INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 06-09-2023

Accepted: 07-12-2023

Published: 12-01-2024

Citation: Sohail MK, Reddy CN, Kumar JS (2024) Vibrational Characteristics of Jute-Banana Hybrid Composites with Effect of Alkali Treatment and PLA Coating. Indian Journal of Science and Technology 17(1): 80-89. https://doi.org/10.17485/IJST/v17i1.2271

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Vibrational Characteristics of Jute-Banana Hybrid Composites with Effect of Alkali Treatment and PLA Coating

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Abstract

Objectives: To investigate the vibration characteristics of jute-banana fiber-reinforced hybrid composites by exploring the influence of surface pre-treatment with sodium hydroxide (NaOH) and coating with Polylactic acid (PLA) using Finite Element Analysis (FEA). **Methods:** Natural fiber reinforced composites (NFRC) have advantages over man-made fibers such as glass, carbon, and Kevlar. However, the hydrophilic characteristic of natural fiber results in poor adherence between fiber and matrix. This reduces the characteristics of the polymer composite. Before constructing the composite laminates, jute and banana fibers are coated with NaOH and Polylactic acid. Experimental vibration and Finite Element Analysis method is adopted to predict the natural frequencies under various end conditions, including Simply Supported (SS), Clamped (CC), and Clamped-Free (CF). Furthermore, it explores the influence of ply orientations on natural frequencies under SS and CC conditions. **Findings:** According to the results of the experiments and FEA, chemical treatment and coating increase the free vibration characteristics of composites by improving the interfacial connection between the fiber and the matrix. The experimental and FEA results are compared, revealing that fiber treatment and coating increase vibration qualities. Specifically, during the experimental study, the NaOH-treated and PLA-coated composites showed a 24.08% increase in natural frequency. Ansys data also showed significant increases of 6.57%, 8.1%, and 26.77% under SS, CC, and CF conditions compared to other specimens. **Novelty:** In this work, woven jute and banana fibers were subjected to eco-friendly and chemical treatment NaOH and PLA coating in order to improve the adhesion with the matrix thereby improving the performances of their composites. The present developed composites can be used for medium-strength applications in the field of automobile, construction and packaging.

Keywords: Jute and Banana Composites; NFRC; Free Vibration; Polylactic Acid Coating; NaOH treatment

1 Introduction

Natural fibers, noted for their eco-friendliness and non-toxicity [1], encompass resources like flax, jute, banana, hemp, sisal, and coconut, offering sustainable and cost-effective alternatives [2]. They serve as robust reinforcements in thermoplastic materials, finding applications in diverse industries such as packaging, construction, marine, automotive, and aerospace [3]. These fibers contribute to a safer and more sustainable environment, outshining synthetic counterparts. Cotton, flax, hemp, sisal, jute, bamboo, and wool are key players in textiles, construction, and composite materials. [4,5]

While natural fibers bring commendable benefits like biodegradability and renewability, they grapple with limitations including moisture absorption, low thermal stability, unpredictable properties, and compatibility issues with other materials. To mitigate these challenges, surface modifications, employing chemical, physical, and enzymatic methods, are adopted. This enhances the bonding between fibers and matrices, resulting in improved properties like water resistance, thermal stability, and mechanical strength [6]. This study employs the finite element method (FEM) to investigate the free vibration characteristics of hybrid jute composite beams. Experimental vibration analysis was conducted on these beams, specifically under cantilever end conditions, to predict natural frequencies. Additionally, the research delves into assessing how factors like stacking order, end condition, and ply orientation influence the vibration and bending properties of hybrid jute composite beams. This comprehensive analysis sheds light on the dynamic behavior and structural performance of these composite materials. [7]

