Examining several aspects of reinforced coir, sugarcane, and glass fiber hybrid composites with $CoFe_2O_4$ and $NiFe_2O_4$ fillers for structural uses

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Abstract. The mechanical and dielectric characteristics of coir and sugarcane fibers are investigated in this work using epoxy composites augmented with NiFe and CoFe metallic fillers. The strength, stiffness, and deformation behavior of four distinct compositions—C1-Coir with NiFe, C2-Coir with CoFe, S1-Sugarcane with NiFe, and S2-Sugarcane with CoFe—were assessed using tensile and flexural testing. With C1 showing the maximum strength of 160.215 N/mm² and S1 showing the highest tensile modulus of 2859.09 N/mm², indicating an improvement in stiffness, the results show that coir-based composites have higher tensile strength. These results demonstrate the promise of composites made of sugarcane and coir as sustainable substitutes for structural applications that need to balance stiffness and strength. More charge storage capacity is shown by a higher dielectric constant in CoFe GFRP (~2.03 pF). The Q factor of NiFe GFRP is much greater, at about 13.4. Their performance for industrial applications in lightweight structures and electromagnetic shielding could be improved by further optimizing fiber-metal interactions and resin composition.

1 Introduction

The demand for lightweight, superior performance, and versatile materials has led to extensive research on polymer-based composites reinforced with metallic fillers. Epoxy-based composites have gained significant attention due to their excellent mechanical properties, chemical resistance, and durability. However, the incorporation of suitable reinforcements is crucial to enhancing their structural performance for various industrial applications, including aerospace, automotive, and electromagnetic shielding.

Due to the biocompatibility natural fibers are gaining prominence. Certain fibers such as coir and sugarcane have gained significant attention in composite materials due to their low density, high specific strength, biodegradability, and cost-effectiveness. Silane, alkali, acetylation and fiber modification techniques are effective in reducing moisture absorption. Enhancing fiber–matrix interfacial bonding[1]. Incorporation of Sugarcane fibers into

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polymer matrices generally results in enhanced tensile and flexural properties. Factors such as fiber content, orientation, length, and the nature of the polymer matrix improves properties further [2]. NiFe with MWCNTs nanocomposites sample with a thickness of 2.00 mm exhibited −30.47 dB SE. and with a thickness of 5.00 mm exhibited a value of −17.39 dB.[3].

The $CoFe_2O_4$/MWCNT composite exhibited the best reflection loss (RL) performance in the X-band at a thickness of 2.18 mm, obtaining a RL of −54.29 dB [4]. $CoFe_2O_4$ nanoparticles possess good conductivity and capacitance, making them potential candidates for energy storage applications[5]. Fe_2O_3/NiO/Ni_2FeO_4 nanocomposites obtained higher magnetic characteristics where the magnetic properties were influenced by the composition and interaction between the constituent phases [6] $CoFe_2O_4$/$NiFe_2O_4$/carbon fiber-coated polypropylene (PP) obtained a reflection loss of −55 dB at 10.6 GHz, attributed to interfacial polarization and ferromagnetic resonance mechanisms [7].

Epoxy- reinforced with varied fibers and fillers got a wide applications, including automotive, aerospace, marine, and electromagnetic shielding. MZA Mahmud et al.[8] reported a tensile strengths of abaca fibers range from 12 MPa to pineapple fiber of 1627 MPa. Verma et al. (2012)[9] reported bagasse fibers when treated chemically shown improved adhesion with polymer matrices.

While previous studies explored the mechanical properties of natural fiber-reinforced composites, limited research has been conducted on hybrid composites incorporating natural and synthetic fibers with inorganic fillers in epoxy matrices. This study aims to address this gap by evaluating the combined effect of hybridization on mechanical and dielectric properties, providing structural performance insights and EMI shielding applications.

