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Research

Experimental investigation on vibration characteristics and damping factor of coir fiber reinforced polyester composite material

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Abstract
This research aimed to investigate the composite material composed of polyester with randomly oriented short coir fibers with a length of 10 mm and varying weight percentages from 5 to 20%. The composite material was fabricated by the hand layup method. The tensile strength, flexural strength, hardness, impact strength, free vibration analysis, and damping characteristics were studied; the SEM images were used to analyze the fractured surface of the composite specimens. The current empirical study identified a conspicuous association between the gradual escalation in fiber content for the natural frequency and the damping attributes of the composite material. The test results showed that the composite with 15% coir fibers worked best for several studies examining characteristics over a wide range of temperatures and frequencies. Coir-based composite material yields a natural frequency of 61,862 Hz and a maximum damping ratio (ζ) of 0.29592, indicating enhanced rigidity and vibration absorption capabilities. The damping factor (tan δ) reached a notably low value of 0.360 at a 10 Hz frequency with 15 wt.% fiber content, demonstrating improved energy dissipation. The results show that polyester composites containing 15% wt.% coir fibers have the best mechanical and damping properties, making them a sustainable choice for industrial uses that need to reduce vibrations.

Keywords Damping factor (tan δ) · Free vibration testing · Mechanical properties · Natural fiber · Polyester resin

1 Introduction

The rapid development in engineering has met the demand for sustainable, lightweight, high-performance materials that have strapped to focus on using natural fiber-reinforced composites. Natural or bio-composites are feasible substitutes for synthetic fiber composites in diverse applications. The composites exhibit notable advantages over their artificial counterparts, encompassing enhanced cost-effectiveness, diminished specific strength, and sustainability [1]. When amalgamated with polymer reinforcements, natural fibers have been extensively employed and shown to contribute significantly to various sectors. The essential properties of natural fibers, characterized by their tensile strength, compression resistance, impact resistance, and flexural strength, provide a fundamental foundation for cohesive resource

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presentations. These composites, which are frequently obtained from renewable resources, exhibit low cost, biodegradability, and reduced environmental impact, making them an attractive alternative to synthetic fiber composites [2].

The mechanical characteristics of biocomposites are predominantly influenced by the specific type of fiber utilized, the proportion of fiber incorporated, and the nature of the matrix material employed. Natural fibers, such as coir, jute, and hemp, have been recognized as reinforcing materials in polymer matrices because of their high mechanical strength/weight ratio and biodegradability [3]. In addition to having a lower tensile strength than synthetic fibers, coir fibers significantly strengthen the flexural strength and impact resistance of polyester composites. Natural fiber composites are in harmony with the creation of sustainable materials. They pointed out that the use of natural fibers not only improves the environmental profile of composite materials but also maintains their performance [4]. The coir fibers obtained from coconut husks have been the object of concern for their unique aspects, such as their high lignin content and longevity. Coir-polyester composites and reported improvements in tensile and impact strengths with adding fiber content. Nevertheless, they observed decreased interfacial bonding efficiency beyond a certain fiber content [5].

The fabrication process also affects fiber-matrix bonding, which, in turn, influences the mechanical and damping features of the composite [6, 7]. Damping constitutes a significant material parameter for dynamic loading and studied composites made from jute fabric and epoxy resin, where a substantial increase in the level of d was found in the case of the reinforced matrix compared with the unreinforced matrix [8]. The interaction between fiber and matrix materials plays a significant role in the damping performance of composites fabricated using natural fibers [9]. In the case of fiber content, changes in fiber weight percentages cause different alterations in composites' mechanical and damping properties. This part suggested finding an optimal proportion where mechanical and damping properties are maximized. Coir fiber-reinforced composites study of suchlike indicated that not only did an excessive amount of fiber (too high toward the proportion scale) lead to agglomeration, but also the stress transfer effect and damping performance were impacted the most [10]. One of the most popular subjects in composite research is the performance of these materials under different thermal and vibrational conditions. Natural fiber composites are inherently sensitive to temperature, impacting their stiffness and damping behavior [11]. In addition to that, the increase in frequency causes stress to be dissipated more throughout the matrix. Frequency variations can intensify the fiber-matrix interaction energy dissipation [12].

Natural fiber composites show a clear correlation between the fibers, their vibrational characteristics, and their influence on structural integrity. Research demonstrates that natural fiber composites exhibit stronger natural frequency responses when modified fiber compositions are used. Composites immediately contribute to improved structural integrity and vibrational behavior, affording critical insights into overall composite performance optimization [13]. Therefore, viability is assessed by adroitly varying fiber. Due to the findings regarding the coir fiber reinforced composites may significantly reduce vibrations caused by their high value of background damping, with the possible management of it effectively [14].

Consequently, it is essential to thoroughly examine the holistic implications of vibrational phenomena in materials to engineer and utilize this composite effectively. The analysis of the mechanical characteristics of polymer composite materials substantially depends on techniques such as free vibration assessments and determining damping coefficients. Noteworthy advancements have been implemented to mitigate vibrations in polymeric substances [15]. The damping characteristics of fiber-reinforced polymer (FRP) composites reveal a marked variation from those in standard polymers. The composite materials incorporate reinforcement representatives that engender intricate core architectures within the matrix. The characteristics of their constituent substances do not exclusively dictate the damping properties of these composite materials; other elements like the proportion of fillers, the robustness of interfacial adhesion, the load direction, and the polymer's degree of plasticization also play significant roles [16, 17]. Fiber-reinforced composite materials exhibit a variety of mechanisms for energy absorption, which encompass the viscoelastic characteristics inherent in the matrix and fiber constituents, friction arising from the interfacial slip at the matrix form of fiber boundary, energy dissipation occurring at the sites of cracks and delamination induced by impact, as well as viscoelastic and thermoelastic damping phenomena [18].

The duration required for the curing phase in the hand layup technique is influenced by the polymer employed in the composite fabrication process. For example, concerning an epoxy-based formulation, the usual time frame for the curing procedure at ambient temperature spans approximately 24–48 h [19]. In general, composite materials are fabricated utilizing the hand layup technique with various materials. This methodology is predominantly suitable for composites derived from thermosetting polymers. The financial and infrastructural demands are comparatively minimal when juxtaposed with alternative methods. The production rate remains modest and poses difficulties in achieving a substantial volume proportion of reinforcement within the processed composites. Hand layup is employed across many industries, such as aerospace, manufacturing, automotive fabrication, marine construction, and deck assembly [20, 21].

A composite material incorporating a filler or reinforcing medium has a complex internal configuration. Numerous variables, encompassing volume fraction, interface properties, polymer plasticization, and loading orientation, significantly influence the efficacy of vibration attenuation. The fiber-reinforced composite employs various approaches to manage energy dissipation, including the matrix's viscoelastic traits, fiber characteristics, frictional interactions due to matrix shifts, energy absorption at flaws and separations in impacted zones, and viscoplastic and thermoelastic damping [22]. An extensive understanding of the dynamics of composites can be obtained through vibration analysis. Natural fiber composites with increased fiber content also have higher natural frequencies; thus, they have improved rigidity [23]. The coir fiber-reinforced composites have superior damping characteristics, effectively reducing vibrations. Optimizing the fiber weight percentage in the composite material achieved better mechanical properties and improved the overall structural performance [24]. The coir fiber content was between 15 and 20 wt.%; it was most balanced regarding mechanical strength and damping performance in polyester composites [25]. The Scanning Electron Microscopy (SEM) method is usually used to image the fiber-matrix bonding areas and fracture surfaces and determine the failure mechanisms. SEM helped identify the fracture surfaces in composites, which proved that high fiber-matrix adhesion leads to increased mechanical and damping properties [26]. This study focused on analyzing the damping and mechanical properties of the short coir fiber-reinforced polyester composites. With this, the elements of their response to the variation are brought to light. This investigation elucidates these materials' distinctive benefits while mitigating particular strengths in the context of sustainability. This study delves into nuanced damping systems tied to fiber-reinforced polymer (FRP) materials, contrasting sharply with standard polymers. Furthermore, the investigation meticulously examines an array of variables that influence damping characteristics, including the additives' volumetric proportion, the interface's integrity, the applied load's orientation, and the polymer's plasticization properties. This research outcome validated how coir fibers with polyester composites with coir fibers can be earth-friendly in the use of various utility buildings.

This study examines the effect of fiber weight percentage on intrinsic damping due to their unique performance. It contributes to the fast-growing research in bio or natural fibers in composite materials. Thus, it is also considered an essential and foremost issue to experiment with directly measuring the fiber content, mechanical properties, and vibrational behavior for making composites meet specific operational demands. The green fields are crowded with natural fiber-reinforced composites instead of synthetic fiber counterparts as they are environment-friendly, cost-efficient, and have good mechanical performance. Proper research was performed to gain a complete understanding of the mechanical, thermal, and damping effects of these composites. Adding symmetrical wavelet transformation (SWT) to Fast Fourier Transformation (FFT) analyses of the construction of spectral energy grams for damage evaluation made it impossible to match better-detected damaged areas with camera-captured affected regions.

2 Significance of the study

The literature studies confirm a strong relationship between the sustainability of the material and the application of the materials; today, engineering industries need sustainable lightweight materials that exhibit high-performance characteristics because of ongoing demand changes. The growing environmental consciousness among materials engineering researchers focuses on biodegradable and renewable resources. Natural fiber-reinforced composites incorporating coir fibers are an attractive substitute for synthetic materials because of their various essential advantages. In the sustainable production of biodegradable materials, coir plays a vital role; coir fibers from coconut waste byproducts foster ecological responsibility through support of sustainable development and deliver high mechanical strength and prolonged service life. There is a gap in biodegradable material research; researchers lack sufficient information about the dynamic properties of natural fiber-based composite materials. Research on the essential mechanical characteristics of natural fiber composites is extensive, although studies on the connection between damping efficiency (tan δ), natural frequency of vibration, and mechanical strength remain limited.

This research helps to bridge this gap by providing comprehensive insights into these crucial properties. The previous study brought practical benefits to the industrial deployment of natural fiber composites. From the point of economic analysis, biodegradable composites have become vital because they investigate affordable alternatives to synthetic composites. These coir fiber-reinforced composite materials demonstrate the achievement of specialized mechanical and damping behavior characteristics and cost benefits, making them suitable for industrial production needs. This investigation aimed to study how the fiber length and weight percentage affect these materials' engineering performance and damping behavior, thus enabling improved optimization for different industrial application requirements. This research

Fig. 1 Extraction of coir fiber

Table 1 Properties of coir fibers (Hao L. C. et al. (2018))

Property	Coir
Density	1.2 g/cm^3
Young's modulus	6 GPa
Tensile strength	220 MPa
Elongation at break	30%

enhances knowledge about complex damping processes in fiber-reinforced polymer (FRP) materials by examining key factors such as material ratios int, surface quality, loading directions, and aspects of polymer material stress.

3 Composite fabrication methodology

3.1 Natural fibers

Plant fibers are extricated from the cellulose-dense cellular structures of flora, establishing them as the preeminent organic material on the planet. Some examples of fibers that fall within this category are coir fibers, including those made from coir [26]. The depiction provided in Fig. 1 elucidates the processed coir alongside the coir fibers utilized in the research endeavor.

3.2 Coir fiber

Coir fiber, often referred to as coir basting fiber or coir stem fiber, is a natural fiber obtained from the outer layer of the stem of the coir plant [27]. It possesses distinctive characteristics that make it suitable for many uses. Coir fiber is derived from the elongated fibers found inside by physically removing the outer layers of the coir plant's pseudo stem or external sheath, which are usually discarded after collecting the fruit. Subsequently, these fibers undergo purification and processing to eliminate contaminants and prepare them for future applications. Comprised mainly of cellulose, hemicellulose, and lignin, along with additional elements such as proteins and minerals, coir fiber exhibits robustness, pliability, and long-lasting qualities as a result of this composition Table 1.