The study's findings unveiled a noteworthy trend as the fiber loading was increased, the damping ratio decreased, while the natural frequency increased. These observed changes strongly suggest a modification in the viscoelastic behavior of the composite matrix. This phenomenon underscores the complex interplay between fiber content and the composite's dynamic properties, offering valuable insights into how material composition influences damping characteristics and natural frequencies in structural applications [8]. A detailed examination was carried out on jute/PLA (Polylactic Acid) composites. Their observations indicated that the application of alkaline treatment had contrasting effects on the composite's mechanical properties. Specifically, it was found that alkaline treatment led to a decrease in composite strength, while concurrently increasing the modulus. These effects were attributed to alterations in the composition of hemicellulose and lignin within the jute fibers. These findings shed light on the intricate relationship between fiber treatment processes and the resulting mechanical characteristics of biocomposite materials, providing valuable insights for the optimization of jute/PLA composites for various applications [9]. Discoveries regarding the impact of alkali treatment on banana fibers. They observed that this treatment process resulted in the removal of small molecular components from the fibers, which in turn, led to a decrease in stability while enhancing the crystallinity of cellulose within the banana fibers. Furthermore, the study revealed that silane coupling agents proved to be more effective in improving the compatibility between the banana fibers (BF) and the PLA (Polylactic Acid) matrix in composite materials. These findings underscore the importance of fiber treatment techniques and the role of coupling agents in optimizing the performance of PLA/BF composites, offering valuable insights for their application [10].

It concludes that the limitations of natural fibers have been notably mitigated, leading to enhanced properties through diverse surface modification techniques. Chemical treatments and eco-friendly approaches have proven effective in augmenting the properties of both the natural fibers and their resulting composites. This underscores the potential for further advancements in surface modification methodologies to unlock even greater potential in natural fiber-based materials. Importantly, hybridizing composites with other fibers has significantly increased both natural frequencies.

In the present work, woven jute and banana fibers were subjected to eco-friendly and chemical treatment NaOH and PLA coating in order to improve the adhesion with the matrix thereby improving the performances of their composites. The present developed composite laminates can be used for medium-strength applications in the field of automobile, construction and packaging. Experimental vibration and finite element analysis (Ansys 2022 R1) were conducted to determine the natural frequencies of developed composites and measure the impact of treatment and coating on these frequencies.

2 Methodology

2.1 Materials

In this study, reinforcing fibers were sourced from Vruksha Composites, India, including jute woven fabric and banana woven fabric. The density of jute fiber is approximately 1200 kg/m^3, while banana weave-type density is around 1350 kg/m^3. The matrix system used consists of epoxy resin Bisphenol A diglycidyl ether (L12) and hardener Triethylene tetramine (K6), which were procured from Alide Engineering Services, India. To make the fibers eco-friendly, they underwent treatment with a NaOH solution, and a PLA coating was applied [(11)].

2.2 Preparation of composite laminates

The fiber treatment process involves immersing them in a 2% NaOH solution at 30°C for four hours. After several washes with running water to remove NaOH residues, the fibers are submerged in a mild HCl solution. Following a final rinse with water, the fibers are dried in a 70°C hot air oven for 24 hours [(12)].

To coat the fibers with a 2% PLA solution, PLA particles are initially placed in a chloroform solution for 8 hours. The solution is then heated to 60°C to ensure even dispersion of Polylactic acid. Jute and banana fibers are soaked in this solution for 5 minutes and subsequently dried in a hot air oven at 60°C for 4 hours, following a 24-hour drying period at ambient temperature [(13)].

A composite is created using hybrid laminates consisting of jute and banana fibers [(14)], along with an epoxy resin matrix. This is achieved using a cold press hand lay-up technique at an ambient temperature of 30°C. The laminates are stacked symmetrically with five layers of woven fiber for individual jute and banana fiber matrices as shown in Figure 1. Epoxy mixture is evenly applied from the first layer to the last. For the hybrid composite, a jute-to-banana fiber ratio of 2:5 is maintained [(15)], with variations in treatment and stacking sequences as indicated in Figure 2 and Table 1. The arrangement of laminates and ply orientations is adjusted accordingly.

Table 1. Stacking sequence of laminates

Sr. No	Laminate code	NaoH Treated	PLA coated	Stacking sequence
1	J1	-	-	J+J+J+J+J
2	B1	-	-	B+B+B+B+B
3	JB1	2%	-	J+B+J+B+J
4	JB2	-	2%	J+B+J+B+J
5	JB3	2%	2%	J+B+J+B+J

2.3 Vibration analysis

2.3.1 Experimental vibrational testing

The final composite laminates were precisely cut to dimensions of 200 mm x 20 mm with a thickness of approximately 3 mm. For free vibration testing in Figure 3, you can see the free vibration test setup, which employs an impact hammer for modal analysis. This setup includes a steel fixture that securely holds the specimen in place, along with an impulse hammer featuring a sharp tip (model 9722A2000).

