



OPEN A comprehensive experimental study of eco-friendly hybrid polymer composites using pistachio shell powder and *Aquilaria agallocha* Roxb

K. Yesuraj¹, R. Sathiyamoorthi², Yuvarajan Devarajan³✉, M. Dinesh Babu⁴ & Nandagopal Kaliappan^{5,6}✉

This study investigates the effects of incorporating pistachio shell powder and a mixture of *Aquilaria agallocha* Roxb (AAR) resin with epoxy on the mechanical, dynamic mechanical, thermal, and biodegradability properties of an epoxy composite. Filler loadings ranged from 10 to 35% by volume, in 5% increments. Scanning electron microscopy (SEM) revealed a uniform distribution of the hybrid polymer materials, particularly at 30% natural resin content, enhancing the load-bearing capacity of the composites. The addition of pistachio shell powder and AAR resin significantly improved the flexural modulus and strength of the composites. At a filler volume of 35%, the hybrid polymer exhibited a maximum impact resistance of 2,718 J/m², demonstrating increased energy absorption. Moreover, the hybrid system enhanced the damping factor by up to 30%, suggesting superior dynamic mechanical performance. Thermogravimetric analysis (TGA) indicated that the hybrid composites displayed better thermal stability compared to pure epoxy resin. These findings suggest that the combination of pistachio shell powder and AAR natural resin offers a sustainable approach to reinforcing epoxy-based composites, providing improved mechanical and thermal performance for potential industrial applications.

Keywords Mechanical properties, Sustainable practices, Waste-to-value, Renewable, Waste

The aerofoil surfaces, compressor blades, engine bay doors, and fan casings are all examples of components that are found in aircraft. Components of the vehicle's structure that are designed to improve safety while simultaneously reducing weight. products for sports such as tennis rackets, golf clubs, boats, and surfboards that require high strength-to-weight ratios are examples of such products. A variety of constructions, including bridges, buildings, and others, that are required to endure impact loads and environmental stresses. In polymer composite constructions, natural reinforcement refers to the use of a natural filler material. Natural filler material has the advantage of being both affordable and biodegradable, which makes it an excellent choice for cosmetic applications. Rice husk (RH) is possible cellulose-based natural filler that is produced as a byproduct of agricultural products and is a byproduct of agricultural products¹. Because RH ash has 94% of the silica concentration found in commercial silica material, The use of RH ash in lieu of commercial silica material is growing². In the water absorption tests, these fillers offer the necessary surface area for the adsorption of water molecules. As a result of the water molecules penetrating through microcracks, the weight of the composite material increased ultimately leading to stress failure³. It is anticipated that the RH filler's hydrophilic qualities, which are made up of components like moisture(7.5%), soluble contents(2.5%), and cellulose content (25–35%)causes the water absorption (WA) behavior. When fillers are added in large quantities, the number

¹Department of Mechanical Engineering, Panimalar Engineering College, Chennai, Tamil Nadu, India. ²Department of Mechanical Engineering, Chennai Institute of Technology, Chennai, Tamil Nadu, India. ³Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Saveetha University, Chennai, Tamilnadu, India. ⁴Department of Mechanical Engineering, Rajalakshmi Institute of Technology, Chennai, Tamilnadu, India. ⁵Department of Mechanical Engineering, Haramaya Institute of Technology, Haramaya University, Dire Dawa, Ethiopia. ⁶Department of Food Technology, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamilnadu, India. ✉email: yuvarajand.sse@saveetha.com; nandagopal.kaliappan@haramaya.edu.et

of hydroxyl(OH) groups in RH based composites rises, strengthening the hydrogen bonds that bind water molecules even more⁴.

The total weight loss of RH powder was approximately 7 weight%, while at 550 °C, high-density polyethylene (HDPE) completely disintegrated, as indicated by TGA and DTG curves⁵. The stable curve for RH residue weight appears when the temperature is raised above 500 °C. Peak 1 - breakdown of cellulose and hemicellulose content, while peak 2 - breakdown of lignin content with RH. In this instance, the breakdown of RH is shown by peak 1 at 330 °C, and the breakdown of the HDPE matrix is responsible for peak 3's rottenness. The peak3 temperature increases from 408 to 448 °C with RH-20. It can also be seen that intensities of peak2 and peak 3 curves grow when relative humidity (RH) content increases. When temperatures exceeded 405 °C, the DTG curves migrated to the right in comparison to the modelled curve. The HDPE matrix disintegrated within the designated temperature range, resulting in weight loss⁶. During the testing period, RH was added to the HDPE matrix, which was observed to enhance thermal stability⁷. The impact of chemical treatment and filler loading on composites made from untreated and treated coconut shell powder was investigated. Tensile strength was found to decrease with the use coconut shell powder, whereas tensile modulus increased. The composite's tensile strength was enhanced by the addition of a silane coupling agent⁸.

The effectiveness of coconut shell powder as a natural rubber reinforcement was studied by Sareena⁹. Natural rubber composites were made by combining various sawdust particle sizes and volume percentages, both modified and unmodified. They investigated rip strength, hardness and tensile strength of the composite and discovered that 10% sawdust reinforcement produced better results than other volume fractions⁹. The physical and mechanical properties of sawdust were enhanced by the addition of a silane coupling agent. Surface morphology was investigated using SEM images and fractography.

To ascertain the water absorption characteristics of CSF-based epoxy composites, Ganesan et al.¹⁰ carried out a 15-day test. 30%, 40%, and 50% CSF composites all showed a decrease in water absorption percentage when compared to the other 3% CSF composites. There was nowhere for water molecules to adhere to the composite laminates due to the improved CSF agglomeration using epoxy matrix, which raised overall performance. The mechanical properties of CSF carbonised particles at concentrations of 10, 20, 30, and 40% by weight in polypropylene composites were investigated in terms of several mechanical parameters. Because the fiber's toughness and flexibility decreased with increasing fiber loading, The fiber's modulus of resilience and elongation at break decreased. The incorporation of fillers led to enhanced adhesion and interaction with the matrix, improving the tensile, flexural, and hardness characteristics of the laminates and minimizing void formation¹¹. Przybytniak et al.¹² examined the interaction between the polyethylene matrix and CSF particles. While modulus and hardness values increased with addition of CSF particles, the strain value increased to 0.9021 for both the 20 and 25 weight% CSF particles. The examination of SEM images revealed that the increased concentration of CSF aggravated the lack of homogeneity between matrix and CSF.

Investigations were conducted into the effects of coupling agent and mineral filler material addition on machining characteristics. Bootkul et al.¹³ employed Saw dust as a high density filler material made of teak wood polyethylene composites were prepared by using Saw dust at 7 different volume fractions such as 10%, 20%, 30%, 40%, 50%, 60% and 70%, and effect of volume fraction on the mechanical properties was reported. The results showed that a filler content of more than 30% lowered the impact strength. The composite samples were then utilized to build the Thai spirit house's external décor.

A wood polymer composite was developed Jamili et al.¹⁴. Phenolic resin served as the matrix material and rice husk and sawdust were used as powdered reinforcements. In matrix, the filler ratio was established at 60:40. Sawdust powder, rice husk powder and both powders were combined to create composites. Experimental research is done to determine how UV light exposure affects the mechanical properties and water stability of composites made of sawdust and rice husk. The results showed that phenol resin composites containing saw dust outperformed rice husk composites in terms of mechanical qualities. Saw dust was shown to have superior phenolic resin adherence than particle rice husk filler material.

Bogiatzidis et al.¹⁵ investigated the mechanical characteristics of an unsaturated polyester matrix using wood dust powder. The results revealed that the composite containing 6% sawdust powder performed better mechanically. It has been stated that wood powder may be utilised as superior reinforcement and can be used to mass-produce composites. Krishna et al.¹⁶ employed Sawdust and fly ash are used as fillers in epoxy resin(2018) The impact of filler loading on a hybrid composite's hardness, compressive strength, and moisture absorption was examined by altering the mix of fly ash and Saw dust. The results showed that when the filler loading above the threshold level, the characteristics began to deteriorate due to inadequate wetting of the reinforcements by epoxy resin. Fourier transform infrared spectra for Nylon6 and Nylon 6/CSNP composites were obtained. The major components of Nylon6 were identified by spectral analysis to include carboxylic acid and amine groups at wavenumbers of 32,925 cm⁻¹, 32,925 cm⁻¹, 2855 cm⁻¹, and 1636 cm⁻¹, respectively. The H-bonded amine group in the crystalline and amorphous portion was represented by the 3296 cm⁻¹ band; CH₂ visibility was represented by the 2925 and 2885 cm⁻¹ bands; and the stretching of the C=O atom was represented by the 1636 cm⁻¹ band. The bands mentioned above in the previous section decoded the information about polyamide's presence in composites. Peak sizes between 3200 and 3600 cm⁻¹ are indicative of OH groups are present in the CSF. Because the moisture content in CSF-based composites evaporates and the cellulose and lignin contents burn, TGA curves initially showed a minimal weight reduction.

