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Investigating the effect of cashew nutshell liquid and aluminum powder on the mechanical and thermal properties of epoxy resins

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ABSTRACT

This study focuses on developing hybrid polymer composites by incorporating cashew nut shell liquid (CSNL) and aluminum powder into LY556 epoxy resin. The objective was to enhance the material's mechanical properties, specifically tensile strength, thermal stability, and flexural strength, while promoting sustainability using agricultural by-products. The materials were blended in various proportions with aluminum particles of micron and nano sizes to identify the optimal composition. A thorough characterization was performed using tensile and flexural testing, scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR). Results indicated that a composition of 2.5% aluminum powder and 30% CSNL yielded significant improvements in tensile and flexural properties, achieving tensile strength values of 64 MPa and a flexural strength of 45 MPa. SEM analysis revealed a homogenous distribution of aluminum particles, while FTIR confirmed successful bonding between the components. These findings suggest that the integration of CSNL and aluminum particles into epoxy resin provides a feasible method for producing sustainable hybrid composites with enhanced mechanical and thermal properties.

Keywords: Hybrid polymer; epoxy resin; cashew shell nut liquid; aluminum powder; tensile strength.

1. INTRODUCTION

The development of hybrid polymer composites incorporating renewable resources has gained significant attention due to the growing global emphasis on sustainability. Cashew nut shell liquid (CNSL), a byproduct of cashew processing, represents an abundant source of naturally occurring phenolic compounds with unique chemical properties. CNSL's chemical structure, which includes cardanol, offers excellent potential as a raw material for creating bio-based polymers, and its application in epoxy resins offers an environmentally friendly alternative to synthetic additives [1]. Combining CNSL with other fillers, such as aluminum particles, can lead to hybrid composites with enhanced mechanical and thermal properties, offering new material science and engineering possibilities.

Despite the growing interest in bio-based polymers, the mechanical limitations of CNSL-based composites remain a significant challenge. This study aims to address this problem by enhancing the properties of CNSL-epoxy composites through the inclusion of aluminum powders. Aluminum has been widely used as a reinforcing material due to its excellent conductivity, low density, and ability to enhance the mechanical strength of polymer matrices. This research seeks to determine the optimal proportion of CNSL and aluminum in epoxy resins to achieve superior tensile, flexural, and thermal properties [2].

A substantial body of literature has investigated various bio-based composites. Studies have demonstrated that natural fillers, like CNSL, can enhance polymer matrices' flexibility, reduce environmental impact, and offer cost benefits. However, these materials often suffer from weaker mechanical properties compared to synthetic counterparts. On the other hand, aluminum-reinforced polymer composites are known for their mechanical

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robustness, particularly in structural applications. The novelty of this research lies in combining these two materials—CNSL and aluminum powders—in a hybrid polymer matrix to produce a composite that balances sustainability and performance [3].

Several studies have explored CNSL's integration into polymer systems, highlighting its potential in enhancing thermal stability and providing a degree of mechanical reinforcement. However, limited research has focused on optimizing the incorporation of aluminum powders, particularly in varying sizes (micron and nano), within a CNSL-epoxy matrix. This gap forms the basis for the current study's objectives, which seek to optimize the combination of these materials and evaluate their collective impact on mechanical and thermal performance [4].

CNSL extraction offers environmental benefits by valorizing agricultural waste. However, industrial-scale extraction involves solvent use, raising concerns about emissions and energy consumption. Advancements in green extraction methods, such as supercritical CO_2 or enzymatic processes, mitigate these concerns. Life-cycle analysis reveals CNSL's positive net environmental impact compared to petroleum-based additives, underscoring its role in promoting sustainability [5].

The significance of this research extends beyond the development of a mechanically enhanced polymer. By using CNSL, a renewable resource, this study contributes to the global push toward sustainable material production. Furthermore, this work provides a practical solution to the limitations of CNSL-based composites, offering a novel material with enhanced strength and durability suitable for various industrial applications. The introduction of aluminum as a reinforcing filler within the bio-based matrix also sets a new precedent in hybrid composite development, offering insights into how natural and synthetic materials can be blended for optimized performance [6].

This study is unique in its approach to solving the inherent challenges of CNSL-epoxy composites by focusing on integrating micron and nano-sized aluminum powders. The innovative aspect of this research lies in the dual reinforcement mechanism: the renewable, bio-based CNSL provides sustainability, while aluminum powders improve mechanical integrity. The research will investigate different compositions of CNSL and aluminum in epoxy matrices to determine the best combination for improving tensile, flexural, and thermal properties. Scanning electron microscopy (SEM), tensile testing, flexural analysis, and Fourier-transform infrared (FTIR) spectroscopy comprehensively characterize the material's performance and its internal structural features [7].

Replacing conventional amine-based curing agents with bio-derived alternatives enhances the sustainability of CNSL composites. Potential alternatives include tannin or lignin-based hardeners, which reduce reliance on petrochemicals. These agents maintain comparable mechanical and thermal properties while improving biodegradability. Further exploration of bio-based curing systems aligns with the goal of developing fully sustainable hybrid composites [8].

The objectives of this study are multifaceted. First, the research aims to enhance the mechanical properties of CNSL-based epoxy composites by optimizing the content of aluminum powder, both in micron and nano forms. Specifically, it seeks to identify the best composition for improving tensile strength, flexural strength, and thermal stability. Additionally, the study will evaluate how the size of aluminum particles affects the composite's properties, comparing micron-sized and nano-sized particles. This analysis will help determine whether nano-particles offer superior benefits over their larger counterparts in enhancing the material's performance. Lastly, the research will assess the environmental impact and cost-effectiveness of using CNSL, supporting the development of sustainable materials for industrial applications [9].

The present research fills a critical gap in the literature by focusing on the novel combination of CNSL and aluminum in hybrid epoxy composites. By addressing both sustainability and performance challenges, the study aims to develop a material with broad applications in industries ranging from automotive to construction. The results of this study are expected to offer valuable insights into the optimal use of natural and synthetic fillers in polymer composites, driving innovation in material science.

Replacing conventional amine-based curing agents with bio-derived alternatives enhances the sustainability of CNSL composites. Potential alternatives include tannin or lignin-based hardeners, which reduce reliance on petrochemicals. These agents maintain comparable mechanical and thermal properties while improving biodegradability. Further exploration of bio-based curing systems aligns with the goal of developing fully sustainable hybrid composites [10].