On the top surface of the specimen, an accelerometer from PCB electronics is securely mounted to the edge of the rectangular composite laminate beam [(16)]. To capture and analyze the data, the displacement signals from the hammer and accelerometer are recorded on a computer equipped with Dewesoft software [(17)]. This computer is connected to an NI 8-channel data acquisition system (DAQ).

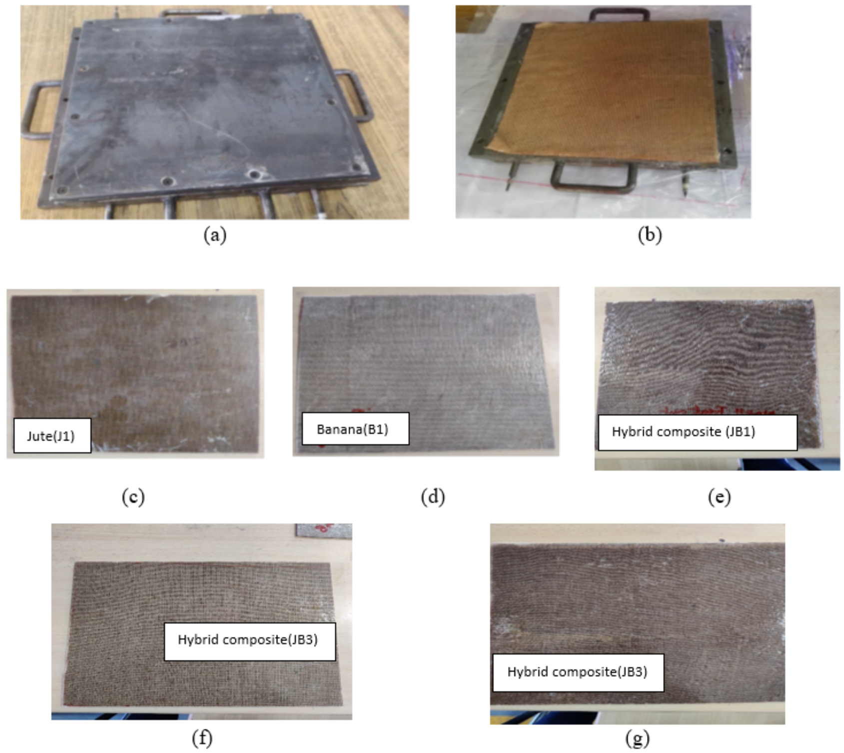

Fig 1. (a) Composite Lamination preparation mould, (b) Fabrication of composite laminate, (c) Jute fiber reinforced laminate (J1), (d) Banana fiber reinforced laminate (B1), (e) Hybrid Jute/Banana NaOH treated fiber laminate (JB1), (f) Hybrid Jute/Banana PLA coated fiber laminate (JB2), (g) Hybrid Jute/Banana NaOH treated and PLA coated fiber laminate (JB3)