Diammonium phosphates (DAP) were first added to CSF at different weight% concentrations. The results show that the 30-weight% CSF-based composite loses weight more quickly and has a higher linear burning rate. Esters are produced when the CSF and cellulose's OH group react, and this happens at CSF levels higher than 30%. Laevoglucose was synthesized because of ester formation, which was mostly facilitated by the catalytic action. Swain et al.¹⁷ used a polyester matrix to create a jute fibre reinforced composite. They made composites out of KMnO₄-treated jute cloth and untreated jute fabric. The influence of nano clay and egg shell powder

was investigated. The mechanical and morphological characteristics of the composite material containing 1.5% nanoclay and 1.5% egg shell powder were examined. The findings showed that this composite material performed better than other compositions in terms of these properties. The chemical treatment of the reinforcement resulted in improved mechanical characteristics and good interfacial adhesion.

Previous research underscores the critical role of filler particles and their characteristics in enhancing polymer matrix composites. These particles contribute to increased strength by affecting key physical parameters such as particle volume fraction, size, and particle-matrix interactions. Collectively, these factors have a substantial impact on the mechanical and thermal performance of the composites. Fillers are also employed to enhance surface properties, including hardness and tribological behavior. The novelty of this study lies in its innovative approach, utilizing pistachio shell powder and *Aquilaria agallocha* Roxb (AAR) resin in combination with epoxy to improve the mechanical, dynamic mechanical, thermal, and biodegradability properties of epoxy composites. By varying filler loading levels, the research explores how natural materials can optimize the flexural modulus, strength, impact force, energy absorption, and damping properties of hybrid polymer composites. Furthermore, the study demonstrates that these hybrid materials exhibit significantly improved thermal stability compared to pure epoxy resin. This pioneering approach highlights the potential for creating sustainable, high-performance composite materials with a wide range of industrial applications.

Materials and methods

Materials

Pistachio shell powder/*Aquilaria Agallocha* Roxb blended epoxy natural resin and LY 556 Epoxy resin were employed in this study. The density of the *aquilaria Agallocha* Roxb was calculated and found to be 1.09 g/cm³. Pistachios hell powder and mixed epoxy of *Aquilaria Agallocha* Roxb was ground to a fine size of 7–15 microns utilizing ball milling to 7 h and natural resin material was integrated into epoxy matrix at various volume percents (10, 15, 20, 25, 30 and 35 Volume percent). To achieve uniform dispersion, a mechanical mixer was used to continually swirl both the natural and synthetic resins for 45 min. The hand lay-up method was used to create Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb with epoxy hybrid polymer material laminates. This was accomplished using a silicon rubber mould with dimensions of 300 × 300 × 3 mm³. The mould was covered on top and bottom with rigid plates. A rigid plate was placed over the mold after a known volume of a mixture of natural and synthetic resins was poured into it. A weight applied with a force of 500–600 N was then placed over the mold to compress polymer material laminate. The laminates were cut for various tests according to the American Society for Testing's guidelines and Materials after they had cured.

Testing methods

Mechanical properties

The Instron Universal Testing Machine was used for tensile and flexural testing. With a velocity of 2 mm/min, A tensile test was conducted in compliance with ASTM D- 638. In compliance ASTM D – 790, The purpose of the three-point bending test was to ascertain flexural strength. In compliance with ASTM D-256 (Fig. 1), the impact strength was ascertained with the Izod technique. For every test, five samples were used and average value was determined (Fig. 2).

Dynamic mechanical analysis

Using the SEIKODMAI-DMSC 6100, the dynamic properties of a mixed epoxy of *Aquilaria Agallocha* Roxb hybrid polymer material and pistachio shell powder were studied under heat and dynamic loading conditions. Dynamic mechanical analysis tests were conducted in a nitrogen environment under the tensile mode, with temperatures ranging from 30 to 180 °C at frequencies of 10 Hz and 5 °C/min increments.

Thermogravimetric analysis

Thermogravimetric analysis, also known as TGA, is a method of thermal analysis that is utilised to evaluate the thermal stability of composite materials as well as their compositional qualities. According to this technique, the change in mass of a sample is measured as a function of temperature or time while the atmosphere is under controlled conditions. Polymer composites, especially those that are reinforced with natural fibres like pistachio shell powder and *Aquilaria agallocha* Roxb, can be characterised specifically with the use of TGA, which is a very useful technique. A TG/DTA 6200 SEIKO TGA analyzer was accustomed to test. The composite's ability to withstand heat specimen throughout a temperature range of 0–800 °C with a 20 °C/min increase. To prevent oxidation, an atmosphere of nitrogen, the powder was heated.

Biodegradability test

Testing the biodegradability of composite materials is crucial for evaluating their decomposition in natural environments, especially when composed of biodegradable polymers and natural fibres. This assessment is essential for evaluating the ecological consequences of composite materials, particularly those intended to be environmentally sustainable. The oldest and most widely used approach for determining degradation is soil burial. Soil contains a plethora of species as a result of the real conditions of waste disposal, forming a dynamic, complex ecosystem that serves as an active degrading resource. The sample's biodegradability was investigated by observing weight loss over time in a soil setting. After the samples were weighed, they were buried in the ground. After 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 days, the buried samples were dug up. The samples were rinsed with water after being removed from the soil and weighed to assess the weight loss.

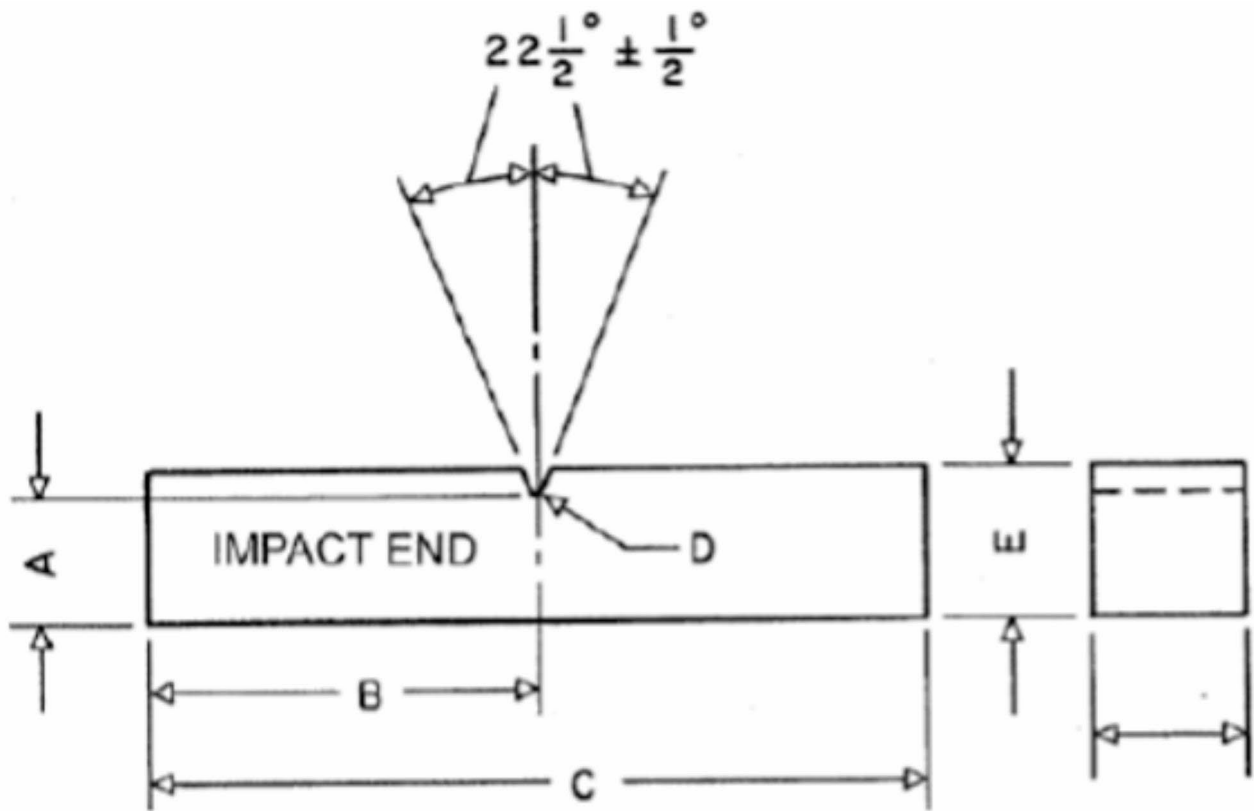


Fig. 1. Dimensions of Impact strength as per ASTM D256.