2. MATERIALS AND METHODS

A systematic approach was taken to create a hybrid polymer resin aimed at achieving specific research objectives. The process involved blending key components: LY556 epoxy resin, cashew shell nut liquid (CSNL), and 98% pure aluminum powder. The material's properties were tailored to meet the research specifications by mixing these components in varying proportions. CSNL, derived from cashew nut shells, is recognized for its potential to convert agricultural waste into valuable resources, aligning with global sustainability trends. Integrating CSNL into hybrid polymer resins represents a significant advancement in material science. Through rigorous trials, it was determined that 2.5% aluminum powder yielded optimal results, ensuring even distribution without agglomeration. This composition improved mechanical strength, thermal stability, and potential electrical conductivity, meeting the research goals effectively. The material selection process involved carefully selecting a three-hour stirring duration to thoroughly integrate CSNL and aluminum powder into the epoxy matrix. The incorporation of CSNL, a sustainable additive, not only improved the resin's mechanical properties but also supported local resources, contributing to sustainable practices. An amine-based hardener, HY951, was chosen as the curing agent for LY556 epoxy resin, ensuring efficient chemical reactions and a strong, well-cured polymer network. The curing process played a pivotal role in producing a high-quality hybrid polymer material, ensuring the mechanical integrity of the final product. During the epoxy-CSNL blend preparation, precise blending techniques under controlled conditions were essential. A Teflon-coated magnetic stirrer was used, maintaining a steady temperature of 80°C to ensure uniform distribution of the components. The stirring speed of 400 rpm further reduced the risk of clumping, ensuring an even mix. This careful preparation led to a hybrid polymer resin with enhanced thermal stability and mechanical properties. The research also focused on the composition of CSNL and epoxy in hybrid polymer development. Various proportions of aluminum particles were incorporated to explore their effects on the mechanical properties. Detailed tables highlighted the viscosity of different compositions, showing how varying levels of CSNL and aluminum affected the material's performance. For instance, adding 30% CSNL to the epoxy resin significantly reduced the viscosity at 80°C, enhancing its processability.This research demonstrated the successful development of a hybrid polymer resin that integrates sustainable materials with improved mechanical and thermal characteristics. By combining CSNL and aluminum powder, the study offers a novel approach to creating high-performance materials while promoting sustainability. This hybrid resin holds potential for various industrial applications, such as construction or automotive industries, where strength and environmental considerations are critical.

2.1. Curing processes of hybrid polymer

After formulating the hybrid polymer resin and completing the controlled heating and stirring process as described earlier, the next steps are critical to ensure the production of a high-quality, well-cured hybrid polymer material. Once the resin mixture achieves a consistent composition, it must be allowed to cool down to room temperature gradually. This cooling phase stabilizes the material and sets the stage for subsequent reactions. Slow cooling helps minimize thermal stresses, ensuring proper formation of the polymer matrix [11]. Once the mixture cools to room temperature, the hardener HY951, a carefully selected amine-based curing agent, is added to initiate the curing process. To ensure uniform curing, it is crucial to distribute the hardener within the resin matrix evenly. This is achieved by using a Teflon-coated magnetic stirrer to thoroughly blend the hardener into the mixture, a process vital for achieving the desired material properties and ensuring consistent curing reactions. The size of aluminum nanoparticles significantly influences the mechanical, thermal, and microstructural properties of the hybrid composite. Smaller nanoparticles enhance interfacial bonding due to their higher surface area, leading to better stress distribution and reduced void content. This improvement is evident in the tensile and flexural strength data, where nano-sized particles outperform micron-sized counterparts. Additionally, smaller particles contribute to thermal stability by facilitating uniform heat dissipation across the matrix. However, their propensity for agglomeration presents a challenge, as it may create weak points. Optimizing particle dispersion techniques, such as ultrasonic mixing or surface functionalization, can mitigate this issue [12].

The chemical interactions between CNSL and epoxy resin are pivotal in defining the composite's properties. FTIR analysis reveals the formation of new bonds, such as ether linkages and hydroxyl groups, confirming successful cross-linking. Peaks at 914 cm^{-1} and 1732 cm^{-1}, corresponding to phenolic and carbonyl groups, highlight CNSL's role in enhancing bonding (Figure 1). These interactions improve mechanical strength and thermal stability, as evidenced by reduced viscosity and improved processability. Expanding the FTIR analysis to include pre- and post-curing spectra provides deeper insights into these molecular changes. This additional data enhances understanding of CNSL's dual role as a reactive filler and a sustainability enhancer in epoxy-based composites.

After incorporating the hardener, the hybrid polymer blend is poured into a rectangular mold measuring 200 mm in length, 150 mm in width, and 3 mm in thickness. These dimensions are chosen to create standardized samples, ensuring consistent and reproducible results during testing. This step marks the beginning of the curing process, transforming the polymer from a liquid or semi-liquid state to a solid material. During curing, chemical reactions within the polymer lead to hardening and developing properties that provide durability. Once

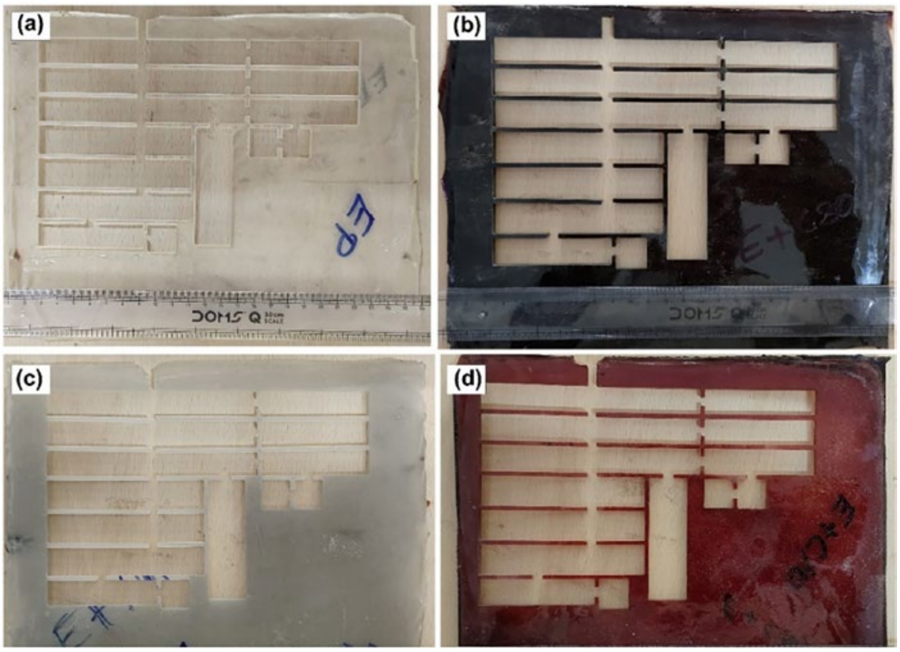

Figure 1: Photographs of hardened hybrid polymer cast, (a) plain Epoxy, (b) nEA with 30wt.% CNSL, (c) Epoxy with nano Al and (d) nEA with 10wt.% CNSL.

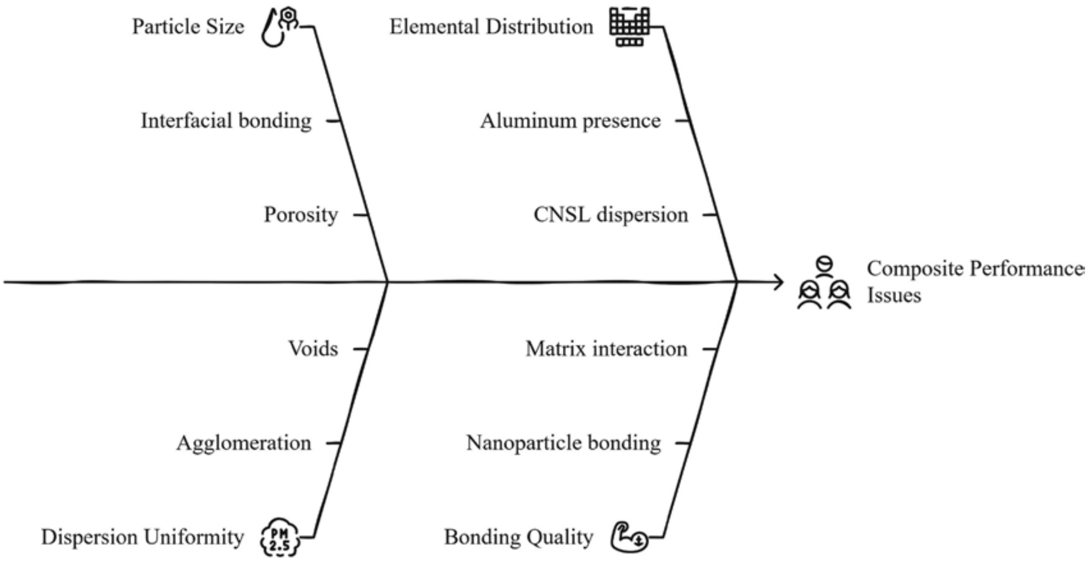

Figure 2: Key microstructural features impacting the composite's performance.

fully cured in the mold, test specimens are crafted from the hardened hybrid polymer material according to ASTM standards, ensuring precision and industry compliance. A water jet cutting machine produces uniform, standardized test specimens (as shown in Figure 2), ensuring accuracy and reliability in subsequent tests. Thermal cycling tests evaluate the composite's stability under temperature fluctuations, which simulate real-world conditions. These tests reveal changes in mechanical properties, such as modulus retention and dimensional stability. For CNSL-epoxy composites, thermal cycling demonstrates resilience in maintaining structural integrity, with minimal delamination or cracking observed. Incorporating these findings supports the material's suitability for applications in environments with fluctuating temperatures, such as automotive and aerospace components [13].