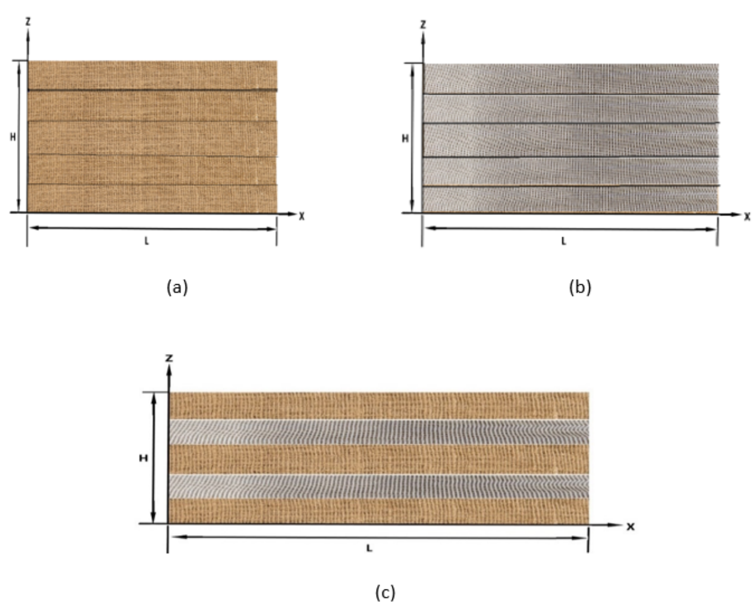

Fig 2. Stacking sequence of laminates (a) Pure jute composite laminate, (b) Pure banana composite laminate, (c) Hybrid Jute/banana composite laminate

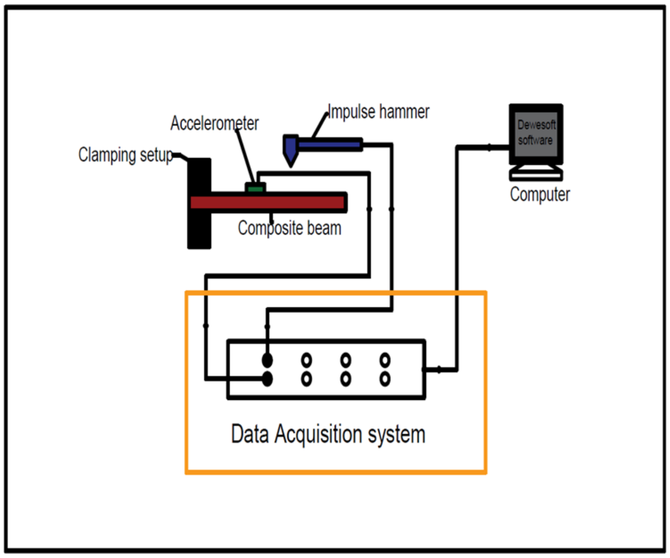

Fig 3. Schematic diagram of vibration test setup

2.3.2 Finite element analysis

In the virtual creation of the composite plate, ANSYS software was employed systematically. The plate was designed with dimensions of 200 x 20 mm and a thickness of 3 mm, comprising five layers of fiber. The ANSYS 2022 R1 interface proved to be user-friendly for this process. The initial step involved modeling the component without specifying specific units.

Table 2 provided all the necessary material data, which were input into the ANSYS Workbench Engineering Data module. These values were determined through calculations using the modified mixing procedure[18].

After inputting the material data, the specimen geometry was drafted using the Design Modeler and subsequently meshed in ANSYS Mechanical. The mesh size, ranging from 1 to 5 mm, was determined based on the specimen's geometry. C3D8R elements were used to assign mesh to each section, with a global mesh size of 5 mm. Mesh sensitivity was ensured by adjusting mesh density and thickness in the plane.

Once the meshing was completed, the model was exported to ANSYS ACP-Pre[19] for tasks such as modeling, material assignment, ply orientation, and layer stacking, as depicted in Figure 3. Each layer of the composite model was assigned unique properties, including fiber orientation and stacking sequence, resulting in a 3 mm thick solid composite model.

The meshed solid composite model was then converted to ANSYS for modal analysis using the APDL solver. Loads and boundary conditions were applied. According to the literature, boundary conditions were selected from the mechanical category's load section. Symmetric/asymmetric/encaster options were chosen accordingly, with CC, CF, and SS boundary conditions provided for each case. CF clamped one end of the specimen, CC clamped all edges, and SS freed the Ux, Uy, Rx, and Ry of the specimen.

Table 2. Material data of natural jute and banana fiber composite

Jute fiber	Banana fiber
E_{12}= 5.21 Gpa	E_{12}= 3.48 Gpa
E_{22}= 4.70 Gpa	E_{22}= 2.96 Gpa
$\nu_{12} = 0.15$	$\nu_{12} = 0.25$
G_{12} = 1.81 Gpa	G_{12} = 2.19 Gpa
ρ = 1198 Kg/m^3	ρ = 1358 Kg/m^3

The study utilized the Finite Element (FE) approach to analyze the vibration behavior of a hybrid jute composite beam. It researched to investigate how the composite beam's parameters responded to different loading conditions (CC, CF, and SS) while considering factors such as boundary conditions, stacking sequence, and ply-orientation[20].