The composite material exhibits a complex internal structure because of filler or strengthening medium. The damping performance of the material depends not only on the properties of the particularmaterials but also on features such as the volume fraction, interface quality, polymer plasticization, and load direction [28]. The fiber-reinforced composite possesses various mechanisms to tolerate energy, such as the viscoelastic nature of the matrix, the properties of the fiber materials, the friction generated by slip in the matrix, the energy tolerance at clefts and delamination induced by dented places, as well as the viscoelastic and thermoelastic damping [29].

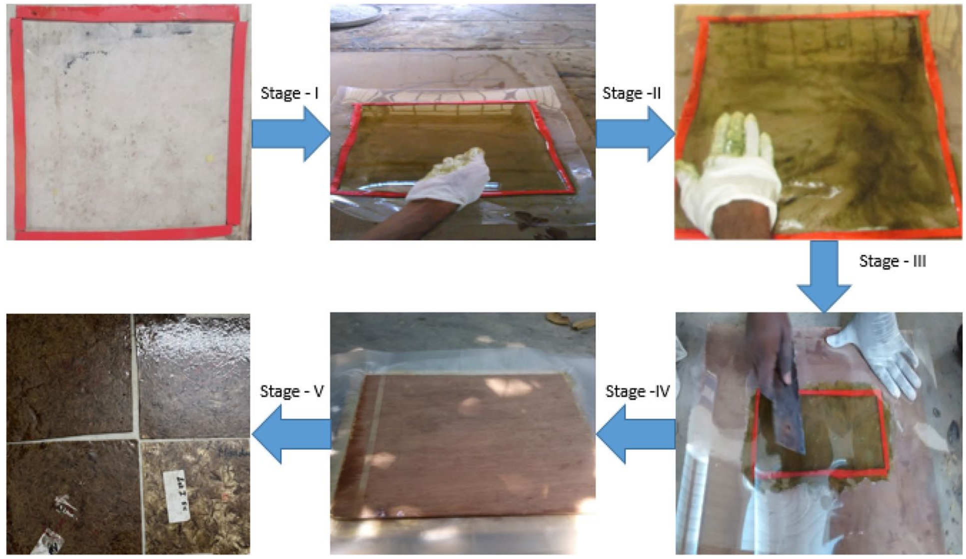


Fig. 2 Various stages of the composite fabrication process using the hand layup method

Table 2 Coir fibers volumes & mass calculations

Sample	Volume (cm^3)	Mass (g)
Sample—1	13.5	16.2
Sample -2	27	32.4
Sample—3	40.5	48.6
Sample -4	54	64

3.3 Experimental methodology

The hand layup method is a simple and flexible process, and it is used to create composite material components by manually arranging reinforcing materials and resin [30]. This technology is widely used in several industries because of its cost-effectiveness and ability to manufacture components of different forms and sizes. The ongoing work centers on producing natural composites using the hand layup process, as depicted in Fig. 2. In this process, polyester resin is employed to create composites with desirable features [31]. Table 2 displays the calculated volume fraction and mass of coir and coir fibers in the produced specimens.

This instance's reinforcing and matrix constituents comprise coir fiber and unsaturated polyester resin. To prepare the samples, the bio-composites were constructed by arranging equally cut coir fibers, measuring 10 mm in length, in a mold with dimensions of 300 mm × 300 mm × 3 mm. The preparation of the samples involved using different mass percentages (0, 5, 10, 15, and 20) of coir fiber.

3.4 Dynamic mechanical analysis (DMA)

Dynamic mechanical analysis **(**DMA) is an indispensable study of industrial applications because, in this study, the material is subjected to a comprehensive analysis of material behavior under dynamic conditions. It is used to assess the viscoelastic properties demonstrated by different substances. The method assesses the modulus, representing stiffness and materials' damping characteristics, linked to energy dissipation as they experience deformation under cyclic loading. The outlined methodology is suitable for analyzing various materials, such as thermoplastics, composites, thermosets, elastomers, films, fibers, coatings, and adhesives.

The dynamic behavior analysis can find the viscoelastic Behavior, Phase Angle, Complex Modulus, Storage Modulus, and Loss Modulus, Fig. 3 illustrates the dynamic mechanical testing equipment. The polymeric materials exhibit viscoelasticity, indicating the simultaneous presence of attributes resembling those of solids and liquids. The level of solid-like or liquid-like traits a polymer manifests is subject to temperature, time, and frequency modulation. It facilitates material selection, optimization, quality assurance, and adherence to regulatory standards, guaranteeing

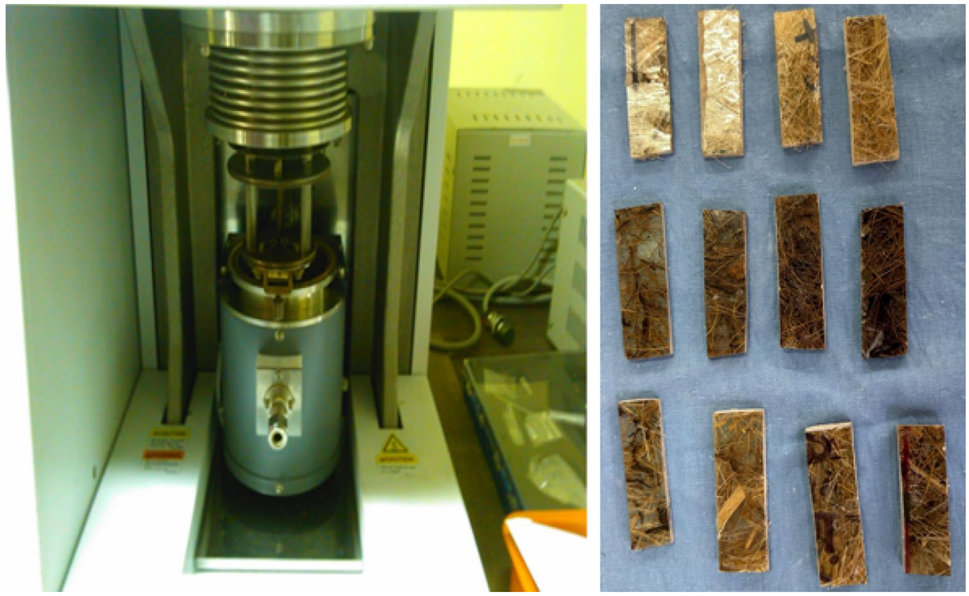


Fig. 3 Dynamic mechanical analyzer equipment for analyzing polyester-based coir composite

that materials satisfy performance criteria across automotive, aerospace, construction, and consumer products. Table 3 shows the specifications of the DMA equipment.

In dynamic testing, the specimens were placed in a cantilever beam, the sample was fastened to the accelerometer at its free end, and vibration was initiated by striking it with a rubber hammer. Four specimens were used for the vibration test, and the resulting average value was presented—the specimen sample size measures 220 mm × 30 mm × 3 mm. Samples undergo oscillatory stress over the interval (− 50–200 °C) at a rate of 2–5 °C/min, and at the same time, the frequencies are 1–10 Hz. The resulting plots of E′, E″, and tan δ against temperature reveal critical transitions, e.g., Tg, besides quantifying stiffness and damping behavior [32]. Specific factors that affect DMP are fiber orientation (random or aligned), moisture content (the hydrophilicity of coir makes it necessary to dry thoroughly), and interfacial bonding quality. The data acquisition system records data with the time history acceleration of vibration. Logarithmic curtailment is employed to determine the cantilever beam's damping ratio (ξ) by analyzing recorded acceleration time histories using the following equation [33]. Equation (1) can be expressed as:

$$\xi = 1/2\pi y \ \ln(ax/ax + y) \tag{1}$$

where ax is the maximum acceleration of the x^{th} peak and ax + y is the maximum acceleration peak of the ycycles following the x^{th} peak.

Table 3 Specification of DMA equipment

S.No	Model	DMA
1	Sample	Shape Geometry Factor
2	Length	40 mm
3	Width	10 mm
4	Thickness	3 mm
5	Minimum Temp	25-degree Cel
6	Maximum Temp	180-degree Cel
7	Increase the temp	2 degrees Cel/min
8	Measurement Mode	Bend (3Point) (Dual Cantilever)
9	Frequency Information	0.5 Hz, 1 Hz, 2 Hz, 5 Hz &10 Hz

4 Results and discussion

4.1 Mechanical properties

The fabricated specimens of coir fiber were used to measure their mechanical properties, as shown in Table 4. Figure 4 depicts the ultimate tensile strength of manufactured specimens. Specimens containing 5% coir demonstrate a lower tensile strength value, while those with 15% coir show the highest tensile strength value among all specimens.

The ultimate tensile strength of fabricated specimens shows variations in strength based on the concentration of coir fiber used. These specimens are constructed using a matrix material, potentially a polymer resin mixed with different levels of coir fiber for reinforcement. The visual representation emphasizes the influence of the coir fiber content on the tensile strength of the produced specimens [34]. The tensile test was carried out using a UTM as per ASTM D3039. During the failure study, the initial crack in the composite occurred in the polyester regions between the fibers. It then propagated to the fiber-matrix interface, leading to debonding in the specimen. Finally, fiber pullout resulted in a rough, fibrous fracture surface. This progression of failure modes is particularly significant in natural fiber composites due to the interaction between hydrophilic natural fibers and hydrophobic polymer matrices. Specimens with C5 coir fiber display reduced tensile strength, suggesting that a small amount of coir fiber may not significantly improve the mechanical properties of the composite material.

In contrast, specimens with C15 coir fiber exhibit the highest tensile strength compared to other fabricated specimens. The diagram likely includes data points for specimens with coir fiber content ranging from C5 to C15 or higher. These specimens may show various tensile strengths depending on the quantity of coir fiber added. The observation that specimens with C15 coir fiber showed the highest tensile strength implies the existence of an optimal or ideal ratio of coir fiber for enhancing mechanical properties.