Fractography study

The study of fractography in composite materials entails analysing fracture surfaces to comprehend failure causes and material behaviour under stress. This research is essential for determining the mechanisms and reasons behind the failure of composite materials, hence guiding design enhancements and improving the reliability of these materials across diverse applications. To evaluate the filler material's dispersion within the polymer matrix, morphological examinations were carried out using SEM. The experiment used a Hitachi S 3400 N scanning electron microscope for the investigation. To avoid charging, Gold was sputter-coated on composite samples.

Results and discussion

Integration of Pistachioshell powder and mixed epoxy of *Aquilaria Agallocha* Roxb with epoxy resin is proposed in this work to improve the properties of hybrid polymer materials. To compare the outcomes with the epoxy resin, a thorough investigation was conducted.

Figure 3 illustrated the tensile properties of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb with epoxy resin qualities of hybrid polymer composites. Figure depicts the composition of the composite's tensile characteristics as a function of natural resin added to epoxy resin. Pure epoxy resin has tensile strength of 17.5 MPa and modulus of 1200 MPa, respectively. The tensile strength is 18.644, 19.845, 21.46, 23.56, 25.17, and 24.13 MPa, respectively, with the addition of natural resin by 10, 15, 20, 25, 30, and 35 volume percent. Similarly, the tensile modulus of epoxy resin increased from 1370, 1410, 1444, 1612, 1712, and 1590 MPa to 1200 MPa for 30% composite. The strength and modulus values of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb bio resin improved by 12.26% and 31.97%, respectively, with a 30-volume percent addition of Pistachioshell powder and mixed epoxy of *Aquilaria Agallocha* Roxb bio resin¹⁸. Furthermore, raising the addition to 35 volume percent decreases both strength and modulus from 25.17 MPa to 24.13 MPa. Figures 4 and 5 showed micrographs of hybrid polymer composites with 30 and 35% natural resin added.

The SEM image in Fig. 4 reveals hybrid polymer materials with 30 volume percent natural resin added. It demonstrates that the natural resin is evenly distributed throughout. Because of this equal dispersion, the load carrying capacity of hybrid polymer composites is improved. The SEM picture of 35 volume percent hybrid polymer material is also shown in Fig. 5. The addition of a volume percent of natural resin causes agglomeration, as seen in the SEM photos. As a result of agglomeration, natural resins is unable to evenly distribute load, and their mechanical qualities begin to deteriorate¹⁹. Figure 6 depicts the elemental spectrum of natural filler using oxford EDAX analyzer. Moreover, it shows the carbon, oxygen, Mg, Si as the main constituents of the filler material. It is observed that the percentage of different constituents is found to be 47.5%, 51.69% and 0.80%.

Figure 7 depicts the composite's flexural characteristics. The epoxy resin's flexural strength and modulus are 34 and 1700 MPa, respectively. Flexural modulus and strength increased to 34.56, 35.74, 36.26, 37.45, 41.72 and



Fig. 2. Impact testing equipment.

39.92 MPa and 2010, 2600, 2850, 3100, 3570 and 2419 MPa, respectively, with the addition of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* natural resin by 10, 15, 20, 25, 30 and 35 volume percent. Flexural strength and flexural modulus of the composite with 30% Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* increased by 15.37% and 22.70%, respectively. Flexural properties of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* with epoxy hybrid polymer materials indicated increases up to 30% volume percent, similar to tensile qualities²⁰.

The impact strength of the Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* hybrid polymer material is shown in Fig. 8. Impact strength of the epoxy resin is 2 J/m², while the impact strength of 10, 15, 20, 25, 30, and 35 volume percent hybrid polymer materials is 2,469, 2,557, 2,648, 2,687, 2718, 2,671 J/m². The hybrid polymer composites with 35 volume percent Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* had a maximum force of impact of 2,718 J/m². The epoxy resin's brittleness accounts for its lower impact strength, whereas Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* has greater adhesion with the epoxy resin²¹. As a result, the composite's ductility has improved, and its impact strength has increased by 18.4%.

Dynamic mechanical analysis

Dynamic mechanical analysis is used to evaluate visco-elastic behavior of polymer. It gauges polymer material's damping capabilities during cyclic loading. Calculating the energy content lost is done. Study investigated impact of mixed epoxy *Aquilaria Agallocha Roxb* natural resin volume percent and pistachio shell powder on the hybrid polymer material's damping factor and storage modulus. The impact of frequency on the storage modulus of materials made of hybrid polymers is also covered.

Storage modulus

The storage modulus signifies the extent to which a material can elastically store energy. An elevated storage modulus indicates a more rigid material, which is advantageous for applications necessitating structural integrity. The storage modulus often diminishes with rising temperature, especially around the glass transition temperature (T_g). Below the glass transition temperature (T_g), the molecular chains exhibit reduced mobility,

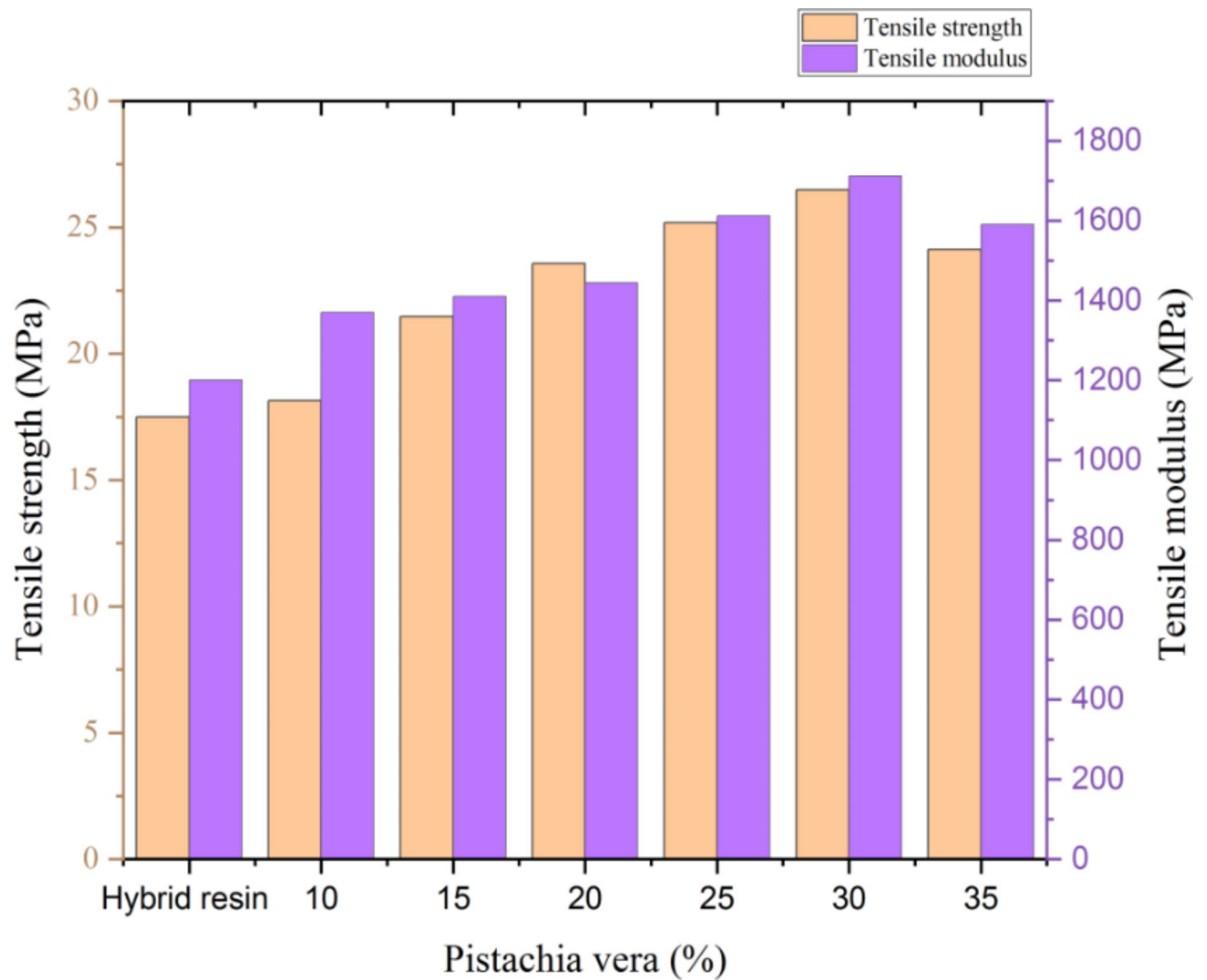


Fig. 3. Tensile properties of Pistachioshell powder and mixed epoxy of Aquilaria Agallocha Roxb with Epoxy Blender Hybrid Material.