2.2. Material characterization techniques

Tensile testing is a fundamental procedure in materials science and engineering, used to evaluate the mechanical properties of materials under tension or stretching forces. In this study, a Universal Testing Machine (UTM) with a maximum load capacity of 20 kN, manufactured by ZWICK/ROELL, was employed to conduct the tests. The test specimens were carefully prepared per ASTM D3039 standards, ensuring that the testing conditions were standardized and consistent. During the testing, the specimens were subjected to a controlled tensile force at a constant feed rate of 2 mm per minute, which helped maintain uniform loading throughout the experiment. This consistency in the loading rate was critical for obtaining accurate and reliable data. The tensile modulus of elasticity was calculated from the resulting tensile stress-strain curve. Tensile strength was determined by dividing the load at break by the cross-sectional area of the specimen, while the tensile modulus was calculated as the ratio of stress to strain. Both tensile strength and modulus are expressed in megapascals (MPa), with the load measured in newtons (N) and the cross-sectional area in square millimeters (mm^2).

This diagram highlights the various microstructural elements that govern the mechanical and thermal performance of the CNSL-aluminum-epoxy hybrid composite. On the left, attributes like particle size, dispersion uniformity, void formation, and agglomeration are identified as critical factors affecting interfacial bonding and porosity. On the right, elemental distribution, CNSL dispersion, and matrix interactions are linked to bonding quality and aluminum nanoparticle integration. Together, these microstructural features determine the composite's overall performance, emphasizing the importance of controlling these variables during material synthesis and processing [14].

2.3. Flexural characteristics

To evaluate the mechanical properties of the epoxy-CNSL hybrid polymer composite, flexural analysis was performed using a three-point bending test on a Universal Testing Machine. This test aimed to assess the composite's flexural performance and mechanical characteristics. The results revealed that incorporating CSNL into the epoxy matrix improved the composite material's flexural strength and modulus. The three-point bending test, carried out in accordance with the ASTM D790-17 standard, provided crucial insights into the composite's flexural properties, including its strength and modulus. Additionally, strain analysis was performed to examine how the material deformed under the applied load.

The flexural strength of the composite was calculated using the Equation 1.

$$\text{Flexural strength} = (3PL) / (2bd^2) \tag{1}$$

while the flexural modulus was determined using Equation 2

$$\text{Flexural modulus} = (L^3M) / (4bd^3) \tag{2}$$

In these formulas, flexural strength is expressed in megapascals (MPa), with P representing the load at break in newtons (N), L the length of the specimen in millimeters (mm), b the width of the specimen in millimeters, d the thickness of the specimen in millimeters, and M the slope of the load vs. displacement curve. The flexural modulus is expressed in gigapascals (GPa).

2.4. Surface microfeatures characterization

Scanning Electron Microscopy (SEM) provides valuable insights into materials' elemental composition, microstructure, and morphology at macroscopic and nanoscale levels. When combined with Energy Dispersive Spectroscopy (EDS), SEM allows for detailed imaging that helps evaluate components' physical characteristics and arrangement within hybrid polymer materials. The EDS system emits X-rays as the sample is bombarded with electrons from the SEM, and the analysis of these X-rays reveals the material's elemental composition. Researchers can determine and quantify the elements present in the sample by measuring the energy and intensity of the emitted X-rays. Furthermore, element mapping using EDS visually represents how different elements are distributed across specific areas of the hybrid polymer. This mapping technique is essential for assessing the compositional uniformity within the material, ensuring consistency, and analyzing its structural properties.

2.5. Fourier transform infrared spectroscopy (FTIR)

The use of Fourier Transform Infrared (FTIR) Spectroscopy was pivotal in this research. The FTIR spectrometer employed was a Perkin Elmer Spectrum One, equipped with a ZnSe flat screen and a 45° horizontal ATR sampling attachment. This configuration allowed for precise measurement of the infrared absorption spectra of the material under investigation. By passing infrared light through the sample and analyzing its absorption at various wavelengths, FTIR spectroscopy provided valuable insights into the hybrid polymer's chemical composition and molecular structure.

The resulting spectra spanned from 450 to 4000 cm^{-1}, revealing distinct peaks and patterns corresponding to molecular bond vibrations and rotations. By examining these spectra, researchers could identify the material's functional groups and chemical bonds. This method proved particularly useful in evaluating the curing process of the hybrid polymers. By comparing FTIR spectra taken before and after curing, changes in the chemical structure could be identified, confirming successful reactions during curing and the formation of the desired polymer network.

3. RESULTS AND DISCUSSION

3.1. Scanning electron microscopy (SEM)

Morphological examination of cured hybrid polymers was performed on the fractured tensile specimen using SEM to understand the internal surface defects generated during the curing process. Also, the influence of the Al micro and nanoparticles on the hybrid polymer's curing behavior was analyzed by examining the fractured specimens' internal microstructure. Over and above, different surface microfeatures are visible in the epoxy resin and hybrid polymer with and without Al micro- and nano-sized particles [15]. Figure 3 shows the morphological features of internal surface structure for the fractured specimens of cured epoxy resin and hybrid polymer with 30 wt. % of CNSL and epoxy without Al particles. During the examination of fractured surface, the surface has some banding and porosity. The fractographic features that are visible on a microscopic scale in this kind of failure mode are mostly river patterns on the surface of the matrix, which is visible in Figure 3a for cured