The analysis elucidates that the observed tensile strength ascends from 56 MPa at 5 wt.% to a peak value of 73 MPa at 15 wt.%, subsequently diminishing to 70 MPa at 20 wt.%. Higher fiber loadings strongly imply agglomeration

Table 4 Mechanical characteristics of coir-reinforced bio-composite materials

S.No	Coir	Fiber	Impact Value (KN/mm)	Flexural Strength(KN/mm)	Hardness Value (HRR)	Ultimate Strength (MPa)
1	5	C5	70	74.5	56	56
2	10	C10	71	74	58	65
3	15	C15	93	92.5	61	73
4	20	C20	91	92	59	70

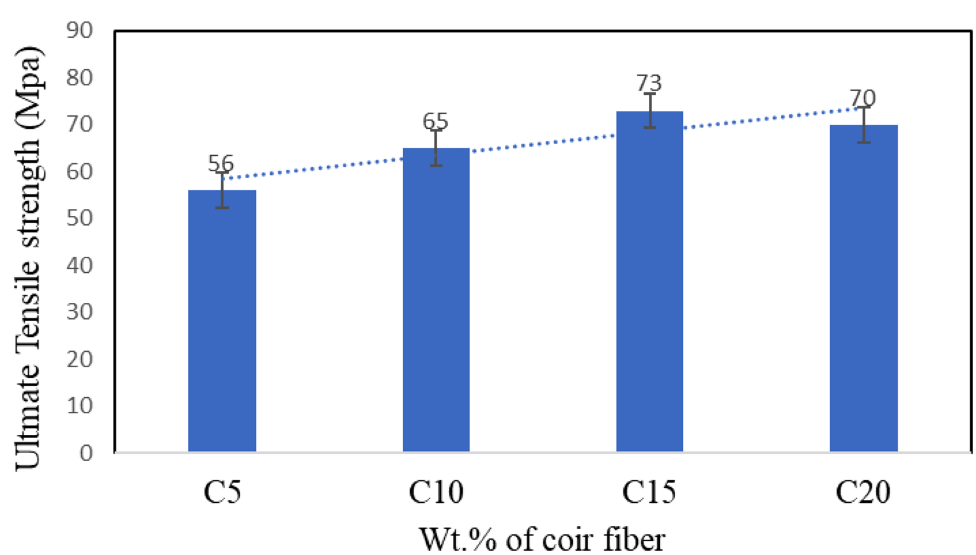


Fig. 4 Wt. % of Coir fiber vs. Ultimate tensile strength

Fig. 5 Wt. % of coir fiber vs. flexural strength

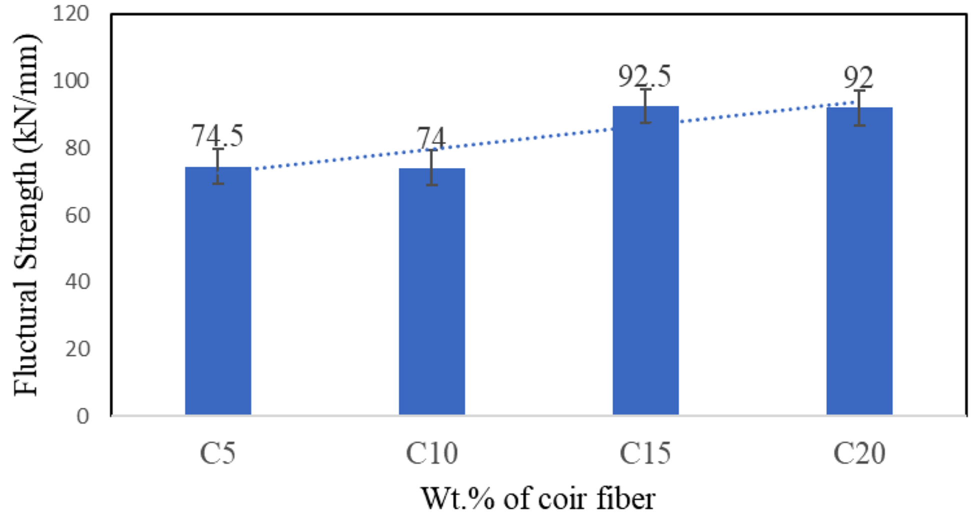
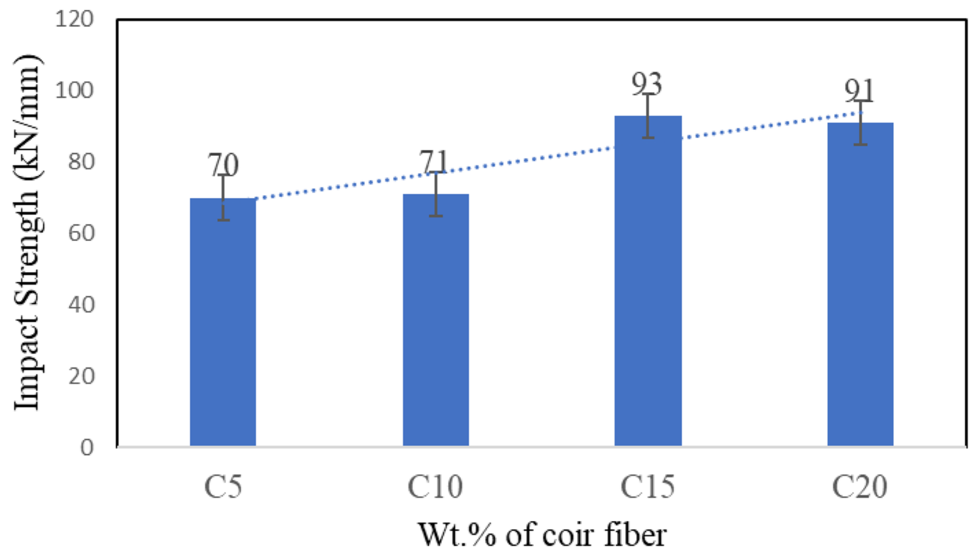


Fig. 6 wt. % of Coir fiber vs. Impact strength KN/mm graph &specimens



effects that undermine stress transfer efficiency within the composite material; in addition to fiber dispersion metrics that quantify the extent of agglomeration, it is also associated with increased fiber loading and potential modifications to manufacturing techniques that may alleviate agglomeration issues, potentially extending the performance benefits beyond the presently observed optimal loading of 15 wt.% [43].

Figure 5 illustrates the flexural strength of the manufactured specimen. Coir C5 shows a lower flexural strength, whereas coir C15 shows the highest flexural strength compared to other fabricated specimens. The fabricated specimens comprise composite materials comprising matrix material, such as polymer resin and coir fibers. Specimens with a lesser proportion of coir fibers (C5) exhibit relatively lower flexural strength, suggesting that the reinforcement offered by the fibers at this level may not significantly enhance the material's resistance to bending. Conversely, specimens with a higher percentage of coir fibers (C15) demonstrate the maximum flexural strength among the fabricated specimens, indicating the achievement of the optimal reinforcement level at this concentration, leading to improved bending resistance and increased flexural strength. The diagram may include additional data points for specimens with varying coir fiber content percentages [35]. These specimens could demonstrate flexural strengths ranging between the values recorded for C5 and C15 fiber content, highlighting the gradual improvement in flexural strength with increasing fiber content. Observing that specimens with C15 coir fiber content exhibit the highest flexural strength suggests an ideal balance between matrix material and fiber reinforcement at this level.

In Fig. 6, the impact strength of the manufactured specimensis shown. CoirC5 presents a lower impact strength, while coir C15 shows the highest impact strength compared to other fabricated specimens. The produced specimens comprise a composite material, a matrix material, a polymer resin, and coir fibers. Specimens containing C5 coir fiber exhibit a decrease in impact strength compared to others, showing that a small quantity of coir fiber may not provide sufficient reinforcement to enhance the material's ability to absorb energy during impact loading. Specimens incorporating C15 coir fiber revealed the most significant impact strength among all specimens created, suggesting that an optimal ratio of coir fiber has been achieved, leading to improved energy absorption and increased impact strength [36]. These specimens might show impact strengths that fall between the values noted for C5 and C15 coir fiber content, displaying a gradual improvement in impact strength as the fiber content increases. The finding that specimens with a C15 coir fiber content show the highest impact strength implies the presence of an ideal balance between matrix material and fiber reinforcement at this specific concentration level. This balance ensures effective energy absorption and resistance to fracturing under impact loading conditions.

Figure 7 illustrates the hardness values of the fabricated composite material specimens. Coir C5 demonstrates lower hardness, while coir C15 exhibits the highest hardness compared to other fabricated specimens. The composite specimens prepared are intricately designed materials comprising matrix material, such as polyester resin and coir fibers. These fibers are integrated into the matrix at different proportions to investigate their impact on hardness. Samples with a 5% coir fiber content displayed decreased hardness levels compared to others, potentially due to insufficient reinforcement associated with lower fiber content, resulting in reduced hardness. Conversely, specimens with a C15 coir fiber content showcased the highest hardness among the fabricated samples. The optimal level of reinforcement achieved at this concentration enhances the material's stiffness and ability to resist deformation, thereby leading to heightened hardness values. Moderate hardness levels are anticipated for samples containing coir fiber content ranging from C5 to C15, indicating a gradual enhancement in hardness with escalating fiber content. Consequently, materials distinguished by higher hardness levels, such as those encompassing C15 coir fiber, might offer enhanced durability and longevity in scenarios subjected to abrasive forces. The revelation that samples with a C15 coir fiber content demonstrate the highest hardness underscores the significance of optimizing fiber content to attain the desired mechanical properties [37].

The water absorption test is one of the essential tests for bio-composite material; the moisture-absorbing ability of coir fibers makes it possible for coir-based composite materials to soak up water. As a result, undesirable consequences arise as the bond breaks up; so, the mechanical performance of the composite material decreases with time, thus diminishing the composite's strength. The amount of water absorbed is determined by multiple variables, such as the resin type, the fiber content, and the fact that the fibers have been treated to reduce moisture absorption. Using hydrophobic composites can contribute to the decrease in the uptake of the water. They also improve when you coat them with chemicals such as NaOH [38]. Measuring how much weight the composite gained over time is a common way to test water absorption; this test was done as per the ASTM D570 standard.

Figure 8 and Table 5 illustrates the water absorption capacity of the produced samples;it is evident that coir fiber showcases a water absorption rate of C5, signifying a decreased water absorption level. The samples ofC20, 20 wt.% of coir fiber, show the highest water absorption levels compared to other fabricated samples. It is linked to the higher concentration of coir fiber in these samples, resulting in amplified water absorption. The fabricated samples comprise