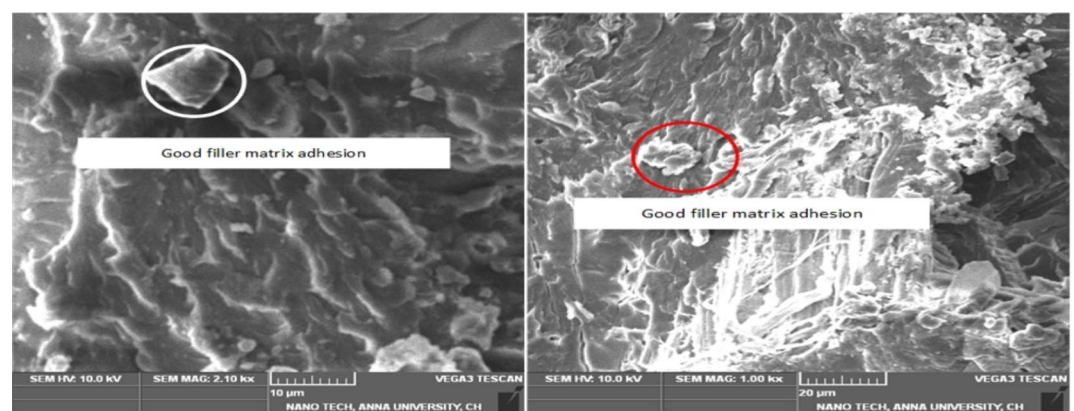


Fig. 4. Vol% Pistachioshell powder and mixed epoxy of Aquilaria Agallocha Roxb with epoxy resin evenly dispersionI

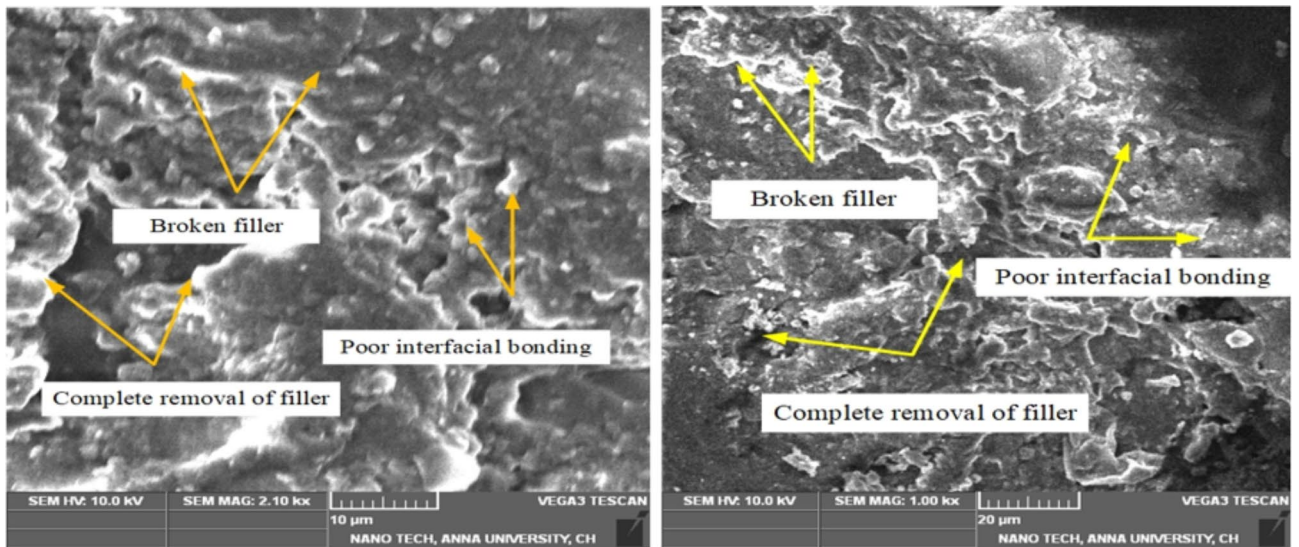


Fig. 5. Vol% Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* with epoxy resin agglomeration.

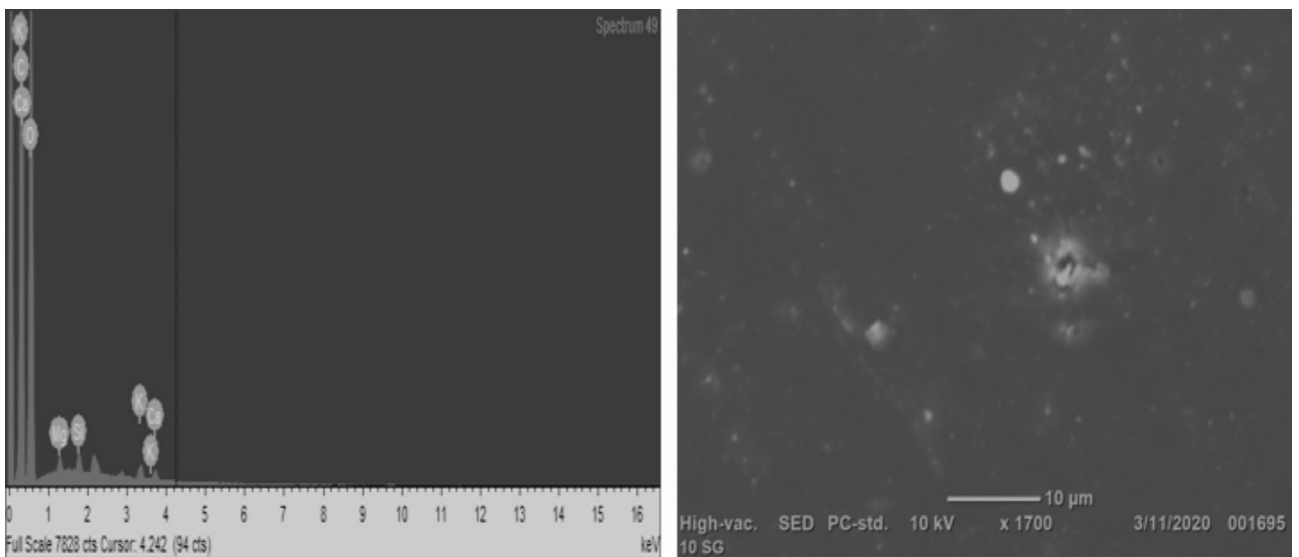


Fig. 6. The elemental spectrum of natural filler using Oxford EDAX analyser.

leading to an increased storage modulus (E'). As the temperature nears T_g , enhanced molecular mobility results in a decrease in E' , facilitating the transition of the material from a glassy to a more rubbery state. The inclusion of natural fibres such as pistachio shell powder might markedly affect the storage modulus of the composite. The interplay between the fibre and polymer matrix augments stiffness and can boost load-bearing capability²².