3 Results and Discussion

3.1 Experimental vibration behavior

Table 3 presents the experimental natural frequencies of pure jute, pure banana, and hybrid jute/banana composites under the CF boundary condition, where one side is clamped, and the other three ends are free. It's marked that hybrid JB3 composite beams exhibit 34.37%, 29.48%, 14.74% and 23.66% higher natural frequencies than the neat jute (J1) and banana (B1) composites, as well as NaOH-treated hybrid JB1 and PLA coated hybrid JB2 composites.

Table 3. Experimental Natural Frequency of Hybrid Jute/banana Composite Beams

Laminate	Experimental Natural frequency (Hz.)					
	1	2	3	4	5	6
J1	14.91	30.12	90.18	98.67	119.63	187.32
B1	16.021	31.134	91.87	107.97	134.65	201.48
JB1	25.375	46.0555	103.259	120.793	158.041	220.906
JB2	22.719	37.8615	99.953	115.232	144.473	213.36
JB3	29.7621	44.2376	116.402	125.686	162.14	228.942

The fundamental frequency of JB1 is 10.46% superior to JB2, primarily because JB1 underwent treatment with NaOH, whereas JB2 was only coated with PLA. Where JB3 is 14.74% and 23.66% higher than JB1 and JB2. This suggests that the combination of NaOH treatment and PLA coating enhances the stiffness of hybrid jute/banana-reinforced composite beams.

3.2 Simulation vibration behavior

Table 4 illustrates how different end conditions impact the natural frequencies of jute, banana, and hybrid jute/banana composite beams. These conditions include simply supported-simply supported (SS), clamped-clamped (CC), and clamped-free (CF). The natural frequencies of hybrid jute/banana composites (JB1 and JB3) are 11.23%, 8.1% and 6.4% higher than those of neat jute (J1), banana (B1), and hybrid JB2 composites across various end conditions. Specifically, under CC conditions, the initial frequencies of the hybrid jute/banana JB3 composite beams surpass those of the J1, B1, JB1 and JB2 composite beams. The inclusion of banana fibers enhances the stiffness of the hybrid beams, while the addition of stronger fibers improves the dynamic characteristics of composites. It appears that Prasad and Maneengam[7] observed a comparable pattern of vibration behavior in jute fiber-reinforced composite beams. The banana fiber-reinforced hybrid jute composite contributes additional rigidity, leading to higher natural frequencies. Interestingly, the natural frequency of the hybrid JB2 composite beam is slightly higher than that of the pure B1 composite beam. This is due to the interaction between the composite's bulk and the stiffness of the PLA coating, which reduces the overall stiffness of the beam. Furthermore, the CF and CC end conditions result in the lowest and highest natural frequencies for hybrid jute composite beams. This is because the CC end condition maximizes the rigidity of the hybrid JB3 composite backing (Figure 3).

Table 4. Natural Frequency of Hybrid Jute/Banana Composite Beams under Various End Conditions

End conditions	Mode	Simulated (Ansys) Natural Frequencies (Hz)				
		J1	B1	JB1	JB2	JB3
SS	1	69.979	70.872	74.132	71.922	75.053
	2	161	166.95	165.5	164.05	171.03
	3	197.99	198.29	216.77	202.12	217.68
	4	279.67	283.23	296.22	285.25	299.89
	5	319.73	334.74	326.8	329.74	341.66
	6	417.13	417.56	434.26	429.46	435.99
CC	1	134.45	136.76	144.3	137.06	146.5
	2	246.29	249.71	255.29	251.79	264.51
	3	301.65	302.68	331.37	326.62	332.4
	4	394.53	400.57	420.96	413.41	426.9
	5	431.33	451.75	442.37	459.15	462.44
	6	561.51	562.01	586.46	573.61	602.16
CF	1	15.606	17.393	22.53	20.829	26.7691

Continued on next page

Table 4 continued

2	31.312	32.629	39.0215	36.6615	41.6176
3	89.28	94.738	101.069	98.253	113.692
4	98.462	109.47	121.849	115.632	124.366
5	123.09	132.56	155.261	140.973	163.57
6	193.62	203.53	216.876	210.96	224.852

Table 5 provides a comparison between the experimental and simulated natural frequencies under the CF end condition. It highlights the differences in the natural frequencies obtained through experimentation and simulation using Ansys. This comparison allows for an assessment of the accuracy and agreement between the two sets of data, shedding light on the reliability of the simulation results in replicating real-world behavior.

