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Research Article

Experimental Analysis of Mechanical and Thermal Characteristics of Luffa/Epoxy Polymer Composite under the Influence of Nanosilica

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In the current work, the experimentations have been accomplished to assess the impact of diffusing nanosilica particles in epoxy matrix on the mechanical and thermal performance of the luffa fibre reinforced epoxy composite material. The matrix and fibre composition are fixed as 80 : 20 throughout the study, and the nanosilica is disbanded in diversified volume fractions of 0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%, respectively, while preparing luffa/epoxy/nanosilica (LES) composite samples. The mechanical characteristics, such as tensile, flexural, and impact behaviour of the composite, and the thermal properties, namely, thermal stability and thermal conductivity, are examined for the LES samples. The experiments are accomplished as per the ASTM standards. The results revealed that the assimilation of nanosilica particles in epoxy has improved the mechanical and thermal characteristics of the composite significantly. The tensile, flexural, and impact strength of the composite have been amended by 157.58%, 66.9%, and 16.5% with 1.5% addition of nanosilica in epoxy. Similarly, thermal conductivity of the composite is improved by 47.53% with the dispersion of 2.5% nanosilica in epoxy matrix. In addition, the thermal stability of the LES composite samples is substantially improved while disbanding nanosilica in epoxy matrix. However, the better results are reported for the LES composites containing 1.5% nanosilica content, compared to the next higher volume fractions of nanosilica content in epoxy matrix.

1. Introduction

The epoxy-based polymer composite materials have been considered as the important type of materials, since they are utilized in various sectors as an alternate material to the conventional materials [1]. As a result, it is being considered as the key thrust area of research in recent days, and a lot of works have been carried out by the scholars in the past few decades [2, 3]. During the past few years, the natural fibres have captured the consideration of researchers as well as engineers due to their exceptional combinational characteristics, in addition to their eco-friendly character. This has

paved the path for naturally available fibres to eventually substitute the artificial fibres in the course of constructing natural fibre epoxy-based polymer composites (NFEBC). Naturally occurring fibres have a number of advantages over artificial fibres, including lower production costs, lower densities, excellent mechanical characteristics, higher specific strengths, lessened impact on the environment, lower levels of health risks, lower levels of power usage, and their high hardness [4, 5]. Furthermore, the term "eco-friendly composite materials" refers to the use of NFEBCs in other kinds of applications that do not necessitate superior mechanical strength, such as supporting structures, panel boards, automobiles interior decoration, packaging commodities, home decors, and so on [6, 7]. Natural fibres that have been produced using renewables have a strong chance of being able to function as alternatives for artificial reinforcing mediums including fibre-glass and carbon-based fibres. Naturally accessible fibres such as jute, hemp, coir, bamboo, banana, sisal, kenaf, flax, luffa, and snake grass are frequently used to be the reinforcing elements in epoxy composites [8]. In comparison to the others, the mechanical characteristics of luffa fibres were shown to be much superior [9].

Luffa cylindrica, often known as spongy cucumber, has been a typical substance that is a part of the cucurbitaceous species and may be normally found in a number of different places. The tender, tubular berry of the luffa plant may be consumed as a vegetable; however, it is a different kind of the luffa plant, which has a bitter flavour since it contains vermifuge compounds and is difficult to consume. When the complex fibre structure of luffa berry is dehydrated, it generally takes on the shape of interconnected mats [10, 11]. In comparison to metal-based cellular substance, the mat of the organic luffa itself boasts amazing strength, toughness, and load bearing capability; therefore, it is an appropriate naturally available fibrous substance which has been effectively exploited in the mechanism of eradicating toxic substances from effluent. Such new cash crop does have the capacity to enhance the economic situation in emerging countries like India [12, 13]. This luffa contains more than 80 percent cellulosic agents along with lignin of around 15 percent. It has a density of 0.820 g/cm^3 and a radius ranging from 13 to 30 m [14]. The natural fibre composite material was manufactured by Mohanta and Acharya [15] using the luffa fibre mats in different layers with the epoxy as the matrix material. After doing their research, they came to the conclusion that the two layers of luff mat in the composite displayed high tensile as well as flexural characteristics. Modifications of luffa fibres that were acetylated and cyanoethylated were explored in a study by Ghali et al. [16], which found that these techniques increased strength properties and adhesiveness among the fibre materials and polymer matrices. When comparing with pure natural fibre polymer composite, Sakthivel et al. [17] discovered that the physical parameters of luffa/coir-based hybrid polymer composites had been improved significantly.