Fig. 7 wt. % of Coir fiber vs. Hardness, HRR graph & specimens

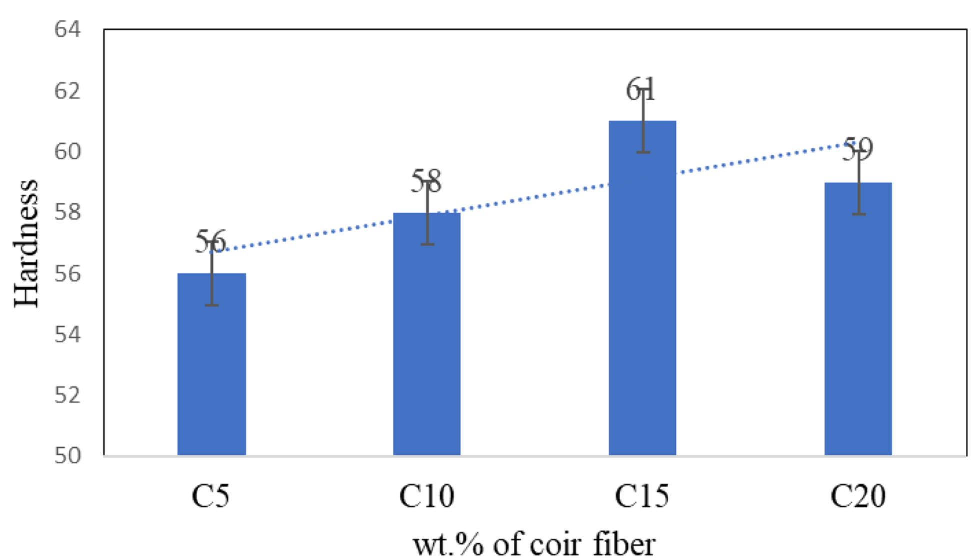


Fig. 8 wt. % of Coir fiber vs Water absorption graph & specimens

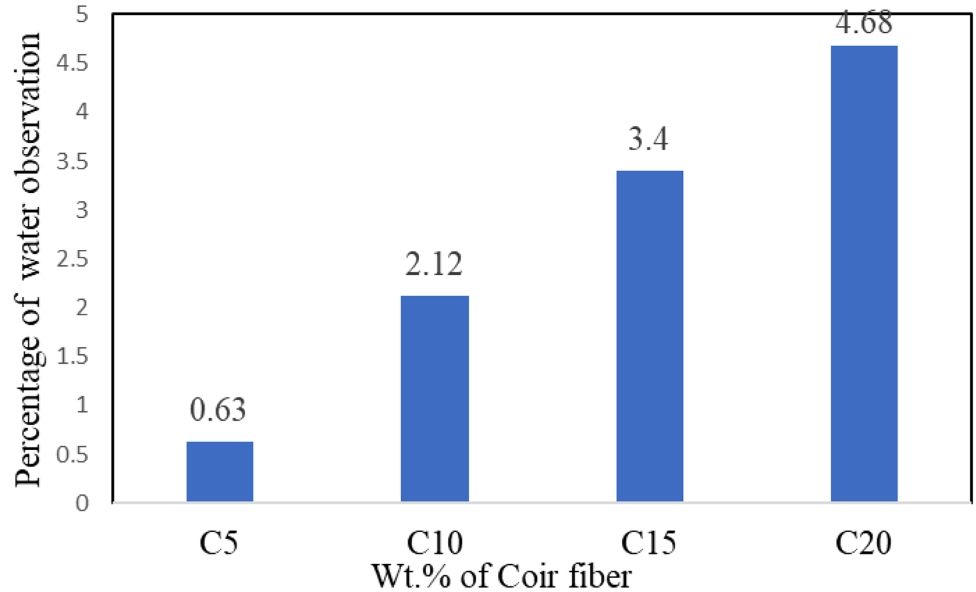


Table 5 Percentage of water observed for coir fiber

S.No	Coir	Fiber	Initial Weight	Final Weight	Increasing Weight	Percentage of waterobservations
1	5	C5	4.7	4.73	0.03	0.63
2	10	C10	4.7	4.8	0.1	2.12
3	15	C15	4.7	4.86	0.61	3.4
4	20	C20	4.7	4.92	0.52	4.68

composite materials comprising a matrix material, potentially a polymer resin, alongside varying amounts of coir fibers. These fibers serve as reinforcement within the matrix, influencing the characteristics of the material, including water absorption. The analysis suggests that a lower quantity of coir fiber in the composite material leads to decreased water absorption, possibly due to fewer pathways for water infiltration and retention [38]. The samples with a higher proportion of coir fibers (C20) confirm the highest water absorption levels among the fabricated samples. The revelation that samples with 5% coir fiber display lower water absorption rates implies that C15 provides some optimal balance between matrix material and fiber reinforcement in reducing water absorption attributes.

4.2 Free vibration testing (FVT)

The study of free vibration testing for bio-composite materials is necessary when it involves investigating mechanical properties, acknowledging optimization, forecasting failure, and the use of automotive and biomedical components. It is a technology that supports innovation and sustainability since it allows for the efficient use of eco-friendly materials. During a free vibration assessment, the natural frequency of a substance or combination is evaluated by exposing it to a disturbance and monitoring the subsequent oscillations [39]. A chart is commonly employed to illustrate the intrinsic frequencies while analyzing the impact of incorporating coir fibers into pristine polyester and polyester composites at different weight proportions (5wt.%, 10wt.%, 15wt.%, and 20wt.%). This graphic facilitates the analysis of how the inclusion of fibers affects the vibrational characteristics of the material.

Figures 9, 10, 11 and 12 display the results of experimental assessments conducted on unfilled polyester and polyester composites reinforced with coir fibers. The fiber mass ratios used in the composites varied between 5wt.% and 10wt.%, 15wt.%, and 20wt.%, and the experimental results can be categorized into multiple sections. The components will encompass the mean damping coefficients, inherent frequencies, and precise statistics illustrating the correlations among frequency, amplitude, and duration.

Figure 13 delineates the focus of the investigation on the inherent frequency characteristics of diverse composite materials, including pure polyester resin and polyester resin augmented with differing weight proportions of coir fibers.

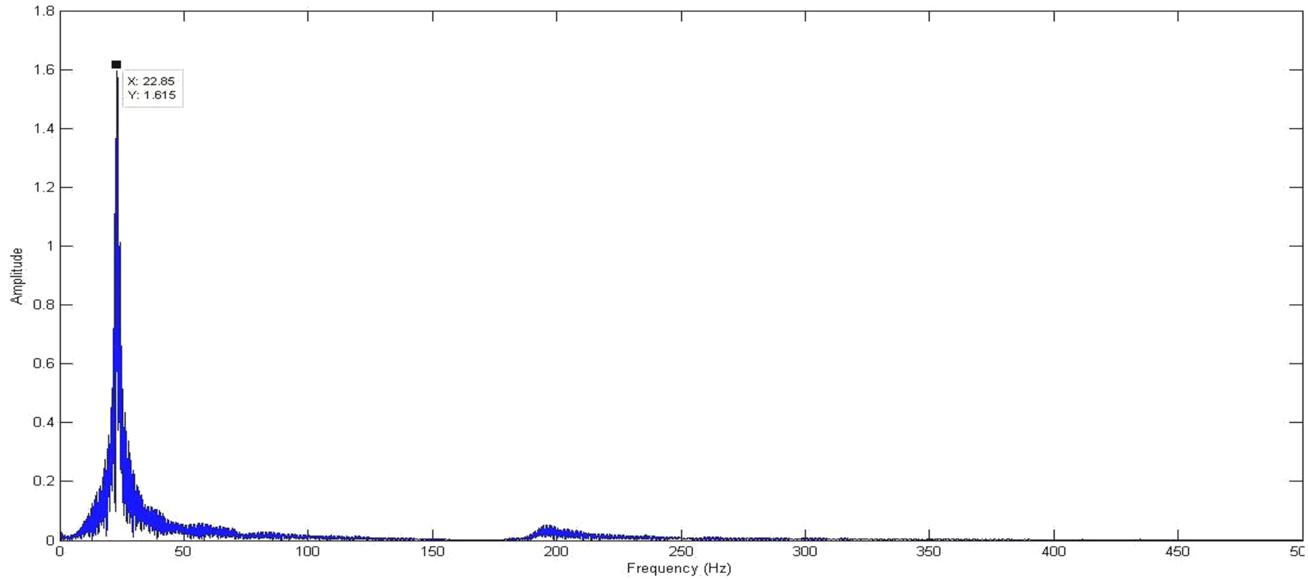


Fig. 9 Amplitude vs. Frequency of the polyester composites with 5wt% of coir fiber

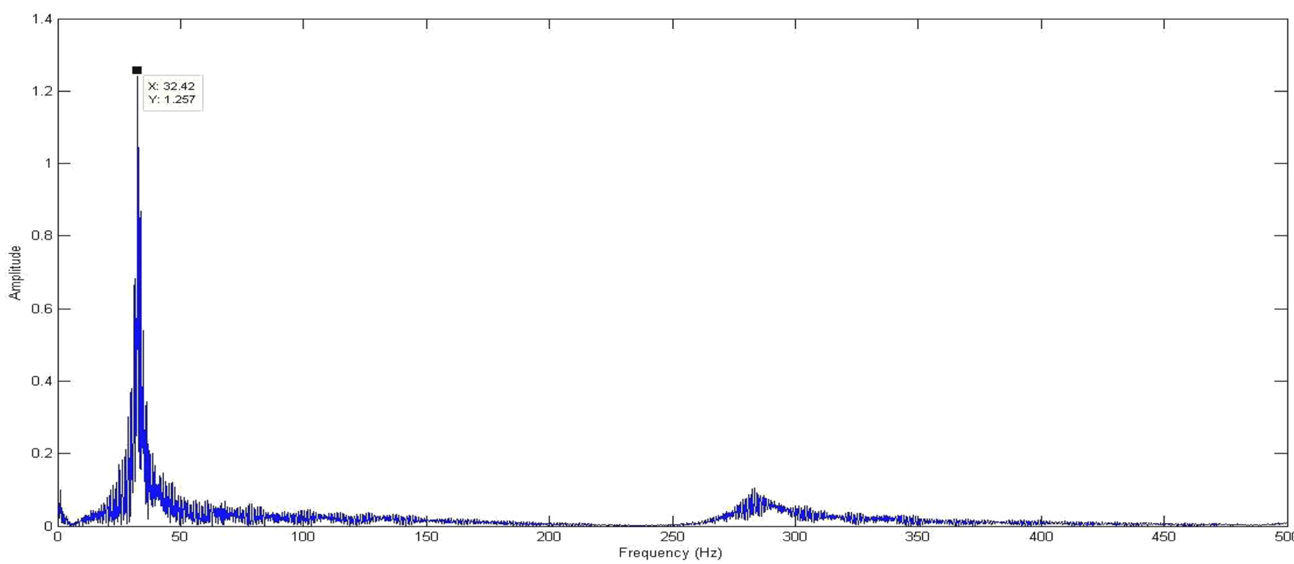


Fig. 10 Amplitude vs. Frequency of the polyester composites with 10wt% of coir fiber

The resulting outcome suggests that the inherent frequency of the initial polyester resin is 14.38 Hz. The 5wt% ofcoir fiber in the composite material shows a significant improvement to 29.431 Hz in the intrinsic frequency, which indicates an improvement in both stiffness and vibrational properties. Augmenting the quantity of fibers, specifically by C10, led to a steady frequency of 47.562 Hz, signifying uninterrupted enhancement. The fiber mix containing C15 achieved the most significant natural frequency of 61.862 Hz, indicating an optimal combination of stiffness and vibrational characteristics. Nevertheless, when the fiber content was raised to C20, the intrinsic frequency decreased to 56.835 Hz. The effectiveness of composites suffers from two main factors: fiber clumping problems and poor fiber-matrix bonding, besides a natural rise in coir fiber frequency before reaching proper standards.

The testing methods to determine natural frequencies depend on stiffness, density, and damping and aid in optimizing design features by selecting proper fiber directions and resin types to reduce noise levels, vibration phenomena, and harshness issues. The analysis of dynamic characteristics permits benchmark measurements with synthetic composites and environmental risk assessments for natural fibers so their benefits can produce safe

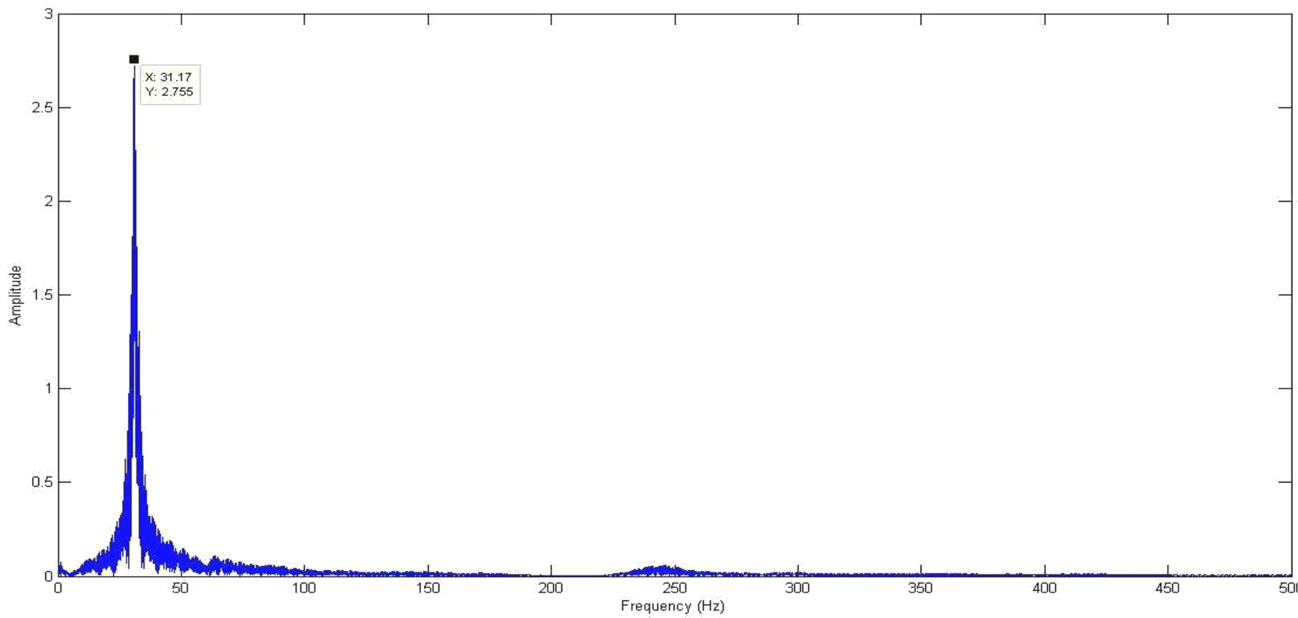


Fig. 11 Amplitude vs. Frequency of the polyester composites with 15wt% of coir fiber