The comparison between experimental and numerical (Ansys) natural frequencies reveals that both sets of data are nearly equal to each other under CF boundary conditions for all composite laminates, indicating good agreement between the experimental and simulated results.

Table 5. Comparison of experimental and FE natural frequency (Hz) of different composite beams

Laminate	Analysis	Natural frequency (Hz.)					
		1	2	3	4	5	6
	Present experimental	14.91	30.12	90.18	98.67	119.63	187.32
J1	Present simulation	15.606	31.312	89.28	98.462	123.09	193.62
	% Difference	4.45	3.80	0.998	0.21	2.81	3.25
	Present experimental	16.021	31.134	91.87	107.97	134.65	201.48
B1	Present simulation	17.393	32.629	94.738	109.47	132.56	203.53
	% Difference	7.88	4.58	3.02	1.37	1.55	1.07
	Present experimental	25.375	46.0555	103.259	120.793	158.041	220.906
JB1	Present simulation	22.53	39.0215	101.069	121.849	155.261	216.876
	% Difference	11.21	15.27	2.120	0.87	1.75	1.82
	Present experimental	22.719	37.8615	99.953	115.232	144.473	213.36
JB2	Present simulation	20.829	36.6615	98.253	115.632	140.973	210.96
	% Difference	8.319	3.169	1.71	0.34	2.42	1.12
	Present experimental	29.7621	44.2376	116.402	125.686	162.14	228.942
JB3	Present simulation	26.7691	41.6176	113.692	124.366	163.57	224.852
	% Difference	10.05	5.92	2.32	1.050	0.88	1.78

3.3 Effect of ply orientation on vibration behavior

Tables 6 and 7 demonstrate the effects of ply orientation on the vibration behavior of hybrid natural fiber composite beams under simply supported (SS) and clamped-clamped (CC) end conditions. Simulations were conducted with various ply orientations (0°, 30°, 60°, and 90°), and the results are presented in the tables.

Under SS conditions, hybrid composite beams with ply angles of 0°, 30°, 60°, and 90° exhibited lower natural frequencies compared to hybrid jute composite beams with the same ply angles under CC conditions. Specifically, the jute composite beam (J1) with a 0° ply orientation had 13.42%, 14.13% and 11.75% higher fundamental frequency than the J1 composite beam with ply orientations of 30°, 60°, and 90°. Furthermore, under CC conditions, the fundamental frequencies of hybrid JB3 beams with a 0° ply orientation exceeded 21.37%, 23.87% and 19.68% higher than those of hybrid JB3 beams with ply orientations of 30°, 60°, and 90°. This is because when all layers are oriented in the 0° direction, the hybrid composite beam attains maximum rigidity along the fiber direction. Finally, the impact of ply orientation on the vibration behavior of hybrid jute composites varies significantly, with specific orientations leading to different natural frequencies under different end conditions.

Table 6. Effect on ply orientation on the natural frequency of hybrid jute/banana composite structures under SS end condition