The addition of fillers to the composite materials has been demonstrated to be a viable solution for boosting the effectiveness of the polymer composite materials that are produced using the polymer substance as the matrix material. Another way, for refining the features of natural fibre-based polymer composites, hybridising the fillers with the natural fibres is a technique that has also been employed [18, 19]. When the matrices as well as the reinforcements are chosen carefully, it is possible to create natural fibre-based polymer composites with the required strength, which is equal to and sometimes superior to that of traditional metal alloys. The escalated quality and strength of the polymer composite materials in manufacturing and building industries through the inclusion of filler particles have proved to be a tremendous potential and, as a result, have recently become a focus of much attention [20]. This is due to the fact that it has displayed a good prospect. To improve and alter the strength of composite materials, various fillers are blended with the composites during their fabrication process. In the large number of cases, the importance of a material's mechanical qualities is seen as being higher than that of its other characteristics.

Nowadays, nano-sized fillers that are possessing high surface-to-volume ratio, including nanometals, nanometallic oxides, nanometallic nitrides, carbon nanotubes, and nonmetal nanoparticles, have indeed been routinely employed in natural fibre composites as nano-sized fillers [21, 22]. The degree of the blending of such nanoparticles, their surface area and shape, and the size of nanomaterials are all important factors in determining whether or not the composites with the nanofiller will exhibit an increase in their physical and engineering characteristics. The fact that nano-sized fillers are devoid of defects has led to the development of newly promising developments in the market of polymer-based composites [23, 24]. These trends have the potential to overcome the limits posed by traditional micro-sized fillers. The elevated matrix-filler interface zone, which would be caused by the homogenous and consistent scattering of nanofillers, is responsible for changing the molecular diffusion rate, as well as the thermophysical properties. Generally, nanofiller materials have been proven to be effective in enhancing the matrix material's chemical, physical, mechanical, and thermal qualities [25]. Among the various investigated nanofillers, nanosilica was found to have synergetic characteristics in enhancing the characteristics of the base material [26, 27].

The naturally accessible fibre materials have been proved to be environmentally safe, and those financially feasible fibre materials may be found in plenty in environment. These resources are being utilized in a judicious and careful manner in the production of natural fibre-based epoxy composite materials [28]. As a result, the development of epoxy composites with superior mechanical strength in its most cost-effective manner can be possible by means of appropriate choice of natural fibres, polymer matrices, and nanofillers becoming one of the primary motivations of several scientists and research scholars [29].

The review of the previous literature revealed that the studies on the natural fibre-based epoxy composites, under the influence of nanosilica, were scarcely reported. Furthermore, the impact of utilizing nanosilica on the properties of the luffa/epoxy composites was not dealt with in

detail. In the current examination, the effect of including nanosilica within the epoxy matrix on the mechanical and thermal properties of the luffa/epoxy natural fibre composite material is examined, which is the uniqueness of this work. The composites had been prepared using machine moulding. The nanosilica has been disseminated in varied volume fractions of 0, 0.5, 1.0, 1.5, 2.0, and 2.5% in epoxy during the analysis, whereas the proportion of epoxy and fibre was fixed as constant. The testing was accompanied as per the ASTM standards. The acquired results are critically analyzed.

2. Materials and Methods

The LY556 epoxy and HY951 hardener had been bought from Herenba Instruments & Engineers, Chennai, which were utilized as the polymer matrix in this work. The acquired luffa fibres had been cleansed using distilled water and sun-dried for three days to eliminate the waxy lignin matters from them. Following the sun-drying process, the fibres were split into the mat-shaped form. The accessible luffa fibres are hydrophilic in nature, and hence, luffa fibres had been treated with the alkali solution containing 5% NaOH (sodium hydroxide) to change its characteristics to water repellent [9]. Throughout this treatment, the fibre had been submerged in a bucket filled with the aforementioned alkali solution for 120 minutes. Afterwards, the submerged fibres were rinsed with clean water to remove the traces of NaOH from their surface. They were then neutralised with a weak acid before being rinsed with clean water once more. At last, the processed fibres were dried at 75°C with the help of an oven. The pure form of nanosilica (NS) having a mean particle diameter of 90 nm was acquired from Intelligent Materials Private Limited, Punjab, India. The used raw materials were presented in Figure 1.