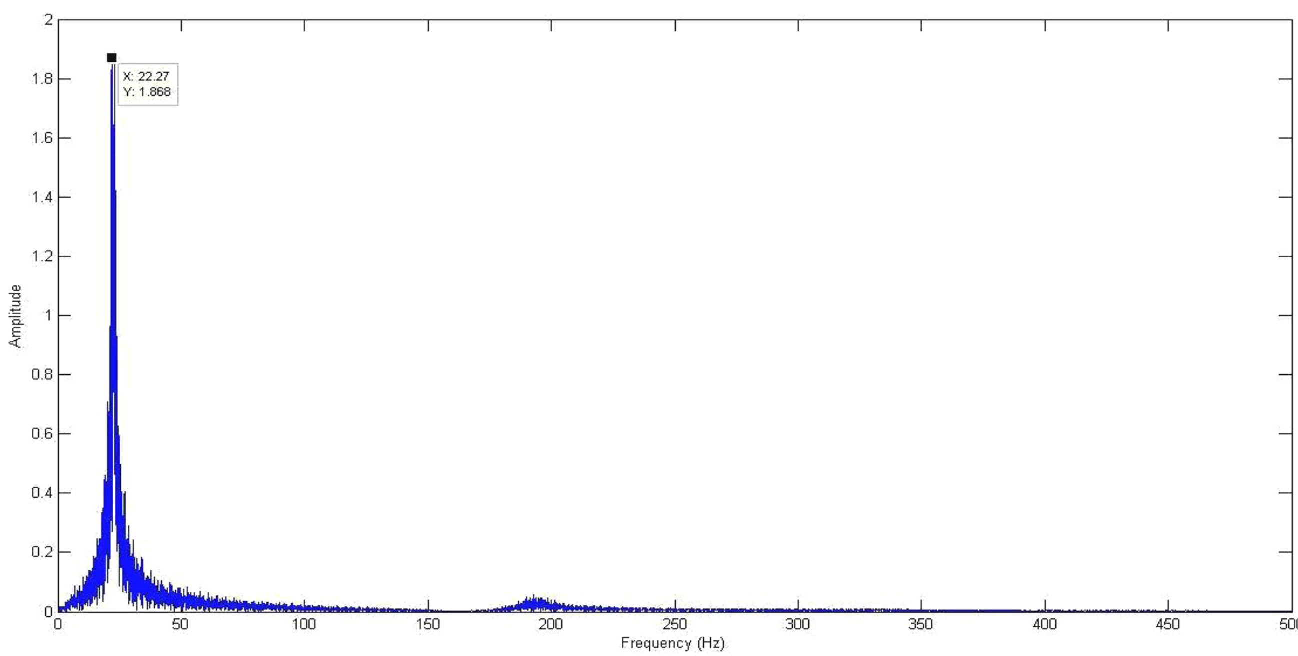
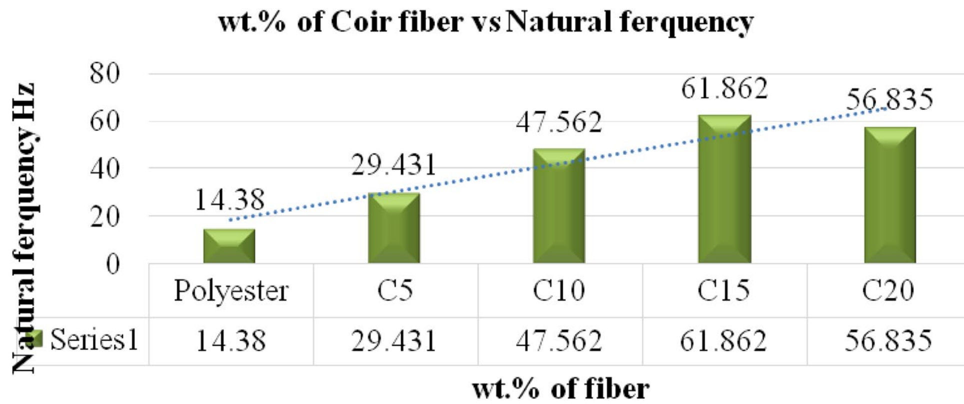


Fig. 12 Amplitude vs. Frequency of the polyester composites with 20wt% of coir fiber

structures in actual environments. The composite materials possess environmental advantages and lightweight properties yet experience resonance effects that generate severe vibrations that might ruin the structural integrity. The coir fiber with a 15-wt. percentage confirms its superiority in the mechanical and natural frequency properties analysis; the composites meet the essential requirement for evaluating their reliability and performance, especially in the automotive and aerospace sectors.

Fig. 13 wt. % of Coir fiber vs. Natural frequency graph &specimens



4.3 Damping curve

Studying the damping ratios of natural fiber-based composites is crucial because it provides insights into their ability to dissipate energy under dynamic loading conditions. Damping is a key property that governs how quickly vibrations diminish in a material or structure, directly influencing performance, durability, and safety in various applications. Natural fiber composites are increasingly used in automotive, aerospace, construction, and sports equipment industries, where dynamic forces are prevalent. By understanding the damping ratios, engineers can predict how well these materials will reduce vibration amplitudes, minimize noise, and control resonance. This is particularly important in applications requiring comfort and structural stability, such as automotive panels, seats, or building flooring.

Effective damping enhances the longevity of components by reducing the risk of fatigue and failure caused by excessive vibrations. Additionally, studying damping ratios aids in optimizing the design of natural fiber composites. Damping is affected by factors like fiber type, orientation, matrix material, and environmental conditions. Analyzing these influences enables researchers to tailor the composite's properties for specific applications, ensuring a balance between energy dissipation and structural stiffness. Natural fibers often exhibit higher damping properties than synthetic composites, making them suitable for applications requiring vibration suppression.

Furthermore, environmental factors such as humidity and temperature can impact the damping characteristics of natural fiber composites. Understanding these effects ensures that the materials maintain consistent performance under varying conditions. Finally, studying damping ratios helps benchmark natural fiber composites against traditional synthetic alternatives, fostering their adoption in sustainable, high-performance designs. In summary, analyzing the damping ratios of natural fiber-based composites is essential for ensuring their effectiveness, safety, and sustainability across a wide range of engineering and industrial applications.

This study examined the natural oscillation and temporal evaluation of pure polyester and polyester composites enhanced with coir fiber. The composites exhibited varying fiber weight percentages, ranging from 5wt% to 20wt% in increments of 5wt% [40]. The natural frequencies of each composite were assessed, and the pure polyester composite exhibited a frequency of 14.38 Hz. The value showed a significant rise to 61.862 Hz when reinforced with 15wt% coir fiber, thereafter, declining somewhat to 56.835 Hz at 20wt%. Examination of the time history data uncovered distinct damping characteristics in the composites. The polyester material showed a slight level of deterioration, whereas the composites with a higher concentration of fibers showed faster decay rates, indicating enhanced damping qualities. The results highlight the advantages of incorporating coir fiber reinforcement up to an optimal weight percentage of 15wt%. However, beyond this threshold, the benefits may be reduced due to factors like fiber aggregation or insufficient adhesion between the fiber and the matrix. These findings provide crucial insights for enhancing composite materials intended for applications that prioritize vibrational properties. Figures 14, 15, 1617 represent graphs of the relationship between time and acceleration for pure polyester. The composite consists of reinforced polyester with coir fibers at weight percentages of 5%, 10%, 15%, and 20%, respectively.

Calculation of Damping Ratio:

The damping ratio of the composite material, using the logarithmic decrement,can be foundin Eq. 2

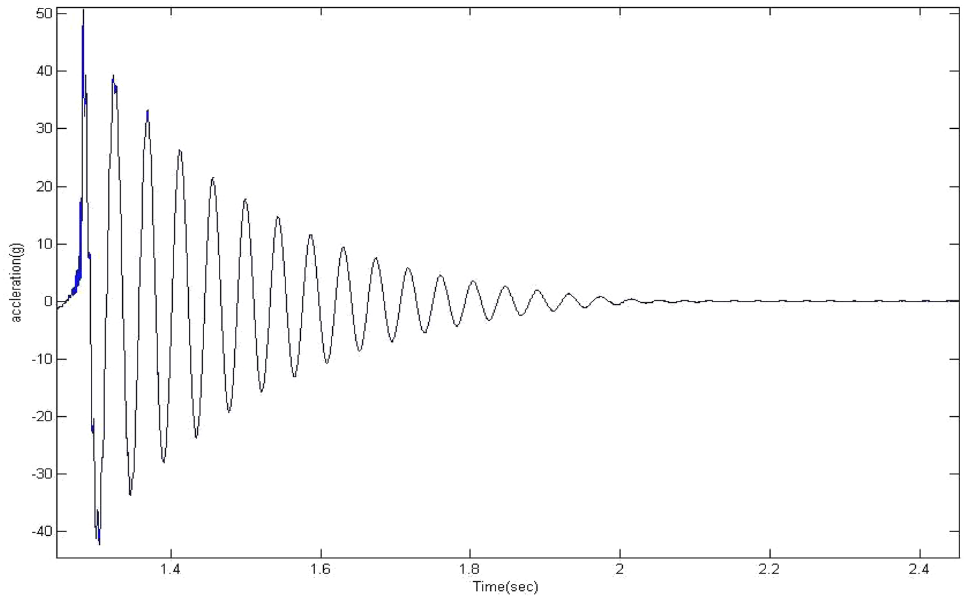


Fig. 14 Time vs. Acceleration graph for 5 wt.% of coir fiber

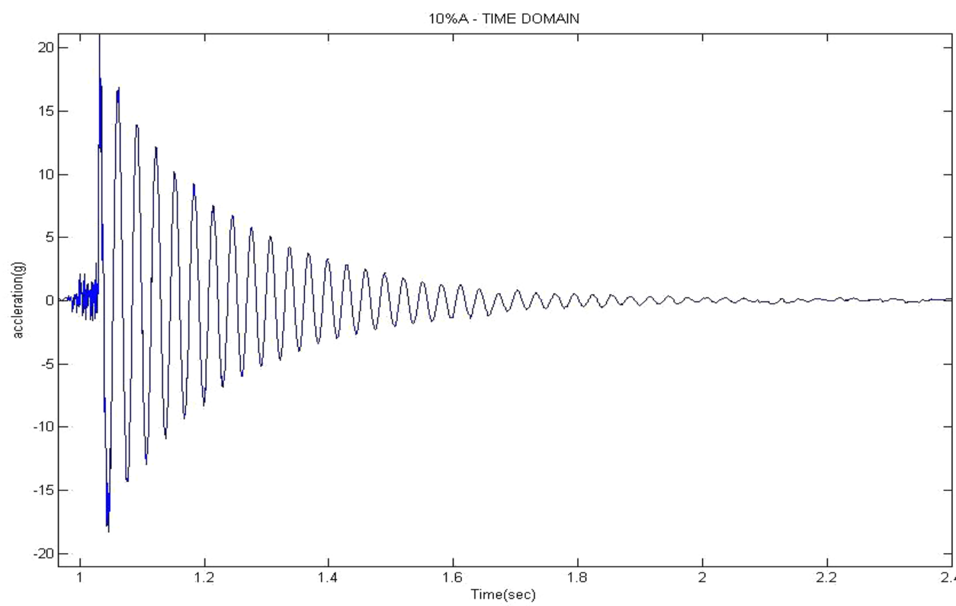


Fig. 15 Time vs. Acceleration graph for 10 wt.% of coir fiber

$$ln\frac{x_0}{x_1} = \frac{2\pi\varepsilon}{\sqrt{1-\varepsilon^2}} \quad (2)$$

where:

X0 is at a peak

X1 is the peak acceleration of the peak after i[t]s peak.