Ply-orientation	Mode	Natural frequencies (Hz) Stacking sequences				
		J1	B1	JB1	JB2	JB3
0°	1	69.971	70.872	74.132	72.37	75.053
	2	161	166.95	165.5	164.25	171.03
	3	197.99	198.29	216.77	204.36	217.68
	4	279.67	283.23	296.22	291.21	299.89
	5	319.73	334.74	326.8	324.69	341.66
	6	417.13	417.56	434.26	419.85	431.99
30°	1	74.051	73.009	75.735	74.918	80.783
	2	170.33	113.2	175.93	156.16	183.54
	3	193.12	144.53	195.09	180.62	211.27
	4	290.02	220.08	298.38	231.98	314.54
	5	339.54	264.28	349.15	341.19	365.07
	6	387.72	311.39	390.38	388.37	423.94
60°	1	74.052	79.087	81.735	79.82	83.942
	2	170.03	177.59	181.63	178.28	184.07
	3	193.48	209.62	213.45	211.95	215.78
	4	290.02	305.55	313.38	307.15	314.36
	5	339.54	355.84	363.15	361.2	366.07
	6	387.71	401.16	417.38	408.88	428.87
90°	1	69.979	70.871	74.232	72.36	77.758
	2	160.64	165.13	166.57	165.965	165.88
	3	198.47	198.77	217.31	206.54	216.27
	4	279.67	283.23	296.22	287.69	285.61
	5	319.72	326.8	334.74	325.76	343.44
	6	403.92	411.14	417.56	416.17	421.64

Table 7. Effect on ply orientation on the natural frequency of hybrid Jute/banana composite structures under CC end condition

Ply-orientation	Mode	Natural Frequencies (Hz) Stacking sequences				
		J1	B1	JB1	JB2	JB3
0°	1	134.45	136.76	144.3	138.98	146.5
	2	246.29	255.71	255.29	256.13	264.51
	3	301.65	302.68	331.37	322.81	332.4
	4	394.53	400.57	420.96	418.75	426.9
	5	431.33	433.75	442.37	451.25	462.44
	6	561.51	562.01	586.46	573.31	602.16
30°	1	132.38	134.88	141.1	138.21	143.62
	2	252.55	260.18	263.79	261.91	271.46
	3	285	287.56	308.25	228.52	310.93
	4	394.03	404.15	415.4	411.04	426.35
	5	450.4	462.93	471.34	469.34	483.32
	6	515.3	518.5	559.11	534.11	562.5
60°	1	131.38	133.88	140.01	139.24	143.47
	2	253.55	250.18	253.79	259.97	261.46
	3	282.7	285.66	302.25	291.05	308.93
	4	391.03	404.52	405.4	403.43	422.35
	5	448.4	460.39	472.41	468.43	481.32
	6	509.3	518.5	529.11	527.12	552.5
90°	1	134.25	136.58	143.31	141.03	140.6
	2	246.19	255.01	252.29	255.19	249.1
	3	303.65	303.68	330.77	323.73	319.15
	4	384.53	401.57	419.96	410.69	392.71
	5	431.73	449.75	440.37	462.44	456.45
	6	561.11	552.1	582.46	573.44	596.44

4 Conclusion

This experiment was done to analyze the vibrations of a jute-banana fiber-reinforced composite beam. This study concludes that jute-banana fiber is a very promising natural fiber that may certainly be utilized to strengthen composite constructions. In the current investigation, the experimental and finite element method (Ansys software) is utilized to calculate natural frequencies under various end conditions. The current approach of using natural fibers aids in sustainable development following environmental policies. The acquired findings are highly exact and demonstrate the current technique's good performance.

- Under the CF boundary condition, the experimental results indicate that the hybrid treated and coated composite JB3 beam has 53.29%, 36.32%, 11.61% and 33.17% higher natural frequency compared to J1, B1, JB1 and JB2.
- Ansys numerical analysis results reveal that under CC conditions, the JB3 composite beam exhibits a 30.65% higher natural frequency, while CF conditions show 43.58% lower natural frequencies. Similar trends are observed under SS end conditions.
- The comparison between natural frequencies obtained through Ansys and experimental results shows a close approximation, indicating good agreement between the two sets of data.
- The effect of ply orientation on the natural frequency of hybrid composite beams was investigated under SS and CC end conditions. It was found that the 0° ply orientation resulted in higher frequencies under both SS and CC conditions compared to different ply orientations.

Overall, NaOH treatment and PLA coating enhance the strength and stiffness of the jute-banana fiber-reinforced composites, according to the results. The future of study in this sector seems positive. Exploring optimal fiber compositions, diverse coating materials, and innovative alkali treatments can enhance composite properties. Additionally, investigating alternative fiber orientations and volume ratios offers potential for tailored designs, while assessing ecological impacts will contribute to the sustainability of natural fiber composites.

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