2.1. Fabrication of Luffa/Epoxy/Nanosilica Composites. The composites were fabricated in six varied combinations as presented in Table 1. The epoxy and hardener had been mixed suitably, and the matrix material was prepared. The total number of fibre and matrix layers had been chosen as seven, based on the earlier literature, and the stacking order and the number of layers were constantly fixed for all the combinations. The luffa/epoxy/nanosilica (LES) composites had been prepared by dispersing predefined quantity of NS within the epoxy resin at the predefined.

The volume fraction of nanosilica was chosen as 0, 0.5, 1.0, 1.5, 2.0, and 2.5% in epoxy resin, while preparing the samples LES0, LES0.5, LES1.0, LES1.5, LES2.0, and LES2.5, respectively. The volume fraction of nanosilica was chosen based on the previous literature [22, 24]. The epoxy/NS mixtures were carefully synthesized by disseminating the measured quantity of NS inside the definite volume of epoxy resin with the support of ultrasonicating bath [22]. The frequency of ultrasonicating bath was turned as 40,000 Hz, and the epoxy/NS solution was agitated relentlessly for 150 minutes for attaining the consistent mixture of epoxy/NS solution. Then, the epoxy solution and the luffa (in the form of mat) were stacked in the sequence, in such a way that the extreme ends were covered with the epoxy layer. As mentioned earlier, the LES composite samples were fabricated with seven stratums with the assistance of a hydraulically operated composite moulding machine as shown in Figure 2.

2.2. Mechanical Testing of the LES Samples. The LES specimens were cut into the required dimension as per the ASTM D3039 specifications for tensile test [22, 30]. Testing for tensile strength had been carried out on digitized universal testing equipment (DUTM). There were three specimens fabricated for each LES composition to assure the repeatability of the testing values. After positioning the specimens between the holders of the DUTM, an increasing amount of force had been given to the specimen until it fractured. Tensile load had been developed on the specimen at a rate of two millimetres per minute. Then, the average tensile values of the specimens had been noted for further analysis. In accordance with the ASTM D790 specifications [30], specimens for flexural testing had been created using three-point bending method. Once again DUTM was utilized in order to carry out the flexural testing of the specimens. Similar to the tensile experiment, three samples for each LES combination were investigated, and the average flexural values had been used for the analysis. Here, the movable head was moved at a velocity of 1.5 millimetres per minute during the test. During the impact testing of the LES specimens, the ASTM D256-Type A specification was utilized [31]. The MCS brand MIT-30 model pendulum kind of impact test equipment had been used to conduct the impact testing over the specimens. The 1.5 kg weight of impact mallet was supposed to hit the specimens with a velocity of 4 metres per second during the test. In this way, three specimens in each LES composition were tested, and their average value was taken during the analysis.

2.3. Thermal Testing of the LES Samples. The investigation on the thermal attributes of the LES composite would help to attain a good knowledge on the thermal stability of the LES composite materials. TGA (thermogravimetric analysis) was carried out using the TGA Q50 testing apparatus, which was manufactured by TA Instruments, Bangalore, India. The assessment was conducted in the nitrogen atmosphere at 10°C/min heating rate. The specimens with the mass of 10 milligrams from each LES combination had been heated at the temperatures between 25 degrees Celsius and 600 degrees Celsius. Following the TGA plot, the temperature of deterioration and the quantity of left-over residues were recorded. In accordance with the specifications of ASTM C518 [32], the thermal conductivity of the LES specimens was assessed with the aid of Fox 200 brand thermal analyser, supplied by TA Instruments, Bangalore, India. The sample size for thermal conductivity testing was a square plate with 204 millimetres on each side. Again, three samples from each LES composition were tested, and their average values were taken for further examinations.

(a) (b) (c)

Figure 1: Materials used (a) epoxy and hardener, (b) luffa, and (c) nanosilica.

Table 1: Composition of luffa/epoxy/nanosilica composites.

Samples	Epoxy (%)	Luffa (%)	NS (%)
LES0	80	20	0
LES0.5	79.5	20	0.5
LES1.0	79	20	1
LES1.5	78.5	20	1.5
LES2.0	78	20	2
LES2.5	77.5	20	2.5

Figure 2: Hydraulically operated composite moulding machine.