Pure Polyester.

x_0= 4.799.

x_1= 3.792.

x_2= 3.323.

x_3= 2.697.

These values are taken from the acceleration Vs. Time graph of pure polyester.

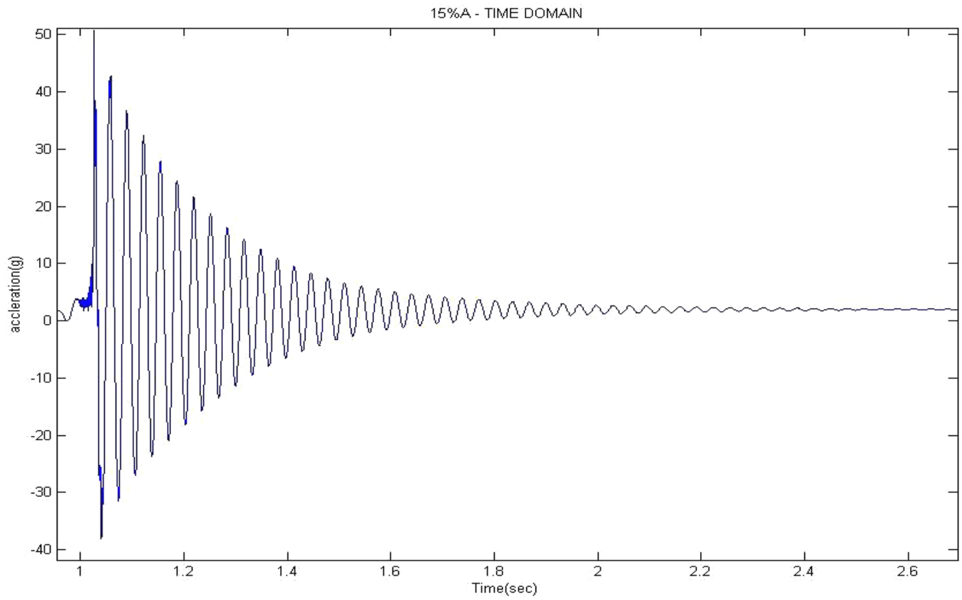


Fig. 16 Time vs. Acceleration graph for 15 wt.% of coir fiber

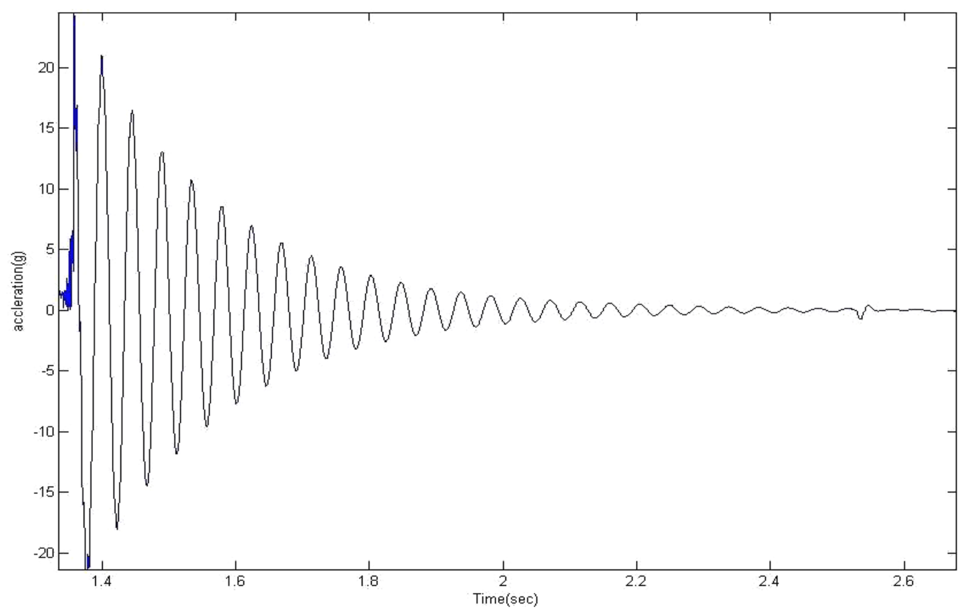


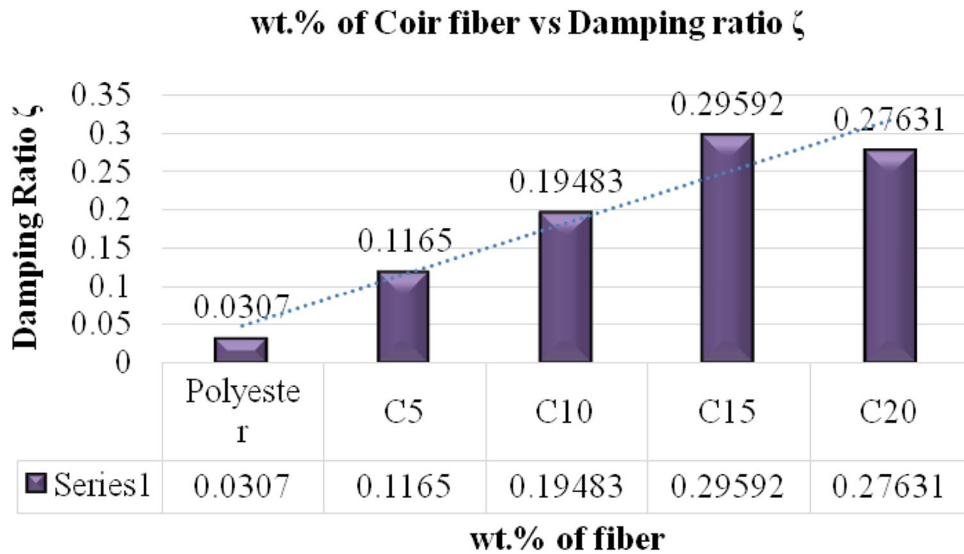
Fig. 17 Time vs. Acceleration graph for 20 wt.%. of coir fiber

$$ln\frac{4.799}{3.792} = \frac{2\pi\varepsilon}{\sqrt{1-\varepsilon^2}}$$

$$\varepsilon = 0.0307.$$

The study examined the damping ratio values of various composite materials, such as pure polyester resin and polyester resin reinforced with varied weight ratios of coir fibers. The damping ratio of the original polyester resin was determined to be 0.0307, as shown in Fig. 18. Adding coir fibers at concentrations of C5, C10, C15, and C20 enhanced the damping ratios to correspondingly 0.1165, 0.19483, 0.29592, and 0.27631. When incorporating C5 of coir fiber, the composite material reached a maximum damping ratio of 0.29592. Incorporating coir fibers in the composite materials led to a substantial enhancement in their damping characteristics, with the maximum improvement observed at a fiber loading of C15 before a slight decline at C20. The findings emphasize the potential of utilizing coir fiber to

Fig. 18 wt. % of Coir fibervs Damping ratios



augment the capacity of polyester composites in mitigating vibrations. This is particularly crucial in scenarios that cause vibration attenuation, such as aerospace or automobile structural elements.

Table 6 of the experiment demonstrated a notable link between the decay time and the inclusion of coir fiber in the composite materials. It was noted that the decay time reduced as the quantity of coir fiber incorporated into the mixture increased. The composite materials with a weight percentage of C15 coir fiber had the quickest deterioration time. By including coir fiber, the composite material experiences an improvement in its ability to dampen vibrations, leading to a faster dissipation of vibrational energy. Out of the analyzed compositions, the composite with a C15 coir fiber content showed the highest effectiveness in dampening. This discovery highlights the capacity of incorporating coir fiber reinforcement to enhance the dynamic response of polyester composites, specifically in scenarios where rapidly diminishing vibrations are crucial for optimal performance and structural integrity.

The damping mechanisms in coir fiber-reinforced polyester composites, specifically at a 15 wt.% concentration, the fibers improve viscoelastic damping capabilities by maximizing energy dissipation across these mechanisms. Using 15 wt.% provides optimal interface friction between fibers and polyester matrix, supporting maximum vibration energy dissipation. An increase in coir fiber content beyond 15 weight percent threatens the material performance through fiber aggregation and deteriorated fiber-matrix bonding. The decay rate increases with higher fiber content levels, demonstrating better damping performance. The damping performance decreases when the weight fraction reaches 20% because structural integrity suffers degradation.

4.4 Damping factor about constant material exhibiting variation in temperature and frequency

Studying the damping factor of natural fiber-based composites under varying temperature and frequency conditions is vital for understanding their vibrational behavior, optimizing material design, and ensuring performance stability in dynamic applications. This knowledge will enable engineers to tailor composites for specific environments, enhance durability, and promote their use as sustainable alternatives to synthetic materials.The evaluation of energy dissipation in a material under fiber loading is established by using the damping factor. The graphical representations provided in Figs. 19, 20, 21, 22, 23 portray the relationship between the damping factor and various proportions of coir fiber within

Table 6 Decay Time

S.No	Sample	Time(sec)
1	Pure polyester	3
2	5wt.% of fiber (C5)	2.6
3	10wt.% of fiber (C10)	1.3
4	15wt.% of fiber (C15)	1.1
5	20wt.% of fiber (C20)	2.4