2 Experimental investigation

2.1 Composite preparation

The materials used for composite fabrication includes epoxy resin & hardener from Herenba industries Chennai., Coir Fiber & Sugarcane Fiber procured from local market Nickel-nitrate, Cobalt-nitrate, Ferric nitrate from CDH Delhi. Glass Fiber Marktech Bangalore. NiFe and CoFe prepared by the coprecipitation method. For synthesis of CoFe 0.5 M Cobalt nitrate and 1.0 M Ferric nitrate taken in abeaker. For synthesis of NiFe initially 291 mM of Ni(NO3)26H2O and 808 mM of Fe(NO3)39H2O taken in beaker and NaOH added to maintain pH 12. Further, the precipitates were washed and dried at 110oC for 12 h.[15].

The composite fabricated by hand lay-up technique. The steps involve initially properly sized coir and sugarcane fibers were dried at 80°C for 24 hours to remove moisture. They were then treated with 5% NaOH. The required amounts of natural fibers and metallic fillers were then gradually added to the epoxy. The epoxy resin and hardener were mixed in a 10:1 ratio. The mixture was stirred to achieve a homogeneous dispersion. This was poured into 12 GF ply of required dimensions. The samples were compressed under a uniform load to remove air bubbles and ensure proper fiber alignment. The composites were further cured in oven. The sample compositions is shown in Table 1.

Table 1. Sample compositions.

C1	epoxy 30g + hardner 3g + coir 0.5g + NiFe 0.5g
C2	epoxy 30g + hardner 3g + coir 0.5g + CoFe 0.5g
S1	epoxy 30g + hardner 3g + sugarcane 0.5g + NiFe 0.5g
S2	epoxy 30g + hardner 3g + sugarcane 0.5g + CoFe 0.5g

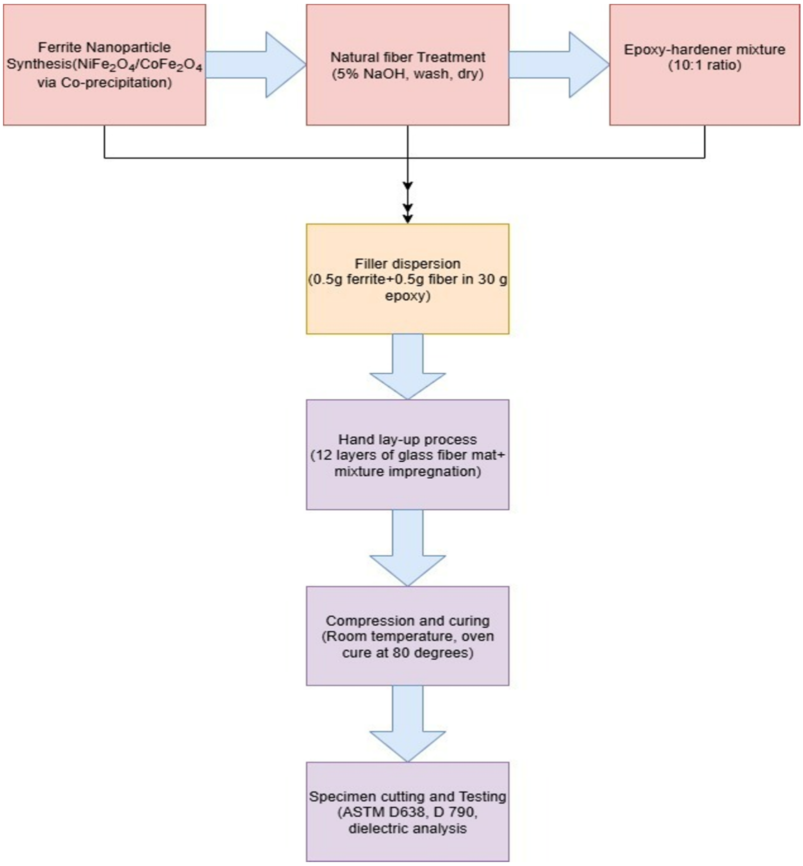

Fig. 1. Flowchart of composite fabrication procedure.