3. Results and Discussion

Figure 3 illustrates the tensile behaviour of the LES composite samples at different fractions of nanosilica (NS) content. The tensile strength of the plain luffa/epoxy composite (with 0% NS) was documented as 7.12 MPa. The loading of the NS with epoxy resin seems to be worked better in enhancing the tensile characteristics of the composite. The maximum value of tensile strength was noticed as 18.34 MPa, when 1.5% NS was dispersed inside the epoxy matrix. It is 157.58% augmentation in tensile strength comparing to the LES composite with 0% NS. It could be possible that the inclusion of the NS would have reduced the number of voids within the matrix, and as a result, the produced composites would have a higher degree of

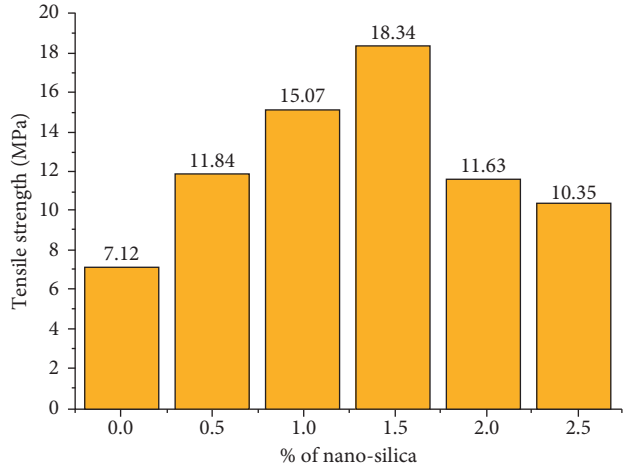

Figure 3: Tensile strength of the LES composite at diversified nanosilica fractions.

strength. There is a possibility that the nanoparticles would have performed the function of a connection among the matrices and the fortified fibre, which had led to the improved coupling between fibre and matrix. The tension that had been caused by the application of the load might be readily transmitted from the epoxy resin to the luffa fibre, which had resulted in an increase in the tensile properties. However, it was observed that the tensile characteristics of the composite significantly enhanced only till the addition of 1.5% NS in epoxy. The tensile strength of the LES composites was recorded as 7.12, 11.84, 15.07, 18.34, 11.63, and 10.35 MPa, corresponding to the inclusion of 0, 0.5, 1.0, 1.5, 2.0, and 2.5% NS in the epoxy matrix. The tensile strength of the composite had begun to drop after 1.5% inclusion of NS in the epoxy. This could be because a rise in the NS causes greater molecule to molecule interactions instead of inducing their interactions between the fibre and the matrix material [31]. Further, the rise in the NS content could have led to an enhancement in the micropores in the material. It could be owing to the conglomeration of NS in the matrix, which could have deteriorated the bonding between NS and epoxy matrix and hence diminished the tensile characteristics of the LES composite plates [22].

The flexural behaviour of the LES composites is demonstrated in Figure 4. The flexural strength of the LES composite samples at 0, 0.5, 1.0, 1.5, 2.0, and 2.5% of NS is recorded as 26.74, 34.53, 39.37, 44.63, 32.41, and 30.26 MPa, respectively. It vividly indicates that the dispersion of NS within the epoxy matrix uplifted the flexural strength of the LES composites significantly till 1.5% addition of NS, and the flexural strength fell greatly afterwards. The maximum flexural strength of 44.63 MPa had been recorded for the LES composite containing 1.5% NS, and it is 66.9% higher than the flexural value of the LES in the absence of NS. It could be because of the improved stiffness of LES composite materials owing to the addition of NS particles. The volume of epoxy matrix could be confined with the surrounded NS particles, which would have prevented the strain over the composite under bending load. As a consequence, the deformation during yielding had been reduced and delayed the crack growth. However, the over dosage of the NS (after adding 1.5%) in epoxy had resulted in the undesirable agglomeration of the NS particles. Hence, NS particles deteriorated the quality of connection between the matrix and fibre, while adding more than 1.5% of NS particles in epoxy matrix.

The impact characteristics of the LES composite materials under the influence of NS particles are shown in Figure 5. The impact strength of the plain composite without any NS content has been observed as 7.88 kJ/m^2. The impact strength of the composite was noticed to be incremented with the inclusion of NS particle fraction to a certain extent (till 1.5% NS in epoxy) and started to fell down afterwards as observed in tensile and flexural behaviour of the composites. It could be accredited to the reduction in impact characteristics of the LES composites due to the weak penetration of the NS particles within the epoxy matrix at the higher mass fraction of NS particles. The maximum impact strength had been observed to be 9.18 kJ/m^2 at 1.5% volume fraction of NS particles in epoxy, and it was 16.5% higher than plain composite without NS content.