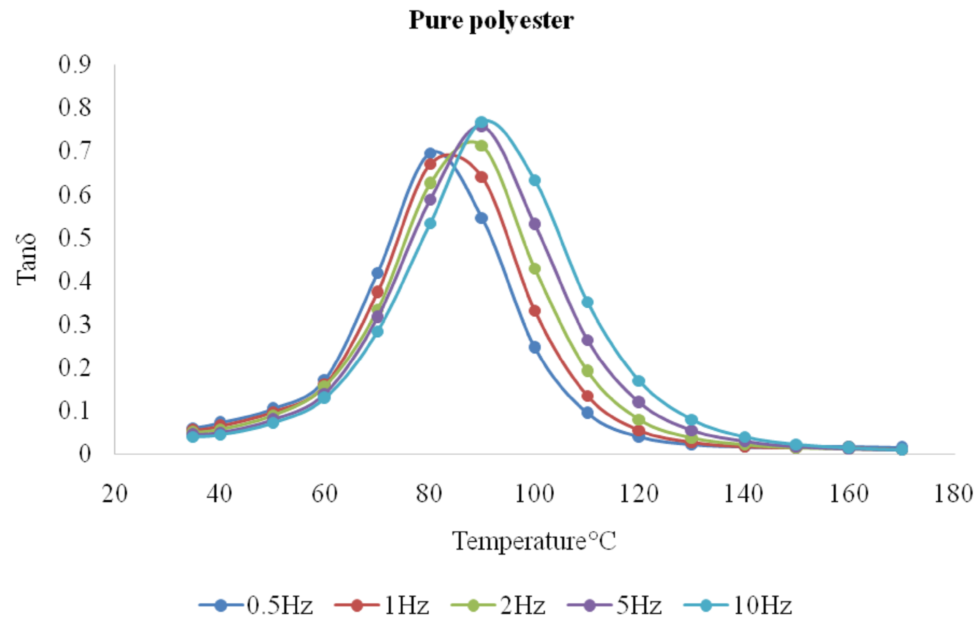


Fig. 19 Tan δ vs. Varied temperature and frequency with uniform material

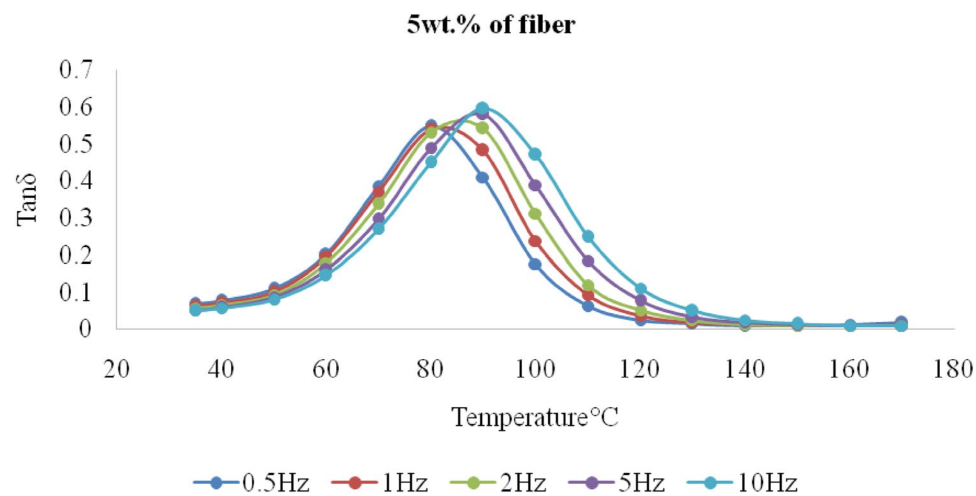


Fig. 20 Tan δ vs. Varying temperature &frequency with constant material

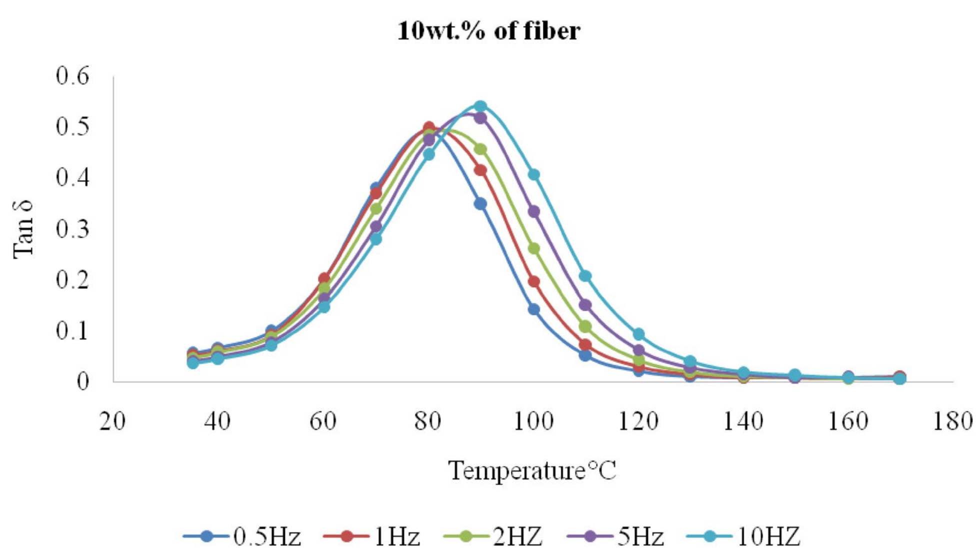


Fig. 21 Tan δ vs. Varying temperature &frequency with constant material

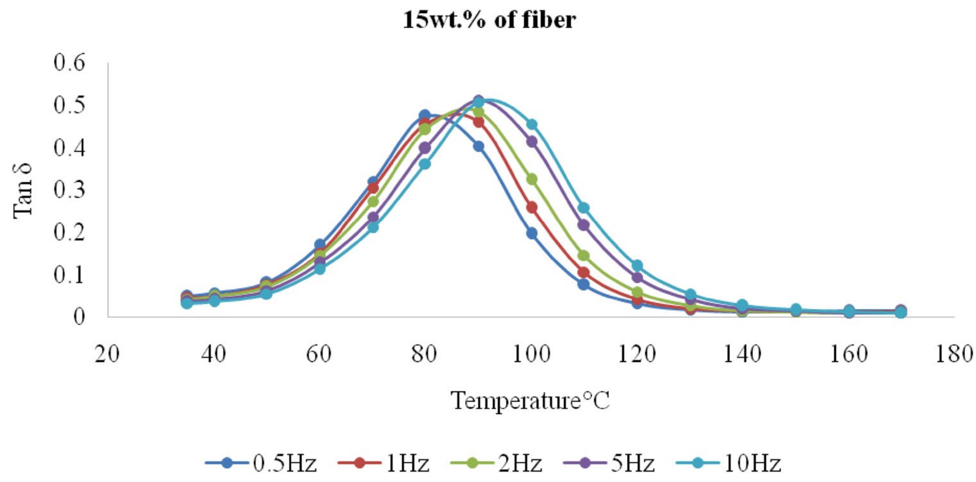


Fig. 22 Tan δ vs. Varying temperature &frequency with constant material

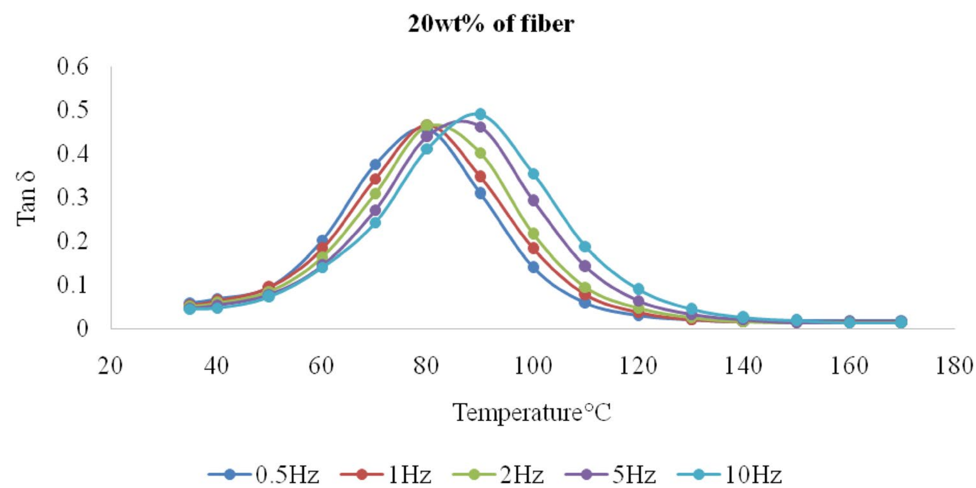


Fig. 23 Tan δ vs. Varying temperature &frequency with constant material

the polyester composite. The specimen undergoing controlled sinusoidal loading determines the glass transition temperature while the temperature gradually increases. The glass transition temperature is identified at the peak of the tan δ curve, where tan δ represents the ratio of loss modulus to storage modulus. The glass transition temperature (Tg) indicates the α-transition that takes place in amorphous polymers. The temperature at which energy dissipation peaks is identified at 85 °C. The amplitude of the peak of the loss factor acts as a gauge of the damping characteristics displayed by the material. A reduced value of the tan delta (δ) peak signifies an enhanced bond between the fiber and matrix, reducing molecular mobility and elevating the material's damping efficacy. Figure 19 illustrates the relationship between the damping factor and varying temperature and frequency while maintaining a constant material. The specimens comprising pure polyester composite material under study exhibit low damping factors at 1 Hz. The damping factors vary across different frequency levels for all fabricated specimens.

Figure 20 Illustration depicts the relationship between the damping factor and varying temperature and frequency while maintaining constant materials. The specimens under study, consisting of 5% coir composite material, exhibit low damping factors at the specified frequency of 1 Hz. It is observed that the damping factors vary across different frequency levels for all fabricated specimens. Figure 20 delineates the correlation between the damping factor and fluctuations in temperature and frequency while the materials remain constant. The specimens under examination, composed of 10% coir composite material, demonstrated diminished damping factors at the designated frequency of 1 Hz. The damping factors exhibit variability across the various frequency levels for all fabricated specimens

Figure 22 illustrates the correlation between the damping factor and fluctuations in temperature and frequency while sustaining constant materials, which is of significant interest in the field of materials science. The specimens under study, consisting of 15% coir composite material, exhibit low damping factors at the specified frequency of 1Hz. It is observed that the damping factors vary across different frequency levels for all fabricated specimens.

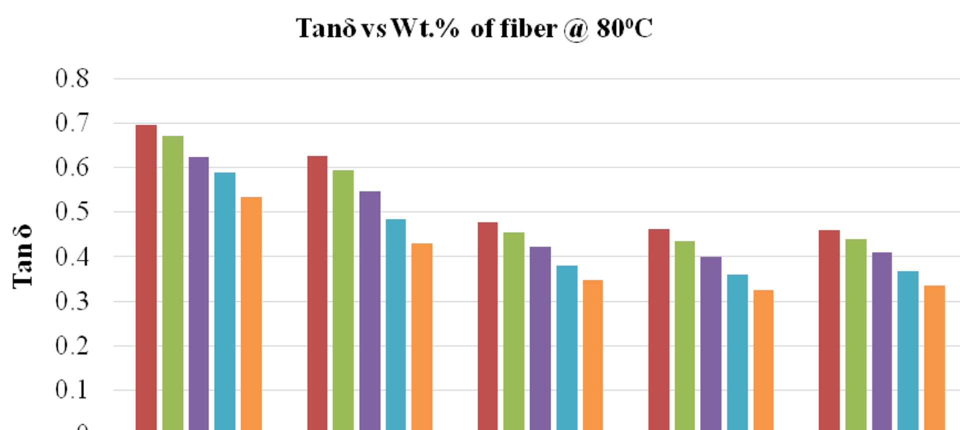
Figure 23 illustrates the relationship between the damping factor and varying temperature and frequency while maintaining constant materials. The specimens under study, consisting of 20% coir composite material, exhibit low damping factors at the specified frequency of 1 Hz. The damping factors vary across different frequency levels for all fabricated specimens.

Figure 24 illustrates the correlation between the damping coefficient and varying weight percentages of fibers while keeping thermal conditions constant and using different frequencies. The graph illustrates the damping coefficient values of various composite materials at a temperature of 80 ℃. To be more exact, the polyester resin exhibits a damping coefficient of 0.533 at a frequency of 10 Hz. Furthermore, the polyester resin samples with five wt. %, 10 wt. %, 15 wt. % and 20 wt. % of coir fiber exhibited respective damping coefficient values of 0.42828, 0.345414, 0.32457, and 0.334564. Incorporating 15 wt. % coir fiber significantly reduces the damping coefficient of the composite material, lowering it to 0.334564. Furthermore, natural fiber composites had a higher damping modulus than pure polyester at the glass transition temperature (Tg).

