oxide nanocomposites through hybridization. *Modern Phys Lett B*. 2023;37:2350151.
78. Siraj S, Al-Marzouqi AH, Iqbal MZ, Ahmed W. Impact of micro silica filler particle size on mechanical properties of polymeric based composite material. *Polymers (Basel)*. 2022;14(22):4830.
79. Chang L, Zhang Z, Breidt C. Impact resistance of short fibre/particle reinforced epoxy. *Appl Compos Mater*. 2004;11: 1-15.
80. Gapsari F, Putri TM, Juliano H, et al. Influence of calcium carbonate fillers on pine fiber reinforced polyester composites. *Polym Compos*. 2022;43(7):4306-4317.
81. Sangeetha VH, Deka H, Varghese TO, Nayak SK. State of the art and future prospectives of poly (lactic acid) based blends and composites. *Polym Compos*. 2018;39(1):81-101.
82. Kfoury G, Raquez JM, Hassouna F, et al. Recent advances in high performance poly (lactide): from "green" plasticization to super-tough materials via (reactive) compounding. *Front Chem*. 2013;1:32.
83. Cree D, Soleimani M. Bio-based white eggshell as a value-added filler in poly (lactic acid) composites. *J Compos Sci*. 2023;7(7):278.
84. Lendvai L, Ronkay F, Wang G, et al. Development and characterization of composites produced from recycled polyethylene terephthalate and waste marble dust. *Polym Compos*. 2022;43(6):3951-3959.
85. Al-Maharma AY, Sendur P. Review of the main factors controlling the fracture toughness and impact strength properties of natural composites. *Mater Res Express*. 2018;6(2):022001.
86. Nurazzi NM, Khalina A, Sapuan SM, Ilyas RA, Rafiqah SA, Hanafee ZM. Thermal properties of treated sugar palm yarn/glass fiber reinforced unsaturated polyester hybrid composites. *J Mater Res Technol*. 2020;9(2):1606-1618.
87. Cichosz S, Masek A. Drying of the natural fibers as a solvent-free way to improve the cellulose-filled polymer composite performance. *Polymers (Basel)*. 2020;12(2):484.
88. Tawakkal ISMA, Cran MJ, Bigger SW. Effect of kenaf fibre loading and thymol concentration on the mechanical and thermal properties of PLA/kenaf/thymol composites. *Ind Crops Prod*. 2014;61:74-83.
89. Chen RS, Ab Ghani MH, Ahmad S, Mou'ad AT, Gan S. Tensile, thermal degradation and water diffusion behaviour of gamma-radiation induced recycled polymer blend/rice husk composites: experimental and statistical analysis. *Compos Sci Technol*. 2021;207:108748.
90. Viswanathan VK, Thomai P. Performance and emission characteristics analysis of elaeocarpus ganitrus biodiesel blend using CI engine. *Fuel*. 2021;288:119611.
91. Ismail NF, Mohd Radzuan NA, Sulong AB, Muhamad N, Che Haron CH. The effect of alkali treatment on physical, mechanical and thermal properties of kenaf fiber and polymer epoxy composites. *Polymers (Basel)*. 2021;13(12):2005.
92. Chen H, Zhang W, Wang X, et al. Effect of alkali treatment on wettability and thermal stability of individual bamboo fibers. *J Wood Sci*. 2018;64(4):398-405.
93. Nascimento RK, Damasceno BS, Melo AN, et al. Hybrid nanomaterial from pyrolyzed biomass and Fe3O4 magnetic nanoparticles for the adsorption of textile dyes. *Cellulose*. 2023;30(4):2483-2501.
94. Boussetta A, Benhamou AA, Charii H, et al. Formulation and characterization of chitin-starch bio-based wood adhesive for the manufacturing of formaldehyde-free composite particleboards. *Waste Biomass Valorization*. 2023;14:1-17.
95. Nandiyanto ABD, Ragadhita R, Fiandini M. Interpretation of Fourier transform infrared spectra (FTIR): a practical