Figure 6 displays the thermal stability of the LES samples under the different fractions of NS particles. A sample weight of 10 mg was taken from each LES specimen and heated within the metal pan from room temperature to 600°C during thermogravimetric analysis (TGA) of the samples. It can be seen that the decomposition of the LES composite initiated at 65°C during the absence of NS particles. The inclusion of NS particles in LES composites delayed the commencement of the degradation of composites by around 10°C–14°C. However, the rate of degradation had become rapid after 332°C in case of composites having no NS particles. In case of LES composites containing NS particles, the decomposition had commenced to happen swiftly only after 358°C. At the end of the TGA by 600°C, the residue leftover was significantly large for the composites containing NS particles. The residue percentage was around 21%–25.5% in case of LES composites containing NS particles, whereas the residue content was only 14% in case of composites having no NS particles. It can be evidently seen that the addition of NS particles proportionally improved the thermal stability of the LES composites. It could be ascribed to the amended thermal resistance characteristics of the composite at the epoxy-NS interfaces, where the nanosilica particles formed a protective

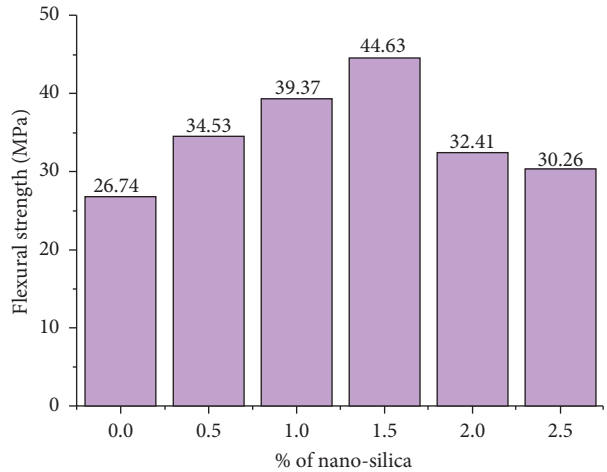

Figure 4: Flexural strength of the LES composite at diversified nanosilica fractions.

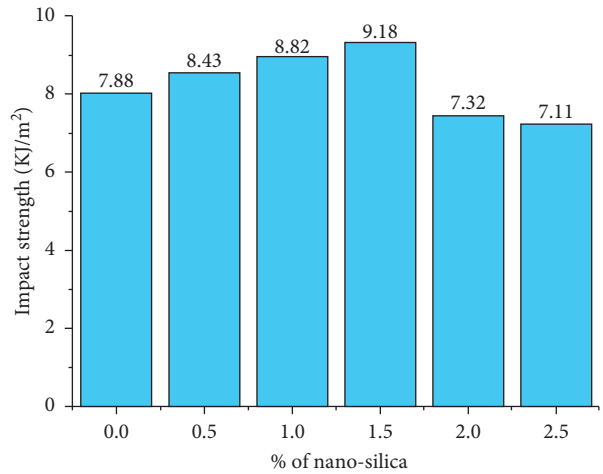

Figure 5: Impact strength of the LES composite at diversified nanosilica fractions.

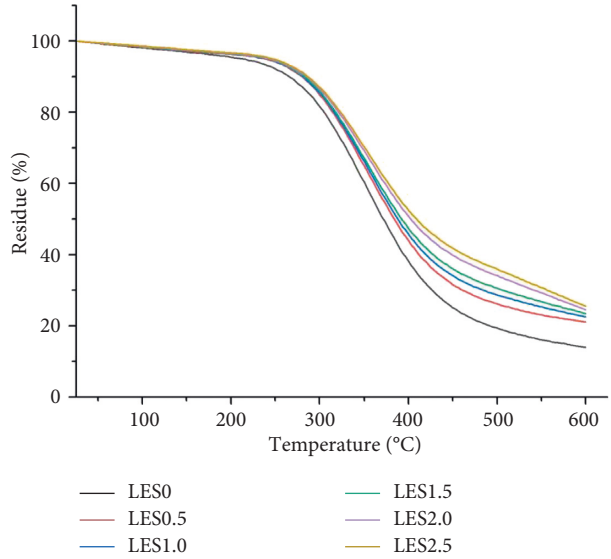

Figure 6: TGA of the LES composite at diversified nanosilica fractions.