The effects of temperature and *Aquilaria Agallocha Roxb* blended epoxy natural resin loading on a hybrid polymer composite's storage modulus at 10 HZ frequencies are shown in Fig. 9. The results showed that adding Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* natural resin increased the hybrid polymer material's absorption energy. This is because the natural material to the pure epoxy matrix enhances the hybrid polymer's ability to store energy. Pure epoxy resin is shown in Fig. 7 by having a lower storage modulus. Composite's glass transition temperature (T_g) increases from 70 to 110 °C as a result of the polymer's free molecular mobility along its chain. According to research, stiffness can be increased by incorporating a polymer matrix into the mixed epoxy of *Aquilaria Agallocha Roxb* natural resin and pistachio shell powder²³. This is done by using hybrid polymer material. Another interesting finding from Fig. 7 is the use of Pistachio shell powder with *Aquilaria Agallocha Roxb* mixed epoxy natural resin. It raises the storage modulus in the glassy and rubbery regions. Research has indicated that shorter exposure times (high frequency) are associated

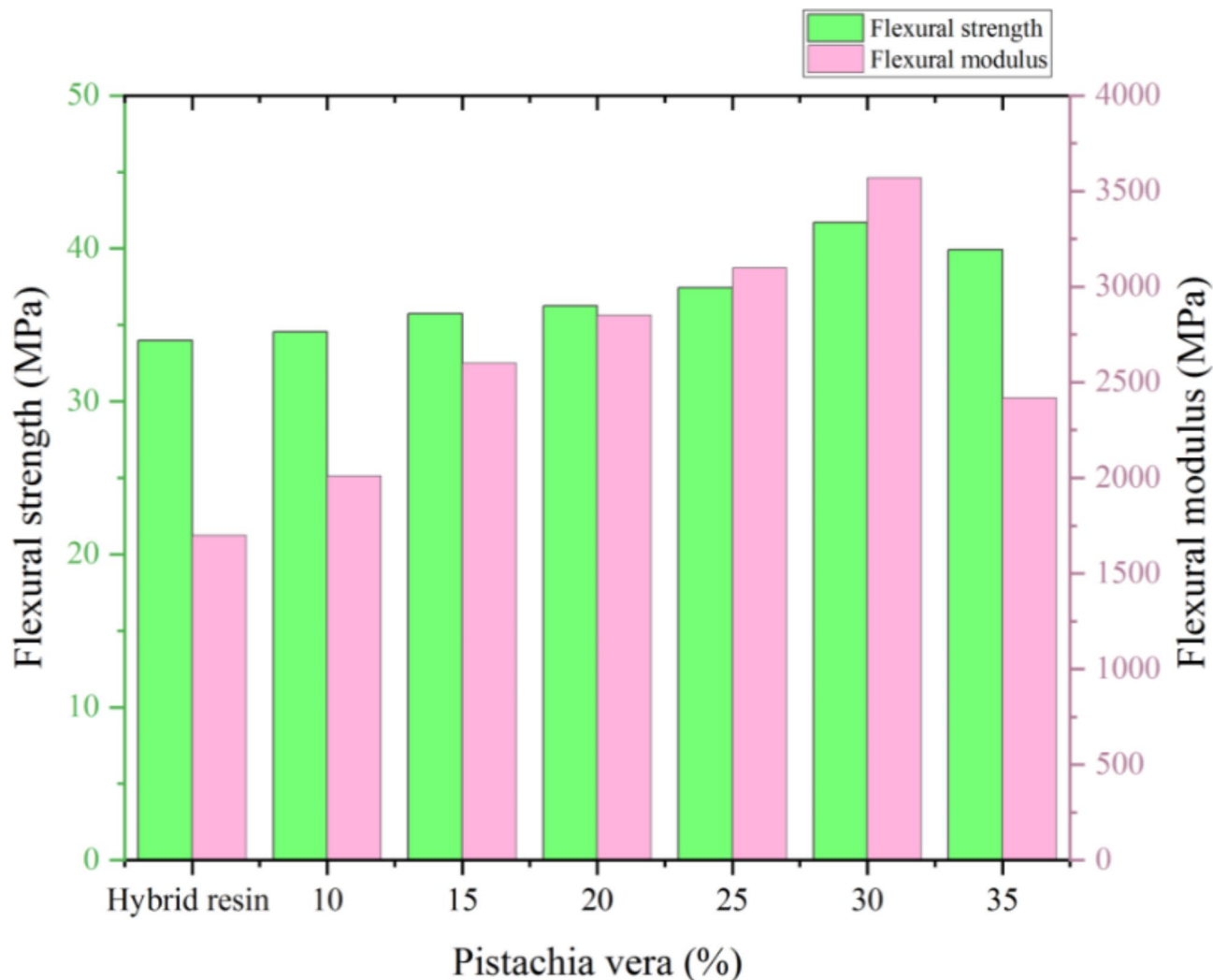


Fig. 7. Flexural properties of *Pistachioshell powder and mixed epoxy of Aquilaria Agallocha Roxb* with Epoxy Blender Hybrid resin.

with higher storage modulus values, while longer exposure times (low frequency) are associated with lower storage modulus values.

Damping factor (Tan δ)

An investigation of the damping factor is crucial for assessing the mechanical properties of eco-friendly hybrid polymer composites, especially those that include natural fibres such as pistachio shell powder and *Aquilaria agallocha* Roxb. This research elucidates the mechanisms by which these materials disperse energy under dynamic loading, which is essential for applications necessitating vibration damping and noise attenuation²⁴.

The material's energy dissipation under the degree of molecular mobility in polymer chain was represented by the damping factor. Figure 10 illustrates the damping factor of pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb natural resin reported hybrid material. The findings indicate that the damping factor can be increased by up to 30% in the polymer mixture by adding mixed epoxy of *Aquilaria Agallocha* Roxb natural resin and powdered pistachio shell²⁵. This means that polymer composites containing a smaller percentage of Pistachio shell powder/*Aquilaria Agallocha* Roxb mixed epoxy natural resin have a higher interaction between synthetic and natural resins. Natural materials' energy dissipation rises as a result of improved interaction. However, as can be shown in Figs. 7 and 8, the larger natural resin content (more than 30% volume percent) minimizes energy dissipation. When compared to Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb natural resin added hybrid polymer material, peak height of Tan (damping factor) for neat epoxy resin is less.

Cole-Cole plot

The polymer composite's linear visco-elastic behavior at glass transition temperature can be examined using the Cole-Cole plot. A Cole-Cole plot at 10 HZ frequencies is produced by graphing Loss modulus (E'') against Storage modulus (E'). Cross-linked polymer undergoes structural change²²s upon the addition of natural Pistachio shell

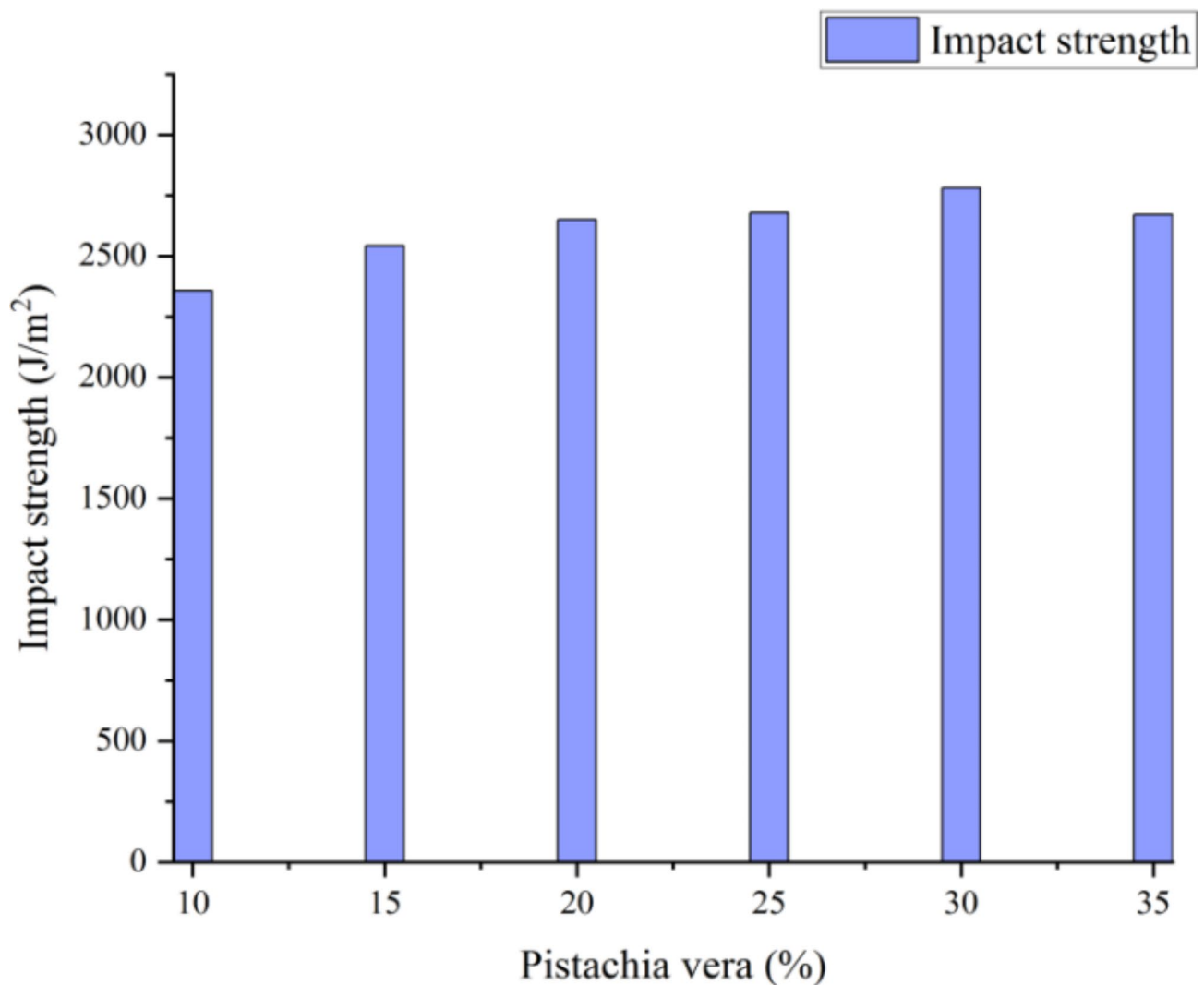


Fig. 8. Impact properties of *Pistachio shell powder and mixed epoxy of Aquilaria Agallocha Roxb* with Epoxy Blender Hybrid Resin.