3 Characterization

3.1 XRD of natural fibers

The developed materials' microstructural characteristics, phase composition, and crystalline structure can all be ascertained using X-ray diffraction (XRD). XRD of natural fiber is shown in Figure 1. XRD is based on the Bragg's Law:

$$n\lambda=2d\sin\theta \tag{1}$$

where: n = Order of diffraction (usually 1), λ = X-ray Wavelength, d = crystal interplanar spacing, θ = Diffraction angle

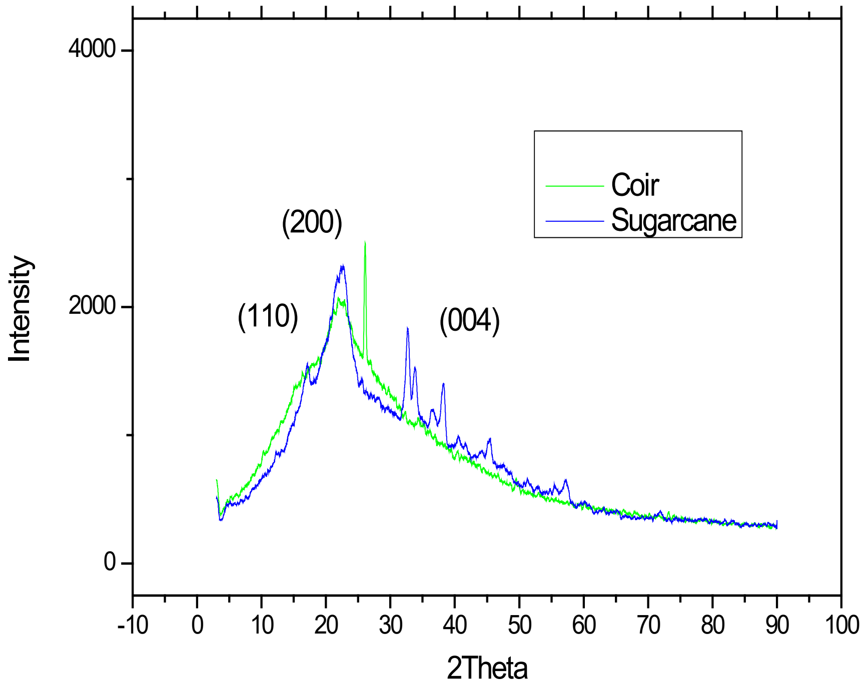

Fig. 2. XRD of coir and sugarcane fibers.

Figure 2 shows XRD that peaks matches with the JCPDS file 03-0289 for cellulose. Strongest peak near 2θ, 22.5° with (hkl) (200) confirms semi-crystalline structure

I_{002} (crystalline intensity) values represent the maximum peak intensity at ~22° 2θ, corresponding to the crystalline cellulose phase.

I_{am} (amorphous intensity) values represent the intensity at ~18° 2θ, which corresponds to the amorphous background in the XRD pattern. These values are used to estimate the degree of crystallinity.

Since higher Iam values indicate a greater amorphous phase, Coir fiber has the highest amorphous content, while Sugarcane fiber has the lowest.
Segal method is used for estimating the relative crystallinity of cellulose or fiber-reinforced composites

$$CI\ (\%) = (I_{002} - I_{am}) / I_{002} \times 100 \qquad (2)$$

Where, I_{002} is the maximum intensity at ~22° (crystalline peak), I_{am} is the minimum intensity at ~18° (amorphous region). Table 2 shows Fiber Crystallinity indices.

Table 2. Fiber crystallinity indices.

Fiber Type	**I002 (Crystalline Peak)**	**Iam (Amorphous Background)**	**Crystallinity Index CI%**
Coir	8874	4167	53.04% (lowest crystallinity)
Sugarcane	8887	1667	81.24% (Highest crystallinity)

Sugarcane fiber has the highest crystallinity (~81%), indicating a more ordered cellulose structure. Coir fiber has the lowest crystallinity (~53%), suggesting a higher amorphous content.

3.2 Mechanical test

Tensile and flexural test performed on Shimadzu agx plus 10kN. Tensile standard adopted as per ASTM D638-14, with a cross-head speed 1mm/min, Gauge length for tensile 30mm. Flexural standard as per ASTMD 790, with a cross-head speed of 2mm/min, Gauge length for flexural is 50mm. Figure 3 shows the Tensile testing set up & fractured specimens.

Fig. 3. Tensile testing set up & fractured specimens.

Flexural Test

Table 3. Flexural test specification.