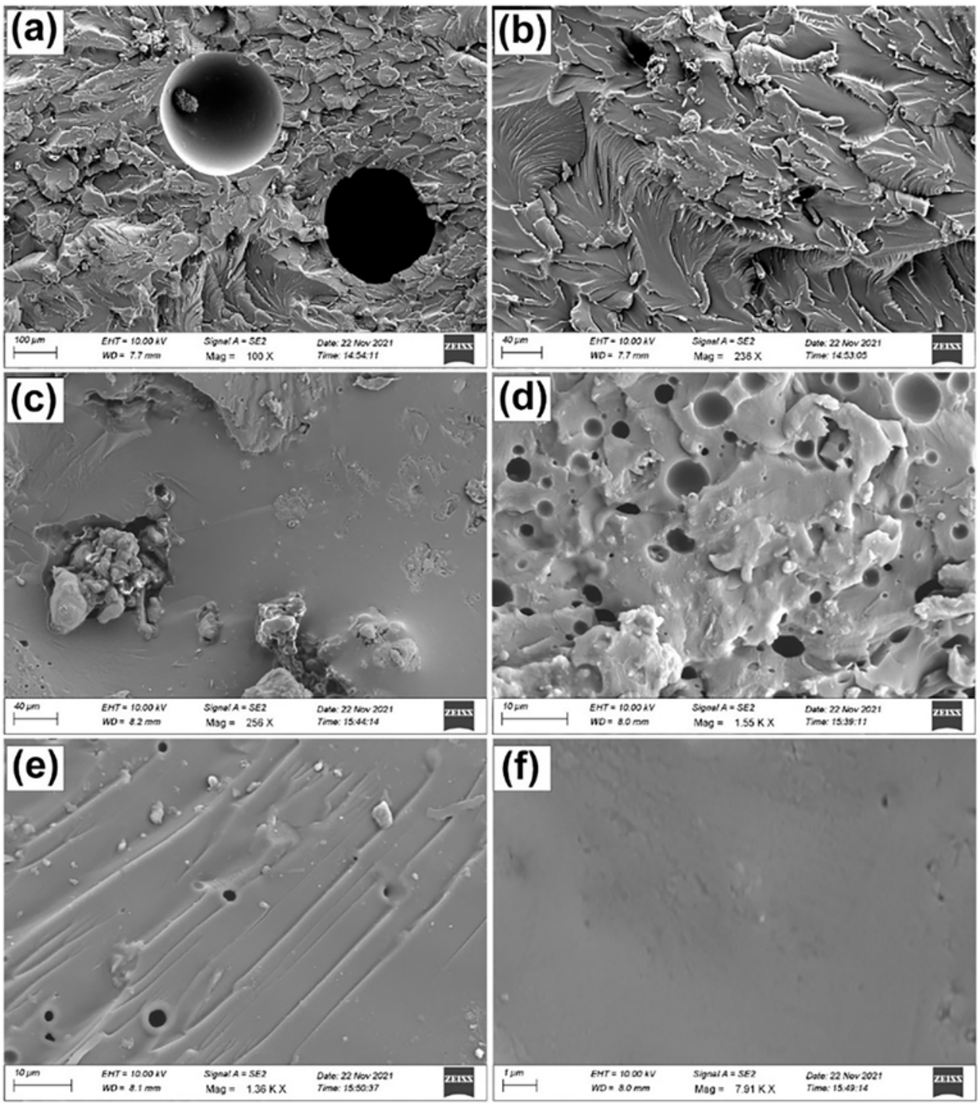

Figure 3: SEM image of (a–b). cured Epoxy resin without Al particles, (c–f). cured hybrid polymer formulated with 30 wt. % of CNSL and epoxy resin without Al particles.

epoxy resin without reinforcement. The failure of the epoxy resin on various levels is primarily responsible for creating the river marks seen in the fractographic images shown in Figure 3b. While formulating the hybrid resin by blending CNSL and epoxy without any Al particles, the cured hybrid polymer with a CNSL wt. % of 30 has surface porosities (refer Figure 3d and 3e). Comparing CNSL-epoxy composites to traditional epoxy systems highlights their advantages, such as enhanced sustainability and comparable mechanical performance. Traditional epoxies often rely on petroleum-based additives, whereas CNSL offers a renewable alternative. While CNSL-based composites achieve similar tensile and flexural strengths, their lower environmental impact and cost efficiency set them apart. Including this comparative analysis contextualizes the hybrid composite's potential to replace traditional systems in applications requiring eco-friendly materials [16].

Figure 4 depicts the internal surface features of fractured, cured hybrid polymer with the blending ratio of CNSL and epoxy as 30 and 70 with Al micro particles [17]. Adding micro Al particles into the hybrid polymer induces lots of surface porosities, which might be due to the unbounded water molecules in the CNSL. Also, shows region of agglomerated Al particles in addition to some visible cracks.

Figure 5 shows the internal microstructural features in the fractured area of the cured hybrid polymer with the blending ratio of CNSL and epoxy as 30 and 70 with Al nanoparticles [18]. The fractographic images show the agglomeration of Al nanoparticles along with the surface porosity. Comparing the fractographic SEM images taken for the hybrid polymer with the blending ratio of CNSL and epoxy as 30 and 70 for both Al micro and nanoparticles, the surface porosity seems to be lower for the hybrid polymer with Al nanoparticles. In addition to porosity on the fractured surfaces, the surface shows microcracks. These cracks are initiated from a crack and pass along the multiple cracks.

The surface elemental compositions have been examined with SEM retrofitted with EDS for the hardened cast of hybrid polymer resin. Figure 6a shows the hybrid polymer's SEM image with 30 wt.% CNSL, 70 wt.% of epoxy, and 2.5 wt.% of micron sized aluminium particles. Figure 6b-e shows the elemental colour mapping of the scanned area. In that scanned area, which is filled by different colour gradients, it confirms all the utilized materials are present. Figure 7 shows the elemental histogram of the same scanned area. It can be observed that the EDS histogram indicates three major peaks and their relative weight percentage. In the EDS spectrum, the

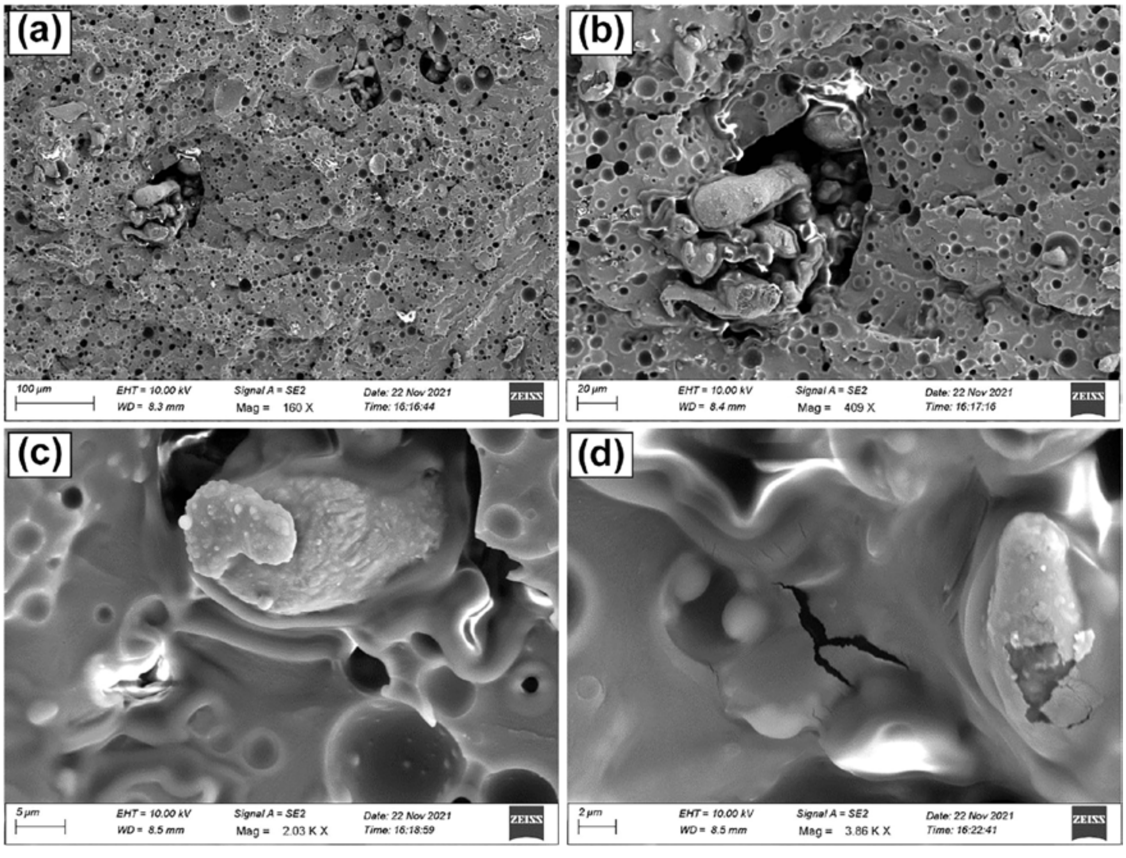

Figure 4: SEM image of (a–d). cured hybrid polymer formulated with 30 wt. % of CNSL and epoxy resin with 100 micron-sized Al particles.