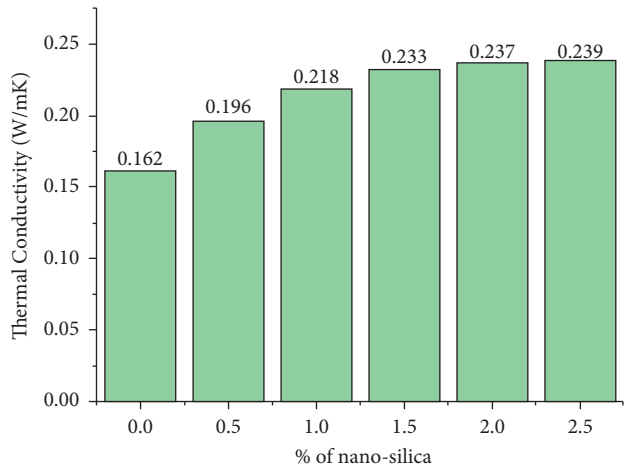

Figure 7: Thermal conductivity of the LES composite at diversified nanosilica fractions.

thermal shielding over the matrix material. It had become reason for the enhanced thermal stability of the LES composites.

The thermal conductivity (TC) of the LES composite was determined experimentally, and the outcomes have been plotted as illustrated in Figure 7. Thermal conductivity of the composite was recorded as 0.162 W/mK before adding NS particles epoxy. But the addition of NS particles supported significantly in enhancing the TC of the LES composite. The TC had been improved progressively with the loading percentage of NS in the epoxy. The TC values of the LES composites were reported as 0.196, 0.218, 0.233, 0.237, and 0.239 W/mK for the NS fractions of 0.5, 1.0, 1.5, 2.0, and 2.5% in epoxy. The maximum TC enhancement of 47.53% had been attained with NS loading of 2.5% in epoxy. The NS particles inside the matrix acted as the permeated network within the epoxy matrix and augmented the TC of the LES impressively. However, it was observed that the improvement in TC of the LES composites had shown the reduced slope after adding 1.5% of NS particles in the epoxy matrix. Once again, it can be acknowledged that the diffusion of NS particles at higher volume fraction ended up with cluster formation, which could be the reason for the detrimental effect at the higher volume fraction of NS in epoxy matrix.

The results obtained from the mechanical as well as thermal testing of the LES composite samples evidenced that the dissemination of nanosilica inside the epoxy matrix of the luffa fibre-based polymer composites would have been the better option for enhancing the mechanical as well as thermal properties of the luffa/epoxy composites. However, the volume fraction of the nanosilica is the key factor for optimizing the properties of the LES composites. The lower volume fraction of nanoparticles is recommended for obtaining better results because the increase in nanosilica content would have ended up in local clustering, which is undesirable in the fabrication of LES composites.

4. Conclusion

The luffa/epoxy/nanosilica (LES) composite materials were prepared by disbanding varied volume fraction of nanosilica (0, 0.5, 1.0, 1.5, 2.0, and 2.5%) in epoxy matrix. The proportion of epoxy resin and luffa fibre in the composite samples was maintained as 80 : 20, throughout the investigations. Following ASTM standards, the mechanical characteristics, namely, tensile, flexural, and impact behaviour and thermal properties, such as thermal stability and thermal conductivity, of the composite samples were assessed. After the critical examination of the results, the major conclusions are given below.

(i) The tensile strength of LES composite was gradual till the diffusion of 1.5% nanosilica in epoxy, and then, the values were declined with further addition of nanosilica. The maximum tensile strength of the LES composite was achieved as 18.35 MPa with 1.5% volume of nanosilica, which is 157.58% greater than the corresponding value of the plain luffa/epoxy composite.

(ii) Similarly, the flexural and impact strength of the LES composite were enhanced to 44.63 MPa and 9.18 kJ/m^2, respectively, with 1.5% nanosilica in epoxy, and they are 66.9% and 16.5% higher than the corresponding flexural and impact values of the plain luffa/epoxy composites.

(iii) The thermal stability of the composites was greatly boosted through the inclusion of nanosilica particles in epoxy. The disintegration of the composites was delayed by around 10°C–14°C, and the residue of the composite after the decomposition was augmented by 7%–11.5% with the help of nanosilica in epoxy.

(iv) The thermal conductivity of the composite was considerably improved proportionally with the nanosilica content in the epoxy. However, the increment in thermal conductivity of the composite became insignificant, with adding nanosilica more than 1.5% in epoxy.

Collectively, the results evidenced that the mechanical and thermal behaviour of the luffa/epoxy composites can be enhanced through the addition of nanosilica in epoxy resin. However, the better results were arrived for the inclusion of 1.5% nanosilica in epoxy, and it can be attributed to the agglomeration of the nanosilica particles, when their fraction was increased above 1.5% in epoxy. The detailed study can be conducted in future to improve the dispersion stability of the nanoparticles within the matrix material.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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