Test Type	Speed	Shape	Size Unit	Thickness mm	Width mm	Lower Support mm
3 Point Bend	1mm/min	Plate	C1,C2,S1,S2	3	14	56

The specification of the Flexural test is shown by Table 3.

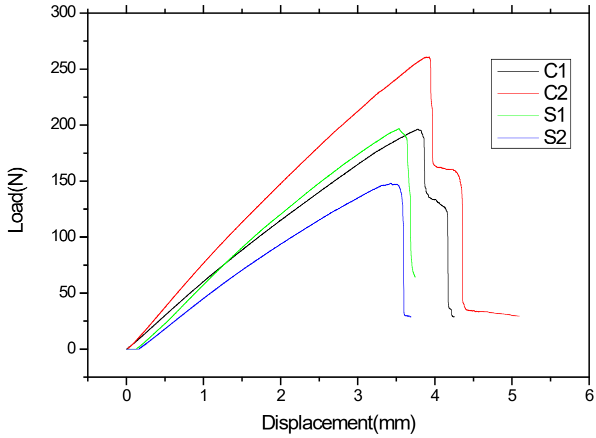

Fig. 4. Flexural load vs displacement graph.

Figure 4. Shows Load vs Displacement graph for various size units.

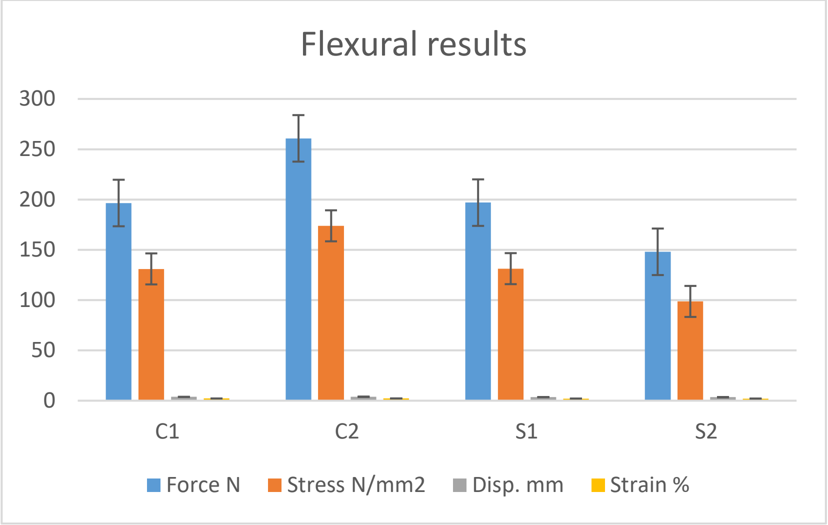

Fig. 5. Bar graph for force, stress, displacement and strain.

Figure 5 shows the comparisons of various samples in terms of force, stress, displacment and strain.

Table 4. Flexural test results.

Sample code	Force N	Stress N/mm^2	Disp. mm	Strain %
C1	196.525	131.017	3.78018	2.16974
C2	260.778	173.852	3.89350	2.23479
S1	196.899	131.266	3.53718	2.03027
S2	148.018	98.6788	3.43518	1.97172

Table 5. Flexural modulus values.

Sample	Flexural Modulus Ef (MPa)
C1	5431.59
C2	7001.47
S1	5821.62
S2	4504.08

Tables 4 and 5 show the flexural test results and Flexural modulus values. C2 obtained the highest flexural stress, strain, and modulus. This indicates strong interfacial bonding, consistent with the SEM images showing good matrix traces on fiber surfaces. Coir fibers work better with $CoFe_2O_4$, whereas sugarcane fibers pair better with $NiFe_2O_4$. The filler likely enhances interfacial adhesion through mechanical interlocking and possible chemical affinity with specific fiber surfaces.

Tensile Test

Table 6. Tensile test specification.

Test Mode	Test Type	Speed	Name	Thickness mm	Width mm	Gauge Length mm
Single	Tensile	1mm/min	C1, C2, S1, S2	2.6	13	60

Table 6 shows the test specification for the tensile test.