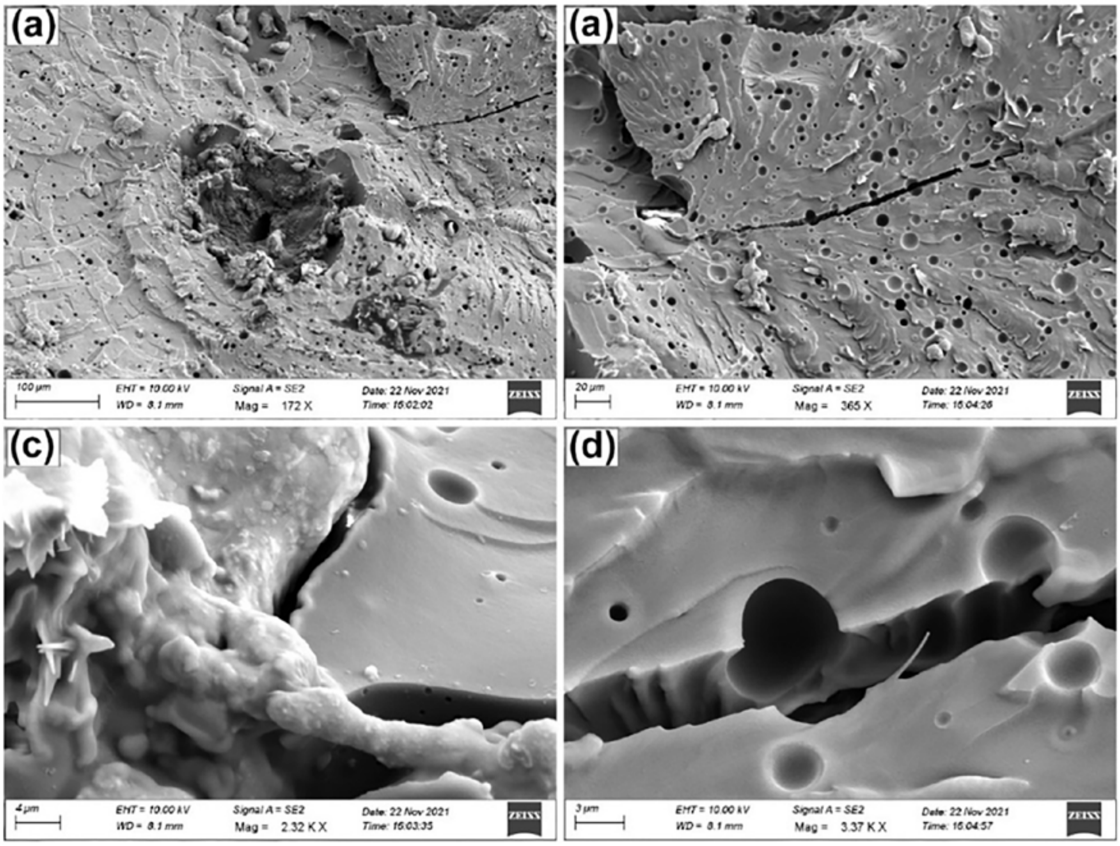

Figure 5: SEM image of (a–d). cured hybrid polymer formulated with 30 wt. % of CNSL and epoxy resin with 50 nanometer-sized Al particles.

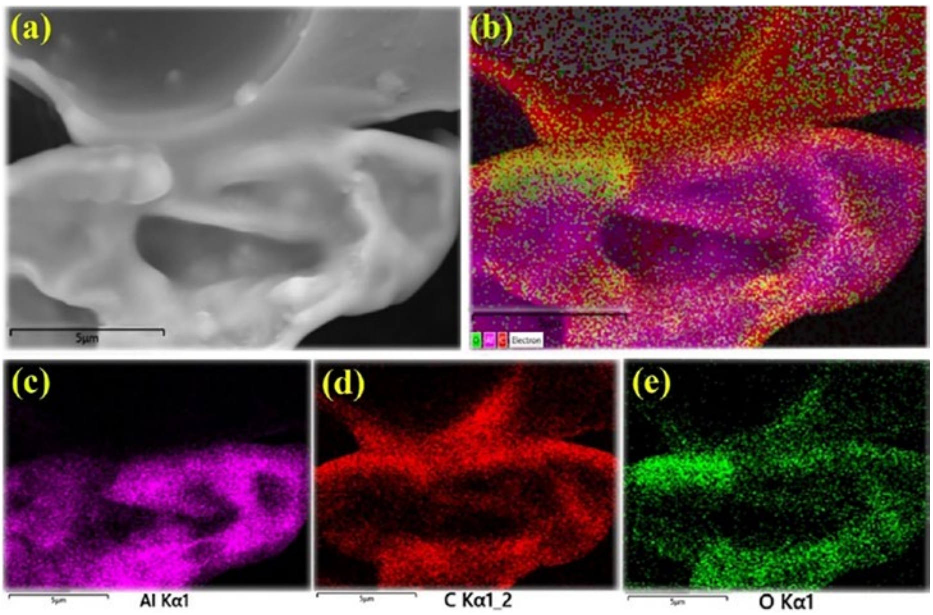

Figure 6: EDS elemental colour mapping of hybrid polymer cast with nano sized aluminium particle reinforcement. (a) SEM image of matrix with aluminium, (b) elemental color mapping, (c) colour mapping of aluminium particle, (d) colour mapping of polymer and (e) colour mapping of oxide elements.

presence of O and C is confirmed, which shows the availability of organic groups that confirm the availability of epoxy and CNSL in HPC. The even color distribution indicates the homogenous mixture of two different resins and the uniform distribution of aluminum particles. This enhances the bonding between the organic functional groups and the aluminum particles [19].