powder and mixed epoxy of *Aquilaria Agallocha Roxb* resin, as this plot illustrates. The following curve serves as an illustration, and the shape indicates material is homogeneous / heterogeneous. The plot elucidates several relaxation processes inside the material, reflecting alterations in molecule mobility and interactions as a function of frequency. The configuration of the Cole-Cole plot can disclose insights regarding the heterogeneity of the composite material. A semicircular arc signifies a singular relaxation process, but variations from this form indicate many processes or heterogeneous conductivity within the material. Through the examination of the Cole-Cole plot, researchers can deduce significant properties such as conductivity, permittivity, and loss tangent, which are essential for applications in electronics and structural components²⁶.

Figure 11 revealed that Cole-cole plot demonstrated how uniformly the hybrid polymer material exhibited a homogenous substance produced by combining 30% pistachio shell powder with mixed epoxy of *Aquilaria Agallocha Roxb* natural material. When 30% volume percent of a blended epoxy natural resin containing *Aquilaria Agallocha Roxb* and pistachio shell powder is added, the material behaves differently from homogeneous to heterogeneous^{24,27}. According to Cole–Cole plot, the curve is semicircular for 30% of the volume; any departure from this semi-circularity suggests that the composite is starting to become heterogeneous.

Thermo-gravimetric analysis (TGA)

Thermo-Gravimetric Analysis is an essential method for elucidating the thermal properties and efficacy of environmentally friendly hybrid polymer composites, facilitating the advancement of sustainable materials with improved attributes. TGA assesses the temperature at which notable weight reduction transpires, signifying the thermal stability of the composite. Composites with treated fibres typically exhibit superior thermal stability relative to untreated fibres, attributable to better bonding and less moisture content. The analysis can identify specific stages of decomposition associated with varying temperature ranges. Initially, weight loss may transpire owing to moisture evaporation, succeeded by the decomposition of hemicelluloses and cellulose at elevated

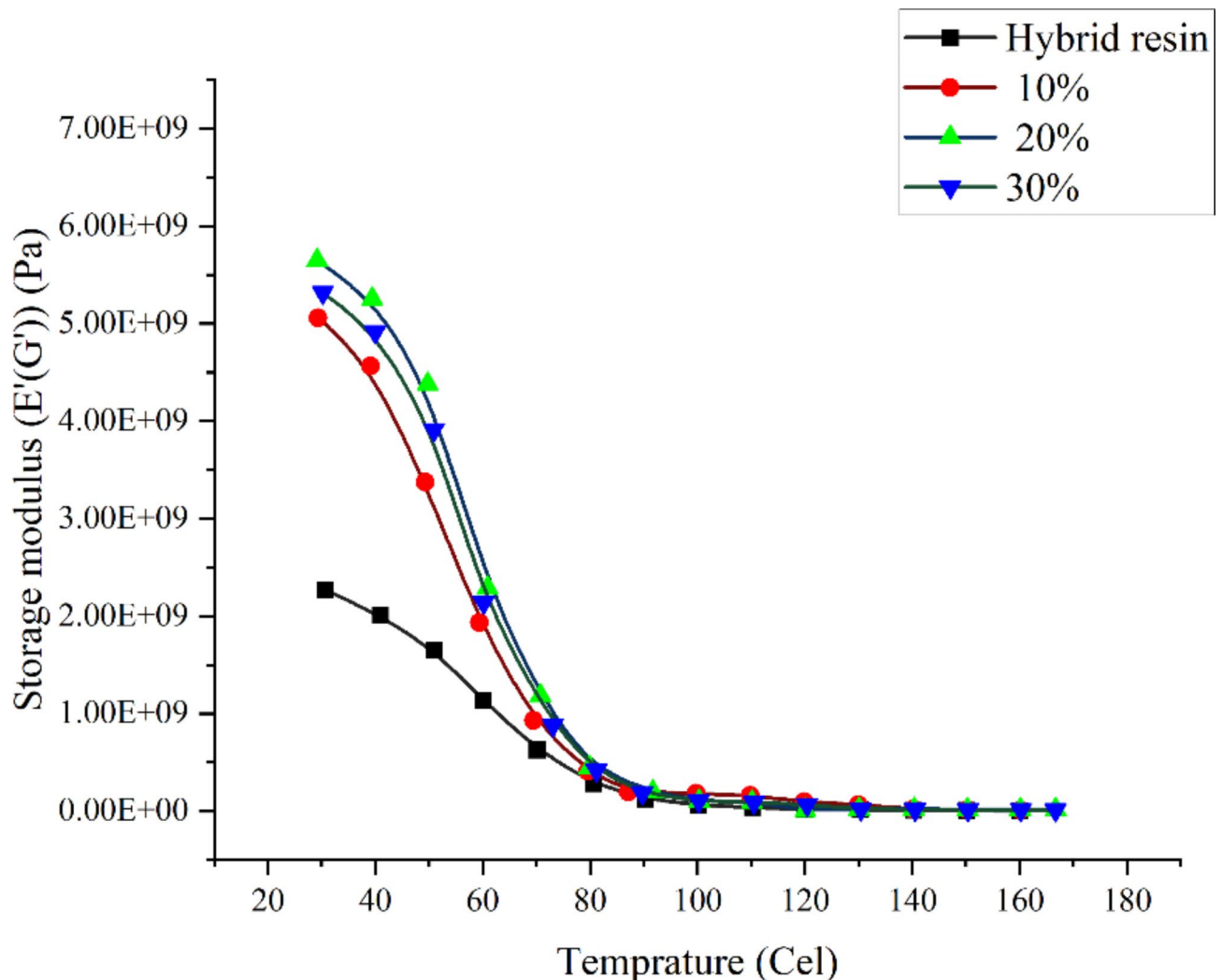


Fig. 9. Storage modulus of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb with Epoxy Blender Hybrid Resin at 10 Hz frequency.

temperatures. The inclusion of natural fibres such as pistachio shell powder can influence the thermal properties of the composite. TGA measurements can demonstrate the efficacy of these fibres in reinforcing the polymer matrix and their impact on thermal characteristics^{28,29}.

The neat epoxy resin and hybrid polymer material's thermo-gravimetric analysis (TGA) curves are displayed in Table 1. It was discovered that blended hybrid polymer material containing pure epoxy with powdered pistachio shell and mixed epoxy of *Aquilaria Agallocha* Roxb resin added had higher thermal stability than neat epoxy resin. The findings indicate that Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb hybrid material. However, there was a slight improvement in TGA values with the Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb natural resin components. First stage of weight loss was brought on by sample's water evaporating^{26,30,31}. Therefore, adding Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha* Roxb epoxy natural resin to the epoxy matrix improves the hybrid polymer materials' thermal stability. Figure 12 depicts the epoxy resin's stability up to 491 °C. The resin dissolves swiftly at this temperature, leaving only 0.3% residue, whereas Pistachio shell powder with *Aquilaria Agallocha* Roxb mixed epoxy leaves no residue. It's stable up to 30% and has a residual content of 9%.