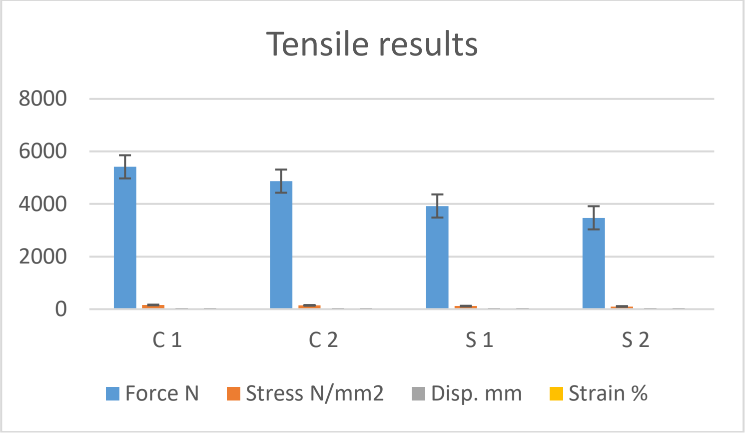

Fig. 6. Tensile results.

Figure 6 and Table 7 shows the tensile results of various specimens in terms of force, stress, displacement and strain%.

Table 7. Tensile test results.

Sample code	Force N	Stress N/mm^2	Disp. mm	Strain %	Time sec
C 1	5415.27	160.215	3.624	6.04	217.5
C 2	4870.99	144.112	3.32768	5.54612	199.72
S 1	3925.37	116.135	2.43718	4.06196	146.29
S 2	3476.03	102.841	2.44168	4.06946	146.56

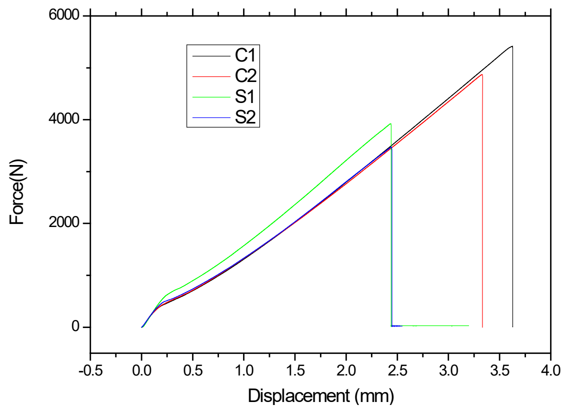

Fig. 7. Tensile force-displacement.

From the Force vs Displacement Graph Figure 7, For C1 gained highest force of ~5800 N), indicating strong tensile strength while C2 obtained ~5400 N, still shows good performance. For S1 lower peak force of ~4300 N, but a longer displacement indicating more ductility. For sample S2 got moderate peak of ~5000 N and highest displacement with an elongation capacity.

Sample S2 obtained highest strain of ~80%, indicating superior tensile behavior with good elasticity and strength. S1 has lower failure strain ~60% and fractures early. For C1 and C2 got relatively lower strain than S2 but high stress, indicating stiffer and stronger composites.

The calculated tensile modulus for each sample are shown in table 8.

Table 8. Tensile modulus values.

C1 (Coir + NiFe):	2652.57 N/mm^2
C2 (Coir + CoFe):	2598.43 N/mm^2
S1 (Sugarcane + NiFe):	2859.09 N/mm^2
S2 (Sugarcane + CoFe):	2527.14 N/mm^2

S1 has the highest modulus of 2859.09 N/mm^2, indicating it is the stiffest among the samples. S2 has the lowest modulus of 2527.14 N/mm^2, meaning it is the least stiff. C1 & C2 have moduli of 2652.57 N/mm^2 and 2598.43 N/mm^2, but slightly lower than S1.

Tensile and flexural qualities are improved by the greater toughness and improved stress distribution of coir fibers. Compared to sugarcane fibers, they have a higher lignin concentration, which improves the composite's overall strength and load-bearing capacity. Additionally, the coir fibers avoid premature failure by acting as efficient crack arrestors.

The increased cellulose content of sugarcane fibers results in improved stiffness, as evidenced by the higher tensile modulus of S1: 2859.09 N/mm^2. Their reduced weight improves interfacial bonding with the matrix by facilitating better resin impregnation.