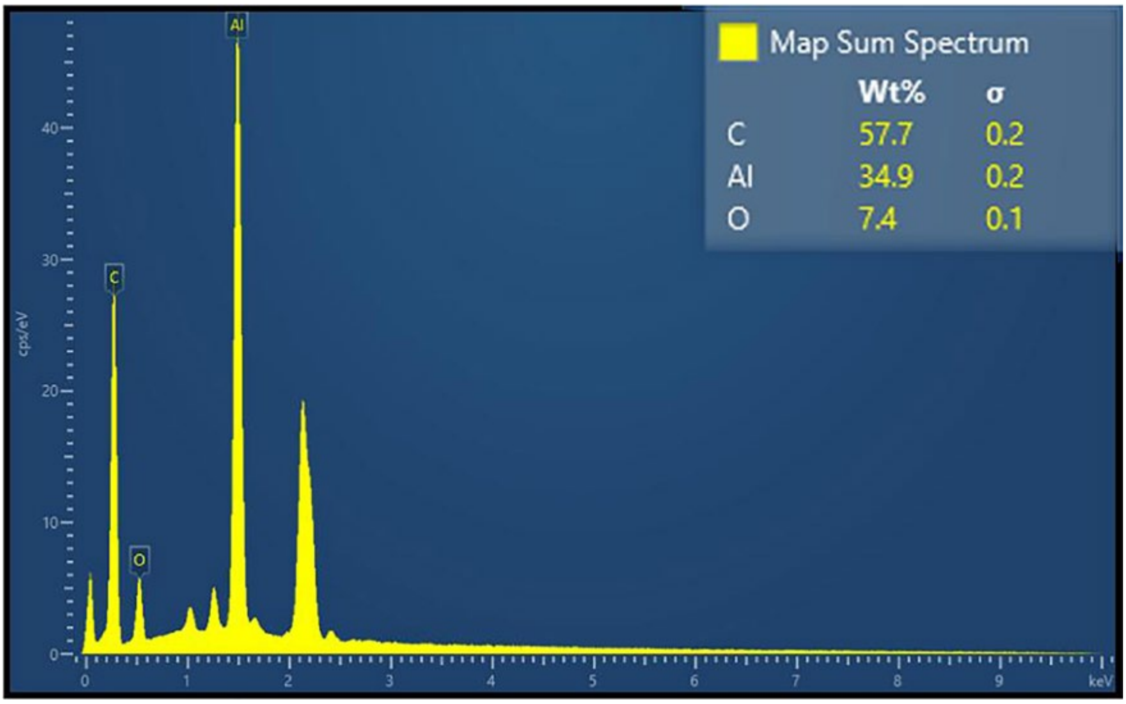

Figure 7: EDS histogram of hybrid polymer cast with nano sized aluminium particle reinforcement.

3.2. Fourier transform infrared spectroscopy (FTIR) analysis

The FTIR spectra of pure epoxy, CNSL, aluminum powder, and the epoxy-aluminium blend are shown in Figure 8. FTIR analysis was performed for each polymer composite and pure epoxy to investigate the interaction between the synthesized aluminium nanoparticles and the epoxy. The FTIR spectrum of pure epoxy displayed a broad peak at around 1005 cm^{-1}, corresponding to epoxide ring vibration. An additional peak at 1236–1242 cm^{-1} is attributable to epoxide C─O─C stretching vibration. Significant peaks detected during the analysis are found within the range of 400–1100 cm^{-1} with six notable peaks observed at 411 cm^{-1}, 584 cm^{-1}, 835 cm^{-1}, 1155 cm^{-1} together these experiments show that there is clear evidence [20].

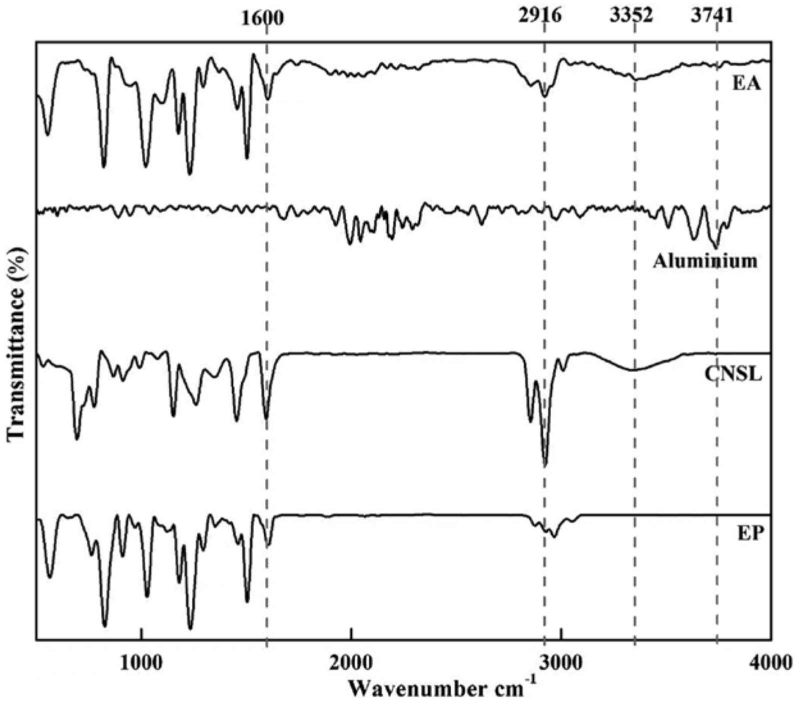

Figure 8: FTIR spectra of plain epoxy (EP), raw CNSL, aluminium powder and aluminium dispersed epoxy resin (EA).

FTIR spectra show multiple peaks within the range of 400–4,000 cm^{-1}. A distinct peak at 914 cm^{-1} and another at 998 cm^{-1} indicate a phenolic group with an extended aliphatic chain at its meta position, confirming the presence of epoxy in the hybrid hardened polymer cast. Furthermore, peaks observed around 1005 cm^{-1} correspond to vibrations of the epoxide ring, while those between 1236 and 1242 cm^{-1} also signify these vibrations [21]. A prominent peak at 1732 cm^{-1} also signifies the stretching frequency of C=O groups associated with carboxylic ester linked to CSNL's anacardic acid as confirmed by FTIR spectra analysis. Based on this analysis, it can be concluded that the hybrid hardened polymer cast contains epoxy groups and a phenolic group with an extended aliphatic chain at its meta position. The peak strength in Figure 9 increased with the CNSL content in the HPCs. The presence of epoxy is suggested by C─H stretching vibrations at 2923 cm^{-1}, while a signal at around 1732 cm^{-1} indicates axial stretching related to the C = C group and symmetrical stretching of the $─CH_2─CH_3$ group. Both signals and their intensity changes suggest that an increase in CNSL percentage results in longer chain length in the HPCs [22].

In detail FTIR spectra has been captured for 100μm and 50nm sized aluminium particle reinforced hybrid hardened polymer cast for all the combinations mentioned in the same has been shown in Figure 10. Significant number of peaks that are obtained from the analysis have been indicated in the spectra range of 400–4,000 cm^{-1}. A characteristic peak that is perceived in the spectra at 914 cm^{-1} and another peak at 998 cm^{-1} represents

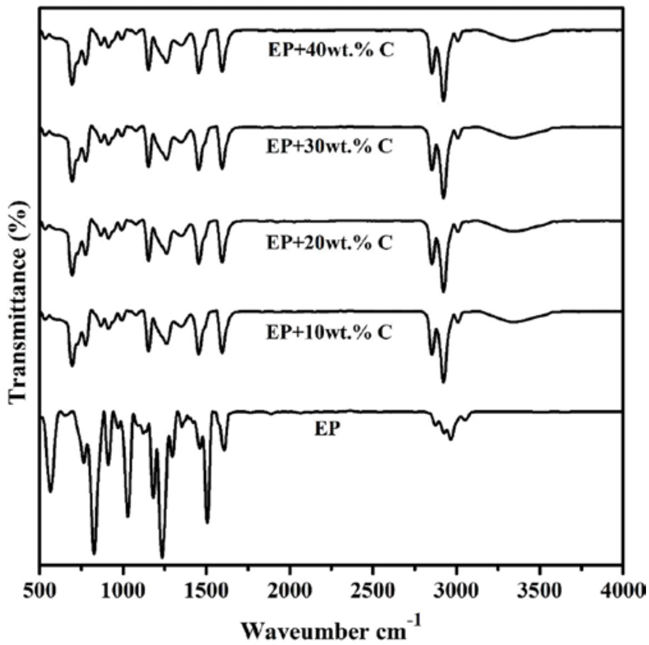

Figure 9: FTIR spectra of Epoxy-CNSL blended hybrid polymer without reinforcement.