approach in the polymer/plastic thermal decomposition. *Indonesian J Sci Technol*. 2023;8(1):113-126.
96. Batul R, Makandar SD, Nawi MABA, et al. Comparative evaluation of microhardness, water sorption and solubility of biodentin and nano-zirconia-modified biodentin and FTIR analysis. *Appl Sci*. 2023;13(3):1758.
97. Kuka E, Cirule D, Andersone I, et al. Photodegradation risk evaluation of polyurethane gluelines in wood products by infrared spectroscopy and mechanical tests. *Construct Build Mater*. 2023;379:131251.
98. El-Sheekh MM, Yousuf WE, Kenawy ER, Mohamed TM. Biosynthesis of cellulose from Ulva lactuca, manufacture of nanocellulose and its application as antimicrobial polymer. *Sci Rep*. 2023;13(1):10188.
99. Nurazzi NM, Shazleen SS, Norrrahim MNF, et al. 9 - Molecular dynamics of nanocellulose-based nanocomposites: a review. In: Nurazzi NM, Ilyas RA, Sapuan SM, Khalina A, eds. *Synthetic Nat Nanofillers Polym Compos*. Woodhead Publishing. 2023;187-213.
100. Andjelic S, Kreuzer M, Hawlina M, Lumi X. Characterization of different types of epiretinal proliferations by synchrotron radiation-based fourier transform infrared micro-spectroscopy. *Int J Mol Sci*. 2023;24(5):4834.
101. Rakipov IT, Petrov AA, Akhmadiyarov AA, Khachatrian AA, Varfolomeev MA. FTIR spectral study of intermolecular interactions of C=O groups of amides in solution. *J Mol Liq*. 2022;354:118838.
102. Carbonaro M, Maselli P, Nucara A. Relationship between digestibility and secondary structure of raw and thermally treated legume proteins: a Fourier transform infrared (FT-IR) spectroscopic study. *Amino Acids*. 2012;43:911-921.
103. Zwar IP, Trotta CV, Ziotti ABS, et al. Biosynthesis of silver nanoparticles using actinomycetes, phytotoxicity on rice seeds, and potential application in the biocontrol of phytopathogens. *J Basic Microbiol*. 2023;63(1):64-74.
104. Calderón F, Haddix M, Conant R, Magrini-Bair K, Paul E. Diffuse-reflectance Fourier-transform mid-infrared spectroscopy as a method of characterizing changes in soil organic matter. *Soil Sci Soc Am J*. 2013;77(5):1591-1600.
105. Talari ACS, Martinez MAG, Movasaghi Z, Rehman S, Rehman IU. Advances in Fourier transform infrared (FTIR) spectroscopy of biological tissues. *Appl Spectrosc Rev*. 2017;52(5):456-506.
106. Gnanasambandam R, Proctor A. Determination of pectin degree of esterification by diffuse reflectance Fourier transform infrared spectroscopy. *Food Chem*. 2000;68(3):327-332.

How to cite this article: Irawan AP, Siregar JP, Cionita T, et al. *Elaeocarpus ganitrus* (rudraksha) seeds as a potential sustainable reinforcement for polymer matrix composites. *Polym Compos*. 2024; 1-18. doi:10.1002/pc.28088

Polymer Composites

COUNTRY

United States

Universities and research institutions in United States

Media Ranking in United States

SUBJECT AREA AND CATEGORY

Chemistry
- Chemistry (miscellaneous)

Materials Science
- Ceramics and Composites
- Materials Chemistry
- Polymers and Plastics

PUBLISHER

John Wiley & Sons Inc.

H-INDEX

94

PUBLICATION TYPE

Journals

ISSN

02728397, 15480569

COVERAGE

1980-2022

INFORMATION

Homepage

How to publish in this journal

pcjournal@mail.pse.umass.edu

SCOPE

Polymer Composites is the engineering and scientific journal serving the fields of reinforced plastics and polymer composites including research, production, processing, and applications. PC brings you the details of developments in this rapidly expanding area of technology long before they are commercial realities.

Join the conversation about this journal

Quartiles

FIND SIMILAR JOURNALS

1
Plastics, Rubber and Composites
GBR
86%
similarity

2
Polymers and Polymer Composites
GBR
84%
similarity

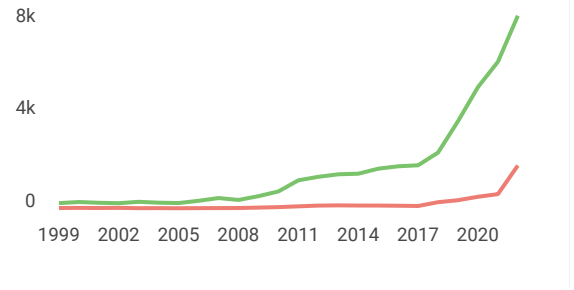
3
Journal of Thermoplastic Composite Materials
GBR
77%
similarity