NiFe has greater stiffness and hardness, which improves the composite's load transfer efficiency. Furthermore, the presence of these ferrite microparticles enhances resistance to the propagation of microcracks and improves stress distribution. This explains why the tensile strengths of C1-160.215 N/mm² and S1-116.135 N/mm² were higher than those of their CoFe equivalents. Although CoFe may be somewhat less stiff than NiFe, it does contribute to increased toughness. CoFe plays a part in altering the stress relaxation characteristics of the composite, resulting in a somewhat reduced strength compared to samples filled with NiFe.

S1 composites are more stiff because sugarcane fibers have a higher crystallinity index of 81.24%, which produces rigid, organized cellulose domains that resist deformation.

Coir fibers, with a lower crystallinity index of 53.04%, have more amorphous regions, allowing them to absorb energy under load and delay failure, which contributes to the higher tensile strength observed in C1. $NiFe_2O_4$ nanoparticles dispersed uniformly within the matrix can act as stress transfer points and reinforcement bridges between fibers and polymer. For C1, the combination of flexible coir fibers and well-dispersed $NiFe_2O_4$ enables efficient load sharing, enhancing tensile strength. For S1, the stiffer sugarcane fibers dominate the response, increasing the modulus, but the slightly lower ability to deform reduces ultimate tensile strength compared to coir composites.

Thus, selecting fibers with higher crystallinity enhances modulus and structural rigidity, whereas fibers with moderate crystallinity can improve energy absorption and tensile strength, depending on filler interaction and matrix compatibility. Table 9 shows the comparison of the results with previous literatures of natural fiber composites.

Table 9. Comparison of results with previous literatures of natural fiber composites.

Sl no.	Material used	Property improvement	Reference
1	Epoxy with Coir and luffa fiber $CaCO_3$ filler	fillers impart brittleness to the samples	Mohana Krishnudu, 2022[11]
2	LY536 resin with Hemp shell filler in 5 - 10 wt.%.	The tensile strength and ductility improved for the composites due to increased stiffness.	Jani, S. P., 2021 [12]
3	Salinized filler particles with kenaf fiber	An increase in tensile strength by 16% with a UTS of 51.69MPa and modulus of 4,281MPa.	Natrayan, L. 2022 [13]
4	Rice husk 40 wt.% as natural fiber with reinforcement coconut coir 10 wt.% composed of SiC 10 wt.% within epoxy 40 wt%.	Gained UTS of 81 MPa, flexural strength of 95 MPa.	Aredla, Rakshitha, et al 2024 [14]
5	$CoFe_2O_4$ & $NiFe_2O_4$ fillers reinforced Coir /Sugarcane/ glass fiber	Coir with NiFe / CoFe modulus of 2652.57 N/mm², 2598.43 N/mm² Sugarcane with NiFe/ CoFe modulus of 2859.09 N/mm², 2527.14 N/mm². UTS ranged from 100-160N/mm2	Current work

3.3 Dielectric impedance spectroscopy

It is to evaluate the capacitance, and dielectric constant, within a frequqncy range of 1000Hz to 1MHz, thereby to understand suitability of composite for high-capacitance, EMI shielding applications. The experimental setup primarily comprised a high-precision Hioki 3522-50 LCR meter, a Hioki 4-terminal probe (9140), a digital thermometer, and a humidity tester, all interfaced via RS-232 to a custom LabVIEW program running on a desktop data acquisition system.

Table 10. Dielectric results NiFe and CoFe Natural Fiber GFRP.

Sample	IMPEDENCE(Ω)	CAPACITANCE (Pf)	TANDELTA(D)	Q FACTOR(Q)
NiFe NF GFRP	3326619.2	1.39	0.309	13.39
CoFe NF GFRP	2666150.2	2.029	0.309	6.91

From Table 10 NiFe composites offer more resistance to AC current flow, potentially due to better interfacial bonding or lower conductivity pathways. Higher capacitance of CoFe NF GFRP (~2.03 pF) indicate more charge storage ability there by a higher dielectric constant in the same. Tan Delta of both got identical dielectric loss tangent values (~0.31), indicating similar energy dissipation behavior. NiFe NF GFRP has a significantly higher Q factor of ~13.4 indicating a lower dielectric losses and better efficiency in storing electric energy.