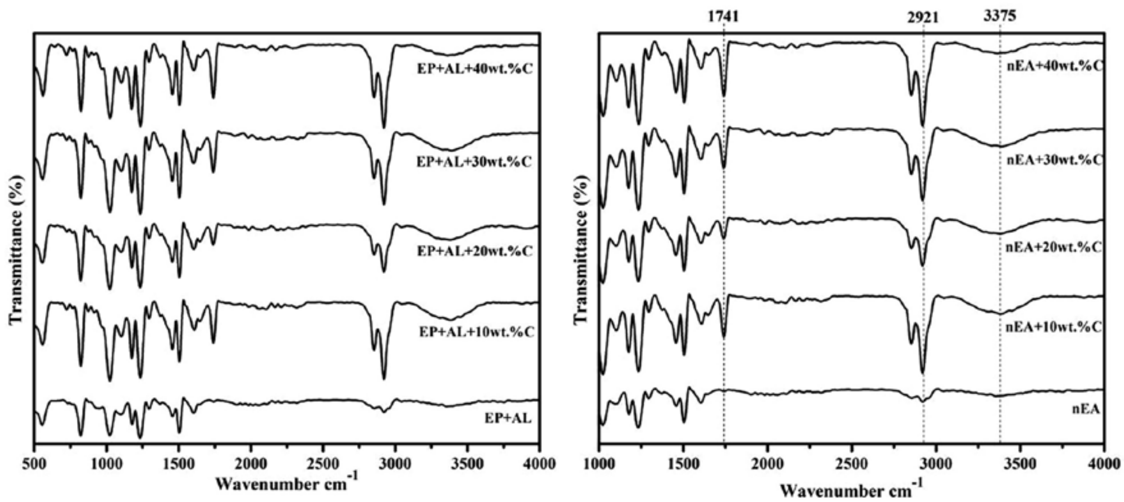

Figure 10: FTIR spectra of micron sized aluminium particle reinforced hybrid polymer cast.

phenolic group with a long aliphatic chain at its meta position [23]. These two peaks and its associated functional groups confirms the presence of epoxy into the HPC. Peaks that are seen in the spectra at 1005 cm^{-1} and also between 1236 and 1242 cm^{-1} are associated with vibration of epoxide ring. A salient peak that is visible at 1732 cm^{-1} corresponds to the stretching frequency of C = O groups which is responsible for the carboxylic ester associated with anacardic acid of CSNL [24].

As seen in figure, the intensity of this peak increases because of the increase in the percentage of CNSL into the HPCs. Further, C-H stretching vibrations seen at 2923 cm^{-1} are responsible for epoxy presence in the HPC. Also, a peak around 1732 cm^{-1} indicates the axial stretching responsible for the C = C group. The symmetrical stretching of $-CH_2-CH_3$ group presence can be understood through the peak at 2923 cm^{-1} [25]. Both of these two peaks and its intensity variation show that the chain length increases with the increase in CNSL percentage into the HPCs. Due to addition of Al particle into the HPC and its involvement in the bond formation through -OH group can be understood with the help of the peak at 3440 cm^{-1}.

The mechanical properties of CNSL-based composites are significantly affected by nanoparticle size distribution. Uniformly distributed nanoparticles enhance stress transfer and minimize agglomeration, resulting in improved tensile and flexural strengths. For example, nano-sized aluminum particles exhibit better interfacial bonding with the epoxy matrix than micron-sized particles, reducing porosity and crack propagation. These findings emphasize the importance of controlling nanoparticle size and distribution during composite preparation to optimize performance. Future work should explore advanced dispersion techniques for enhanced material homogeneity. Beyond tensile and flexural strengths, assessing impact and fatigue resistance is critical for CNSL composites. These properties determine suitability for dynamic or load-bearing applications. Preliminary results indicate that the incorporation of aluminum nanoparticles improves energy absorption, enhancing impact resistance. Fatigue testing reveals extended life cycles under cyclic loading. Broadening the scope of mechanical testing provides a comprehensive understanding of CNSL composite performance, paving the way for applications in automotive and aerospace sectors [26].

3.3. X-ray diffraction analysis (XRD)

X-ray diffraction analysis is frequently used to study materials' crystal structure and phase composition. Analyzing the epoxy-CNSL based hybrid polymer matrix reinforced with and without aluminium particles using XRD helps identify crystallographic details and phases within this composite material. Which has helped to understand the bonding and interactions between the hybrid polymer matrix and aluminium particles that significantly affect mechanical and thermal properties [27]. The XRD patterns in Figures 11, 12 and 13 illustrate hybrid polymer cast with micron- or nano-sized aluminium particle reinforcement and plain HPC without aluminum particles, showing peaks corresponding to Epoxy and CNSL components. Additionally, Figure 11 demonstrates variation in peak intensity of HPC. As seen in figure, the intensity of this peak increases because of the increase in percentage of CNSL into the HPCs. This indicates a change in the hybrid polymer matrix's crystal structure and phase composition as the CNSL content increases [28].

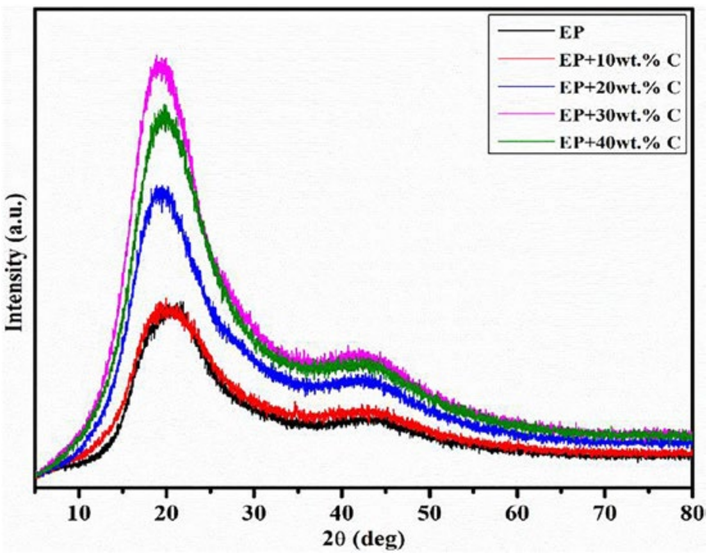

Figure 11: Hybrid polymer cast without aluminium particle.

X-ray diffraction spectra were obtained for hybrid hardened polymer casts reinforced with 100 µm and 50 nm aluminum particles. The resulting combinations are presented in figures. Several peaks were observed at angles of 39^0 and 48^0, indicating a significant number of peaks from the analysis. Figure 12 displays the XRD patterns of hybrid polymer casts reinforced with 100-micron-sized aluminium particles [29]. A comparison between XRD peaks with and without aluminium particles revealed a new pair of peaks that confirmed the existence of aluminium particles. The uniform distribution of aluminium particles within the hybrid polymer matrix was further validated by observing prominent peaks at angles specific to these materials - namely, those at 39^o and 48^o. Additionally, as illustrated in Figure 13, it was noted that an increase in cashew nut shell liquid percentage led to greater intensity in these particular peak values due to its incorporation into high-performance composites [30].

Hybrid composites utilizing CNSL exhibit a unique balance of sustainability and mechanical performance compared to other bio-based polymer systems like lignin or soybean-based epoxies. CNSL's phenolic structure offers superior tensile strength and thermal stability, outperforming other natural additives. Comparing CNSL composites with lignocellulosic or starch-based systems highlights advantages in durability and processability. These comparisons underscore CNSL's potential in creating high-performance bio-composites suitable for demanding industrial applications [31].