Biodegradability test

Polymer composites possess a higher degree of biodegradability when natural fillers such as pistachio shell powder and fibres derived from *Aquilaria agallocha* are incorporated into their composition. These materials not only lessen the dependency on synthetic polymers, but they also help to the development of waste management solutions by breaking down into byproducts that are not harmful, thereby reducing the amount of pollution that is released into the environment²⁶. An item sample is buried in wet soil to test its biodegradability. Figure 13 illustrates how the powdered pistachio shell and *Aquilaria Agallocha* Roxb blended epoxy hybrid polymer materials are affected by biodegradability²⁸. The sample's original weight was noted prior to it being buried in the ground. After that, the sample was taken periodically, and testing was used to identify any changes in

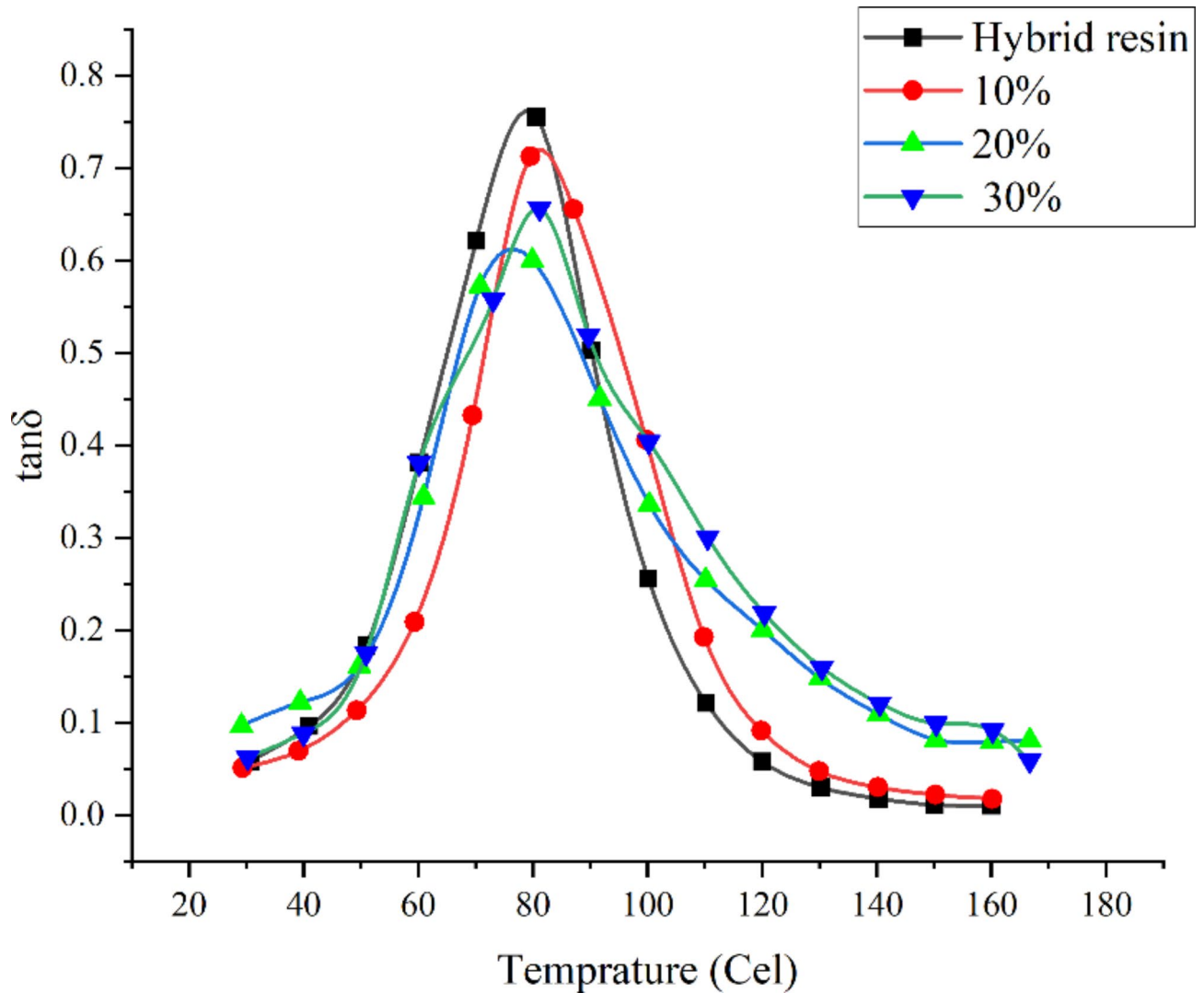


Fig. 10. Tan δ of Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* with Epoxy Blended Hybrid Resin at 10 Hz frequency.

weight. The sample had lost 5.2% of its total weight after 120 days. The sample's weight initially increased due to moisture absorption, but it eventually began to decrease³¹. Reaction of macro and micro-organisms with composite sample over an extended period was the reason for the weight loss^{32–34}.

Conclusion

The present study highlights the effective use of pistachio shell powder and a blended epoxy of *Aquilaria agallocha Roxb* resin as reinforcements in an epoxy composite, revealing significant enhancements in its mechanical, dynamic mechanical, thermal, and biodegradability properties. Filler loadings ranging from 10 to 35% by volume were explored, with the optimal performance observed at 30% filler content. At this concentration, the tensile strength increased by 12.26%, and the modulus improved by 31.97%. A further increase to 35% filler volume resulted in diminished mechanical performance due to agglomeration, as confirmed by SEM analysis. This phenomenon is attributed to the reduced load distribution caused by the high volume of natural resin, which negatively impacts mechanical properties.

Notably, the addition of 30% pistachio shell powder and *Aquilaria agallocha Roxb* resin improved the flexural strength by 15.37% and modulus by 22.70%, indicating consistent enhancement in both tensile and flexural properties. The composite also exhibited improved ductility and impact resistance, with an 18.4% increase in impact strength, reflecting the positive effect of the natural fillers on adhesion and toughness. Thermal stability was significantly enhanced, as evidenced by increased glassy and rubbery storage modulus values. Dynamic mechanical analysis demonstrated that higher frequencies increased storage modulus, while lower frequencies reduced it, highlighting the frequency-dependent behavior of the composite. The synergy between the pistachio shell powder and the blended natural resin promoted better interaction within the polymer matrix, enhancing energy dissipation and overall composite performance.

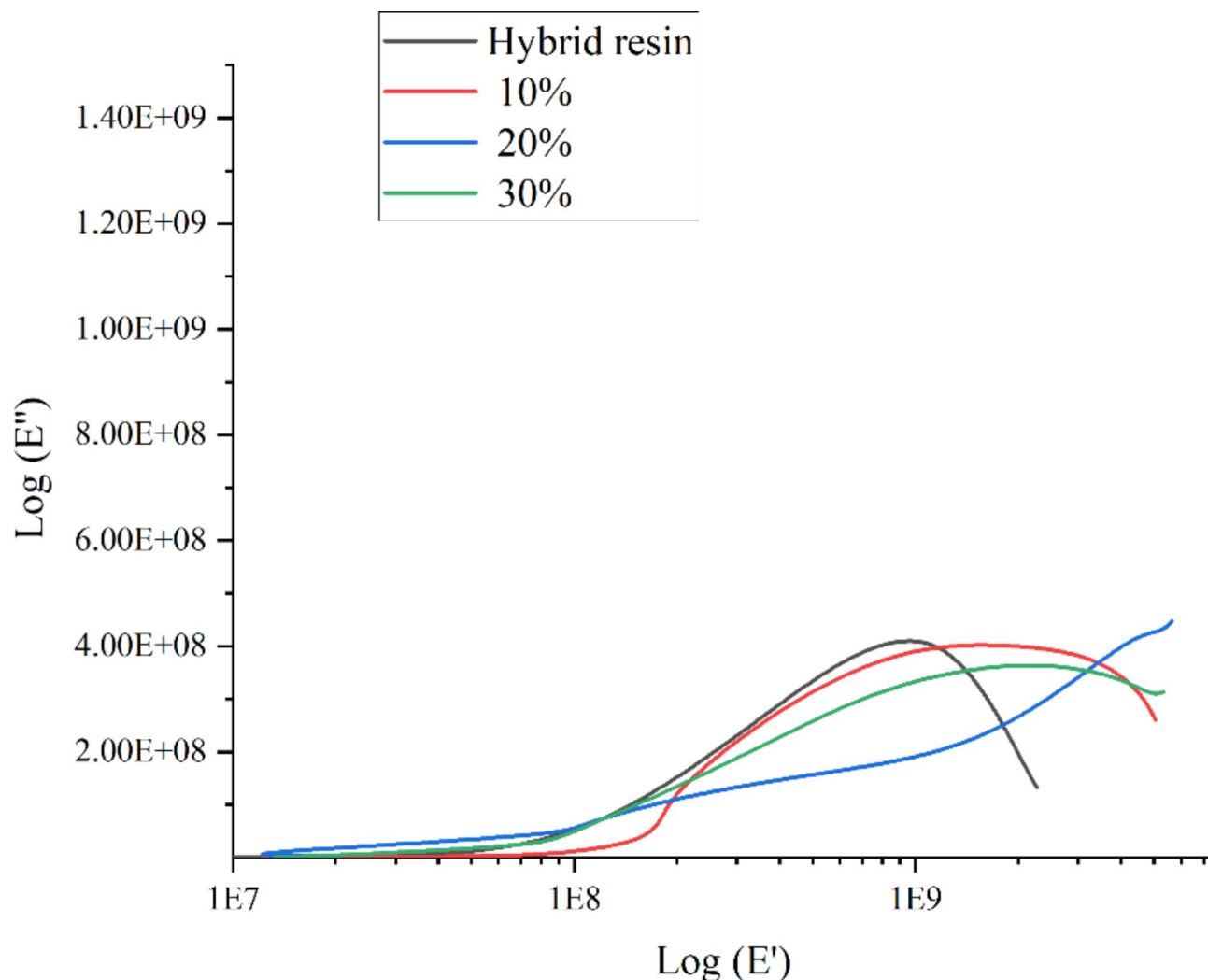


Fig. 11. Cole-Cole Plot Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* with Epoxy Blender Hybrid Resin.