4
Composite I
GBR
7
si

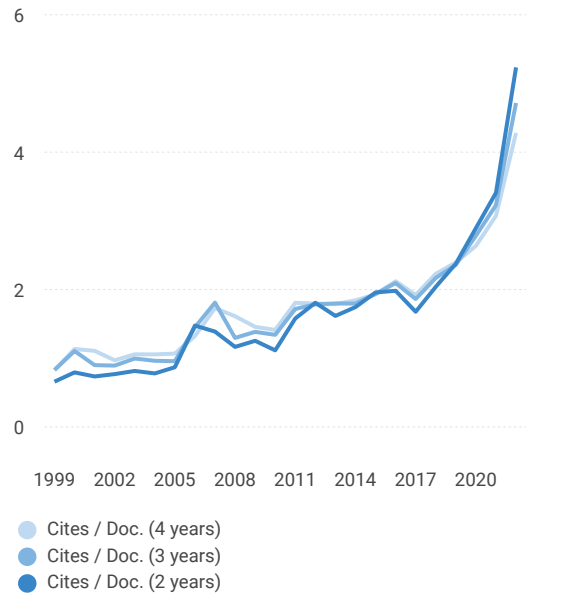
SJR

Total Documents

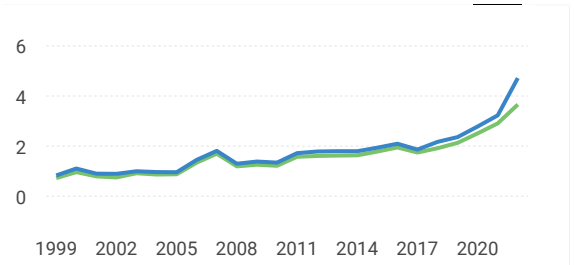
Total Cites Self-Cites



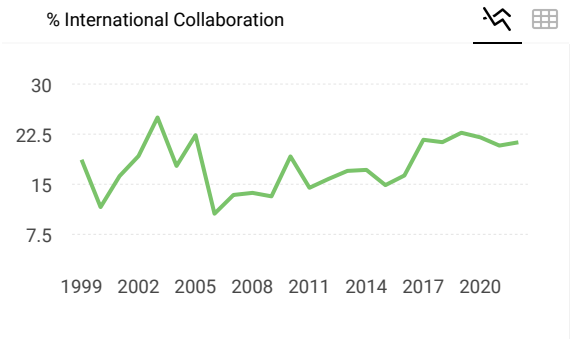
Citations per document



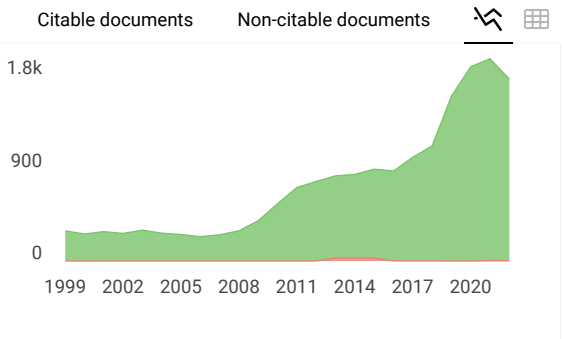
External Cites per Doc Cites per Doc



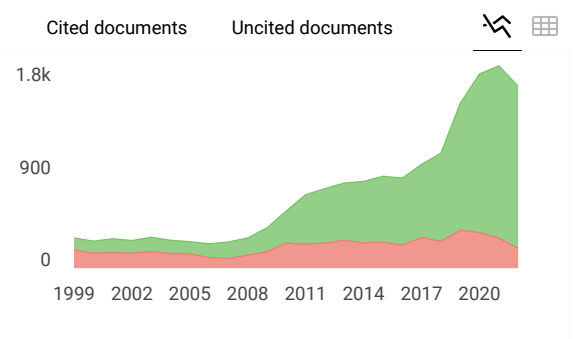
% International Collaboration



Citable documents Non-citable documents



Cited documents Uncited documents



← Show this widget in your own website

Just copy the code below and paste within your html code:

```
<a href="https://www.scimag
```

SCImago Graphica

Explore, visually communicate and make sense of data with our **new data visualization tool**.

Source details

Polymer Composites

Scopus coverage years: from 1980 to Present

Publisher: Wiley-Blackwell

ISSN: 0272-8397 E-ISSN: 1548-0569

Subject area: Materials Science: Polymers and Plastics | Materials Science: Materials Chemistry | Chemistry: General Chemistry | Materials Science: Ceramics and Composites

Source type: Journal

CiteScore 2022
6.7

SJR 2022
0.672

SNIP 2022
1.146

View all documents > | Set document alert | Save to source list | Locate full-text(opens in a new window)

CiteScore | CiteScore rank & trend | Scopus content coverage

Articles in press >

Year	Documents published	Actions
2024	547 documents	View citation overview >
2023	690 documents	View citation overview >
2022	707 documents	View citation overview >
2021	534 documents	View citation overview >
2020	449 documents	View citation overview >
2019	635 documents	View citation overview >
2018	709 documents	View citation overview >
2017	376 documents	View citation overview >
2016	377 documents	View citation overview >
2015	270 documents	View citation overview >
2014	276 documents	View citation overview >
2013	255 documents	View citation overview >
2012	288 documents	View citation overview >
2011	231 documents	View citation overview >
2010	240 documents	View citation overview >
2009	235 documents	View citation overview >