The glass transition temperature (Tg), as determined from the damping modulus, was lower than the value derived from the Tan δ curves. The elastic modulus (Eo) drop was evident across all scenarios when there was a temperature change. At the glass transition temperature (Tg), coir fiber composites exhibited higher Eo values than pure polyester. Modifications in the damping modulus exposed alterations in the glass transition temperature (Tg) of the polymer matrix induced by fiber reinforcement, underscoring the substantial influence of fibers on Tg. The coir composites exhibited the lowest peak intensity of Tan δ, while the polyester matrix showed the highest peak intensity. The anticipated analyses encourage the integration of coir fibers in manufacturing economically advanced hybrid composites that exhibit suitable rigidity, damping properties, and heat resistance.

4.5 Damping factor vs. different Wt. % of fiber with constant temperature varying frequency

The characteristics of the damping factor for natural fiber-based composites with different weight percentages of fiber under constant temperature and varying frequency are critical to optimizing the material's performance and ensuring sustainability for various dynamic applications. Studying the damping factor of natural fiber-based composites with varying fiber weight percentages under constant temperatures and varying frequencies is essential for optimizing their performance in dynamic environments. This analysis provides insights into how fiber content influences the material's ability to dissipate vibrational energy under different loading frequencies, which is crucial for achieving desired mechanical and vibrational properties. It helps identify the ideal fiber content for balancing energy dissipation and structural integrity,



	Polyester	C5	C10	C15	C20
0.5Hz	0.69631052	0.62519604	0.47593534	0.460501879	0.459685802
1Hz	0.67002213	0.592070222	0.452815294	0.433896631	0.438615173
2Hz	0.624166548	0.545508385	0.421233296	0.399334878	0.40905574
5Hz	0.588539243	0.482976377	0.379332393	0.358521938	0.367388606
10Hz	0.533121765	0.428280443	0.34541434	0.324570477	0.334564209

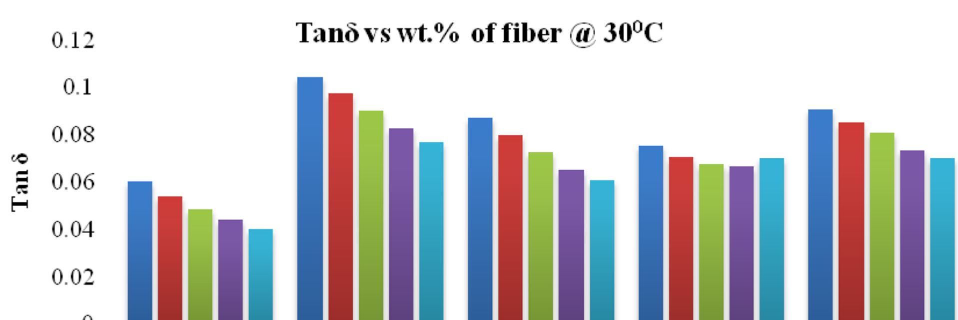
Different Wt.% of fiber

Fig. 24 Tan δ vs. Varying temperature at a constant frequency ensures compatibility with application-specific requirements, and supports the design of sustainable, lightweight, and high-performance materials. The damping factor serves as a quantitative measure for the dissipation of energy within the material during the loading of fibers. The relationship between the damping factor and different proportions of coir fiber in the polyester composite is depicted in the plots shown in Fig. 25. The glass transition temperature (Tg) represents the α-transition occurring in amorphous polymers. The peak energy dissipation occurs at a temperature of 30 °C. The magnitude of the loss factor peak function shows the damping properties of the material. A decrease in the value of the tan δpeak suggests an improved bond between the fiber and the matrix, reducing molecular mobility and enhancing the material's damping capacity.

Figure 25 illustrates the relationship between the damping factor and constant temperature at 30 °C while varying the frequency by 0.5 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, and 10 Hz. The samples were prepared to contain C15 coir, demonstrating low damping factors consistently at a constant temperature across different frequency levels for all samples generated. Natural fiber composites exhibited an increased viscous modulus compared to pure polyester above the glass transition temperature (Tg). The determination of Tg via the viscous modulus showed a lower value than that derived from Tan δ curves. A significant decrease in elastic modulus (Eo) was noted with changes in temperature under all conditions, with coir fiber composites presenting superior Eo values at the Tg when compared to pure polyester. Alterations in the viscous modulus corresponded to variations in the Tg of the polymer matrix influenced by fiber reinforcement, underscoring the impact of fibers on Tg. The peak value of Tan δ was minimal in coir composites and maximum in the polyester matrix. These investigations are expected to promote the integration of coir fibers in developing cost-effective advanced hybrid composites with appropriate stiffness, damping characteristics, and thermal resistance.

5 Microstructural analysis of coir and coir fiber composite materials

Figure 26 depicts scanning electron microscopy (SEM) images. Electron microscopy utilizes a focused electron beam to scrutinize the surface of the specimen, thereby helping the cohort of visual representations. The interaction between electrons and the atomic structure within the specimen engenders a variety of signals that provide valuable information regarding the surface topography and chemical composition of the specimen. Figure 26a illustrates that the inclusion of 5% of coir fiber content can cause a decrease in the tensile strength of materials to 56 MPa. Fibers, especially in composite materials, enhance strength by distributing stress and obstructing the spread of cracks. Reducing fiber content reduces the material's ability to resist tension, resulting in a loss in tensile strength. This phenomenon is evident in materials like reinforced plastics or concrete, where fibers enhance mechanical characteristics. When the coir fiber content is increased to 15% of coir, as shown in Fig. 26c, there is an increase in the tensile strength of materials to 73 MPa. Increasing the fiber content involves adding more of these strengthening components, enhancing the material's ability to withstand tensile stresses. As a result, this causes an



	Polyester	C5	C10	C15	C20
05Hz	0.060250785	0.104506038	0.087367117	0.07557065	0.090748072
1hz	0.054139704	0.09737508	0.079704851	0.07068187	0.085466392
2Hz	0.048440482	0.0903356	0.072579846	0.067624815	0.080830067
5Hz	0.04385997	0.0830459	0.065391049	0.066642821	0.073638327
10Hz	0.040227469	0.077013277	0.060896855	0.069855012	0.070242763

Fig. 25 Damping factor vs. constant temperature with varying frequency of 0.5 Hz, 1 Hz, 2 Hz, 5 Hz & 10 Hz

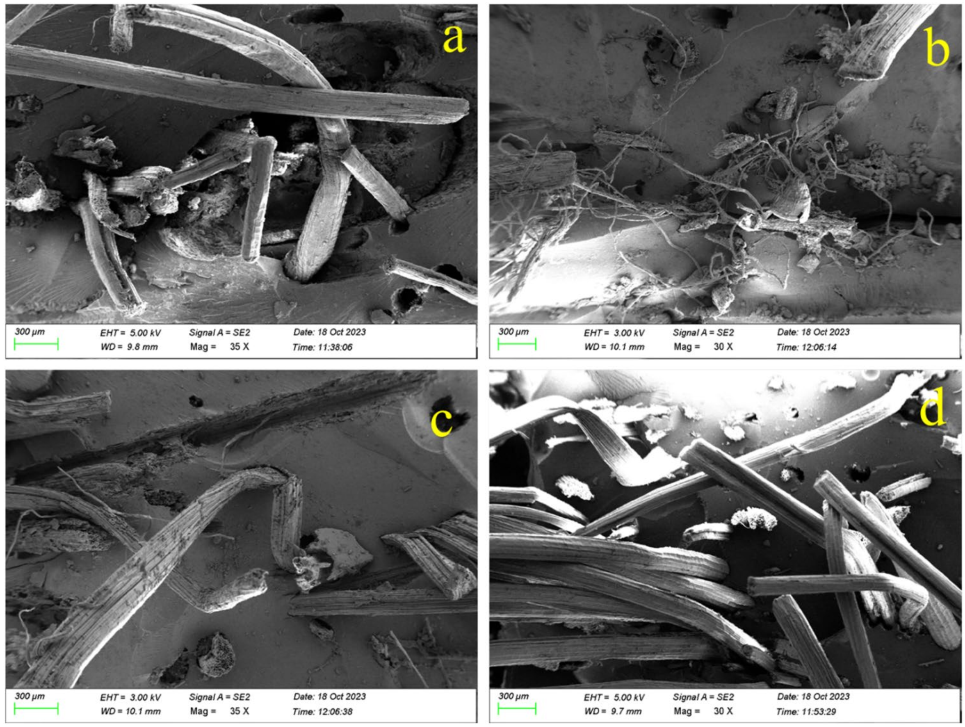


Fig. 26 SEM images of coir fiber at various tensile test conditions

increase in tensile strength because the fibers distribute stress more effectively and prevent cracks from spreading. Adjusting fiber composition to achieve specific mechanical qualities, such as tensile strength, is a common strategy in producing composite materials.

The 15 wt.% composites prove the suitability characteristics that can be used in many industrial applications; the following applications are lesser than the 15 wt.% coir composites material. Currently, the automotive interior components withstand 73 MPa tensile strength along with a 0.29592 damping ratio; in marine vehicles, for cabin interiors and storage boxes, water moderately (3.4%) yet reduces vibrations from engines and waves. In construction, the vibration-damping properties of materials, mainly acoustic ceiling tiles, partition walls, and flooring underlayment, significantly reduce sound transmission between spaces while providing adequate mechanical support.

6 Conclusions

This research investigated the impact of the coir fiber weight percentage with the polyester for the damping characteristics and mechanical properties; it contributes to the sustainable development of natural fiber composites.

- The damping and natural frequency studies confirm a significant correlation between the weight percentage of fiber content, material properties, and vibrational behavior; the composite can meet the industrial requirements.
- The polyester composite material with the addition of 15 wt. % coir fiber optimally performs very well in all the characteristics,i.e., tensile strength, flexural strength, hardness, impact strength, natural frequency, and damping characteristics study.
- The polyester composite with a 15% coir fiber content revealed the highest natural frequency, measuring 61862 Hz. This shows that it has improved rigidity and the ability to sustain loads. The coir fiber with 15 wt. % polyester composite yieldsagood damping ratio (ζ) of 0.29592 and decay time composite, recording a minimum value of 1.1.
- When 15 wt. % of coir fiber is present, the damping factor (tan δ) value is significantly low, measuring 0.360 at 10 Hz. The polyester with 15 wt. % of coir fiber compositematerial conformsto apromisingcombination for better mechanical properties and damping characteristics.

7 Limitations of the research work

1. This research used 10 mm length choppedfibers; no specific orientation pattern was followed.
2. This study utilized raw fibers; however, the result of alkali-treated fiber, which may influence it, may improve.
3. The weight percentage of fibers was limited to four equal intervals of 5%, ranging from 5 to 20%.
4. The composite material was prepared using polyester resin. However, varying resins (e.g., bisphenol or epoxy) can influence and may affect the final properties of the composite.

Author contributions K.V. Nikhil: Contributes to conceptualization, methodology, formal analysis S. Ramasubramanian: Contribute to original draft, data curation and analysis Avinash Gudimetla: Contributed to creation of figures and Tables, and validation. Gunti Amarnath: Formal analysis, methodology and final review. G. Sathishkumar: Contributed to writing—review & editing. R. Pugazhenthi: Conducting experiments and their explanation. Mithilesh K. Dikshit: Supervision, data analysis and final writing Vimal Kumar Pathak: Original draft, methodology, final editing.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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