Composition	Degradation temperature (°C)			Residue (%)
	IDT	MDT	FDT	
HYBRID RESIN	302	352	391	0.2
10% VF AA	305	373.4	397	9
15% VF AA	307	375.4	398	10
20% VF AA	308	375.6	398	15
25% VF AA	311	385.7	399	17
30% VF AA	313	386.4	401	19
35% VF AA	316	391.3	407	18

Table 1. Thermogravimetric analysis Pistachio shell powder and mixed epoxy of *Aquilaria Agallocha Roxb* with Epoxy Blender Hybrid Resin.

The damping properties, as indicated by the damping factor ($\tan \delta$), improved by 30%, with the hybrid composite outperforming the plain epoxy resin. The biodegradability study showed that the composite exhibited a 5.2% weight loss over 120 days, suggesting that this material can achieve environmental degradation through interactions with microorganisms. Incorporation of pistachio shell powder and *Aquilaria agallocha* Roxb natural resin into epoxy composites offers a promising pathway to developing environmentally friendly, high-performance materials. The results demonstrate the potential of this hybrid system for applications requiring

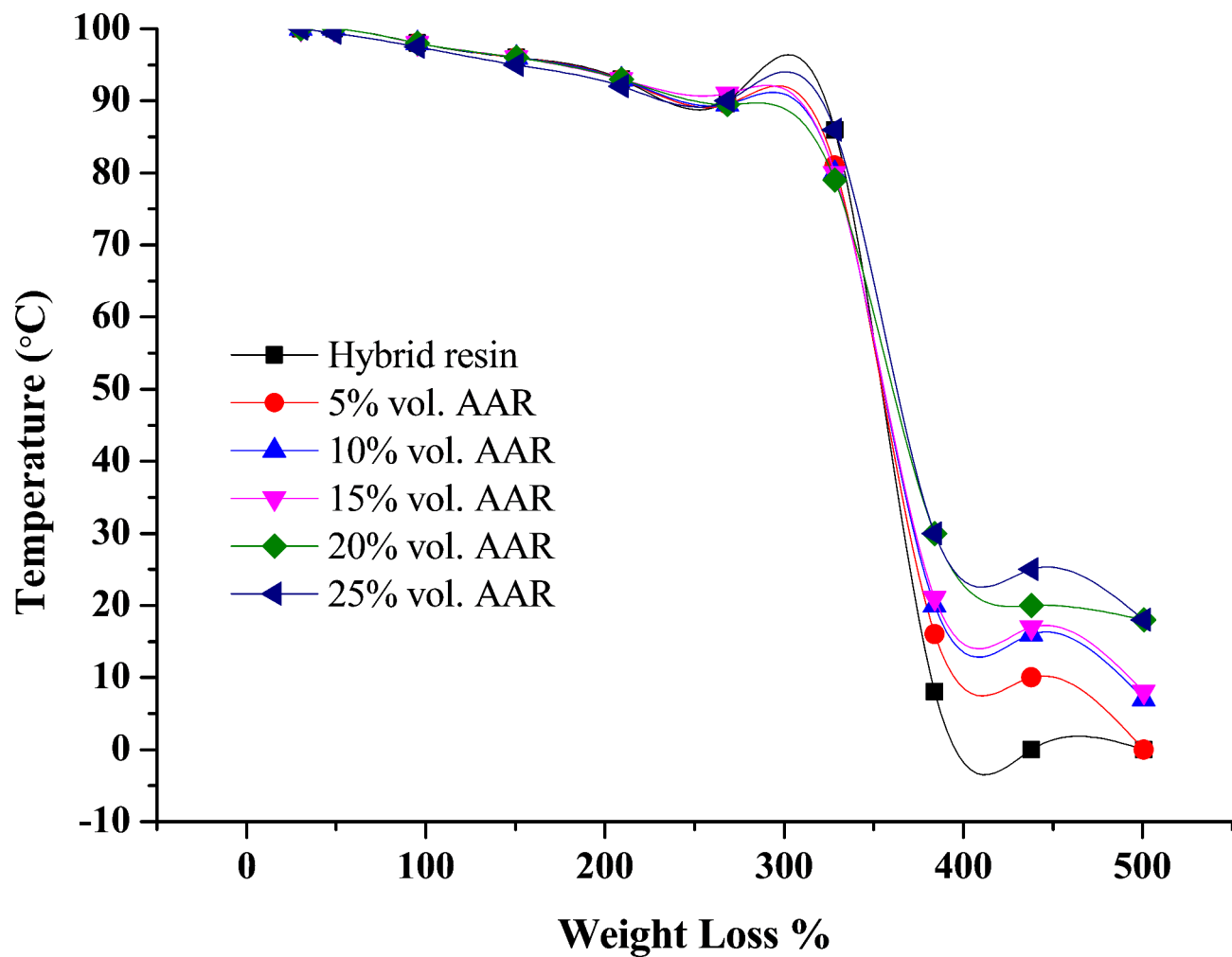


Fig. 12. Thermogravimetric analysis (TGA) for temperature vs weight loss %.

enhanced mechanical, thermal, and biodegradation properties, making it suitable for a range of industrial uses while supporting sustainability goals.

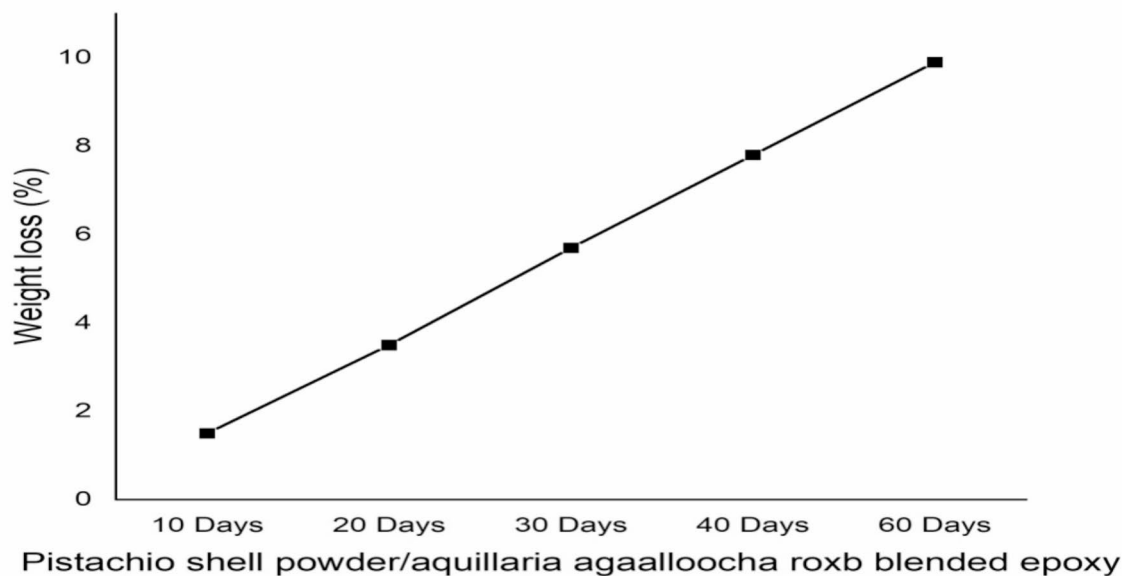


Fig. 13. Bio-degradability test for powdered pistachio shell and Aquilaria Agallocha Roxb blended epoxy hybrid polymer materials.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 19 July 2024; Accepted: 30 September 2024

Published online: 16 October 2024

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Author contributions

All authors have equally contributed to the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Y.D. or N.K.

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