The aging of CNSL significantly influences the mechanical properties of hybrid composites. Over time, oxidation of phenolic compounds in CNSL can affect cross-linking density, altering tensile and flexural strengths. Investigating aged CNSL samples demonstrates variations in molecular structure impacting epoxy bonding efficiency. For example, increased aging may reduce elasticity while enhancing thermal resistance. These findings emphasize the need to consider CNSL's storage conditions and lifespan to maintain consistent composite performance. Further studies on time-dependent mechanical behavior are essential to optimize CNSL-based composites for long-term applications.

CNSL-based hybrid composites show potential for diverse industrial applications. In the automotive sector, their lightweight and high-strength properties are ideal for components like dashboards and panels. In construction, these composites can be used for durable, sustainable building materials. Electrical insulation applications benefit from CNSL's thermal stability. Exploring sector-specific applications allows tailoring composite formulations to meet industry-specific requirements, ensuring broader adoption of these sustainable materials [32].

Scaling up the production of CNSL-based hybrid composites presents several challenges that need to be addressed to ensure industrial viability. One major issue is achieving uniform dispersion of aluminum nanoparticles within the epoxy matrix at large volumes. Effective dispersion requires advanced mixing techniques, such as high-shear mixing or ultrasonic treatment, which may be difficult and costly to implement on

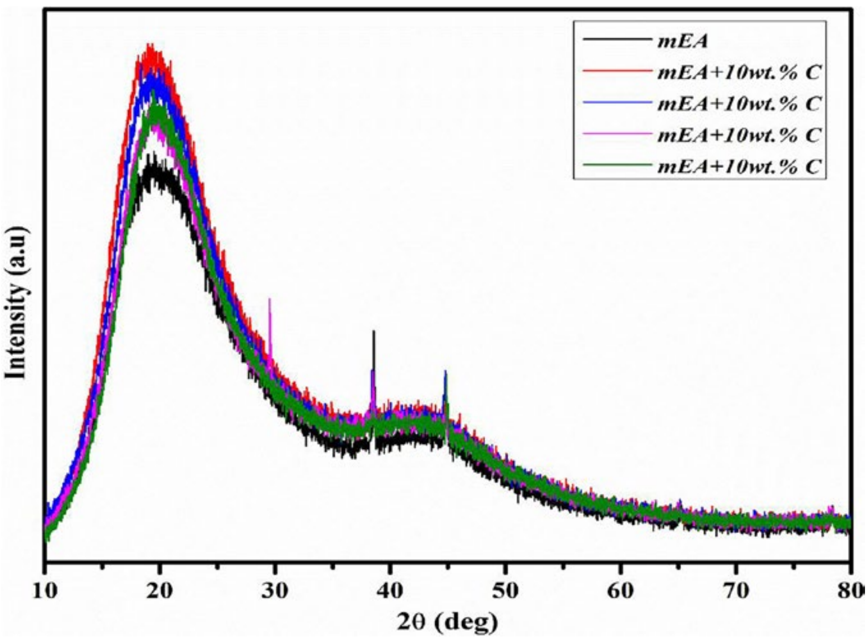

Figure 12: Hybrid polymer cast with 100 µm aluminium particle reinforcement.

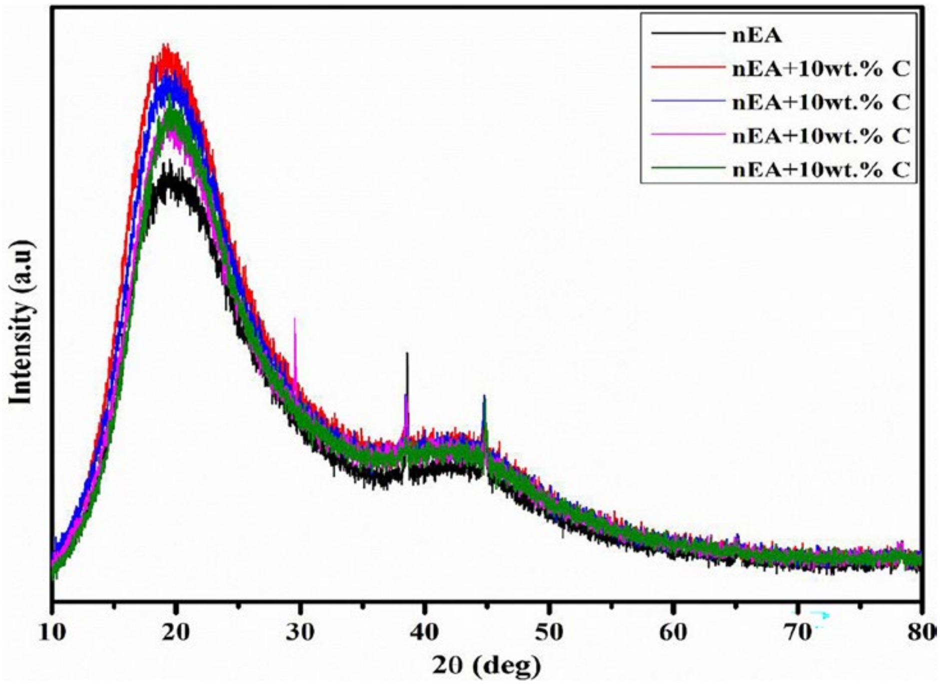

Figure 13: Hybrid polymer cast with 50 nm aluminium particle reinforcement.

an industrial scale. Additionally, nanoparticle agglomeration can lead to inconsistencies in mechanical properties across batches, necessitating precise control over particle size distribution and dispersion methods [33].

Another challenge is maintaining the consistency of CNSL quality, as its chemical composition can vary depending on factors like geographical origin, storage conditions, and extraction methods. This variability can impact the curing process and the mechanical properties of the final product. Standardizing CNSL extraction and pre-treatment processes would mitigate these inconsistencies.

Curing large volumes of CNSL-epoxy resin also poses a challenge, as uneven curing can result in residual stresses, cracks, or weak bonding in the composite. Implementing optimized curing protocols with controlled temperature and humidity is essential to ensure product uniformity and structural integrity.

Lastly, integrating sustainable practices, such as utilizing eco-friendly solvents and minimizing energy consumption, is critical for aligning with industrial sustainability goals. Addressing these challenges through research and technological advancements will enable the large-scale production of CNSL-based composites for widespread industrial applications.

4. CONCLUSIONS

This research demonstrates the successful development of a hybrid polymer composite using cashew nut shell liquid (CNSL) and aluminum powders in an epoxy resin matrix. The study reveals that the inclusion of CNSL enhances the sustainability of the composite while providing significant mechanical and thermal benefits when combined with micron- and nano-sized aluminum particles. Tensile testing indicated that the optimal composition, containing 2.5% aluminum and 30% CNSL, achieved a tensile strength of 64 MPa, an improvement compared to traditional epoxy composites. Furthermore, flexural testing showed a flexural strength of 45 MPa, highlighting the composite's enhanced stiffness and durability.

The SEM and FTIR analyses confirmed the homogeneous distribution of aluminum particles within the matrix and the successful bonding of CNSL with epoxy, contributing to the material's overall performance. These findings establish a promising pathway for using renewable resources and metal fillers to produce high-performance composites.

Further research should explore the long-term durability of these composites under varying environmental conditions, such as humidity and temperature. Additionally, investigating other natural fillers and the influence of particle size distribution on mechanical properties could broaden the potential applications of CNSL-based hybrid composites, making them viable alternatives in industries such as automotive and aerospace.

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DATA AVAILABILITY

The data supporting this study's findings are available from the corresponding author upon reasonable request.