A higher dielectric constant that is appropriate for high-frequency absorption was produced by CoFe. NiFe has a lower loss rate and more effective energy storage. Better attenuation of low-frequency electromagnetic waves may result from NiFe's higher impedance.

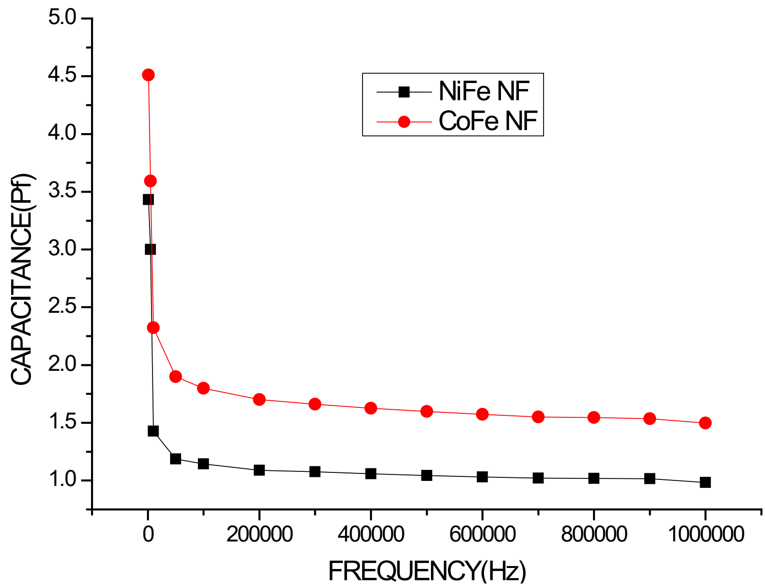

Fig. 8. Graphical representation of capacitance vs. frequency.

The capacitance (pF) change with frequency (Hz) for $NiFe_2O_4$-NF and $CoFe_2O_4$-NF is shown in Figure 8. Both composites show strong capacitance at low frequencies, which progressively drops as frequency increases. In comparison to the $NiFe_2O_4$-filled composite, the $CoFe_2O_4$-filled composite exhibits consistently higher capacitance across all frequency ranges.

The capacitance values for both samples appear to settle above about 200 kHz, suggesting less polarization effects. Strong Maxwell–Wagner interfacial polarization occurs at lower frequencies because the charge carriers have more time to align with the alternating electric field. As a result, there is more stored charge, which raises capacitance.

The dipoles and charge carriers are unable to keep up with the quickly shifting electric field as the frequency rises. As a result, capacitance decreases as polarization lags behind. $CoFe_2O_4$ enhances polarization and capacitance by having a higher dielectric constant and a higher electron hopping rate between Fe^{2+} and Fe^{3+} ions at octahedral sites.

$NiFe_2O_4$, on the other hand, has a greater Q-factor, which indicates a lower dielectric loss, but a relatively lower capacitance because to its lower electrical conductivity and polarization. $CoFe_2O_4$ and $NiFe_2O_4$ reinforced natural fiber composites showed magneto-dielectric behavior, which combined dielectric and magnetic responses. This improves sensor performance by increasing sensitivity and multipurpose detecting capabilities and permits efficient EMI shielding through electromagnetic wave absorption. $CoFe_2O_4$-filled composites have higher losses but may hold more charge at low-to-intermediate frequencies for energy storage or capacitive applications. When lower dielectric loss is crucial, such as in high-frequency sensors or EMI shielding materials where energy dissipation must be minimized, $NiFe_2O_4$ fillers may be chosen. Interfacial polarization is further altered by the coir/sugarcane fiber synergistic effect, which can be adjusted for particular frequency-dependent dielectric performance. Table 11. shows the relative improvement over previous natural fiber composites.

Table 11. A comparison chart showing the relative improvement over previous natural fiber composites.

Sl. No	Material System	Tensile Strength (MPa)	Flexural Strength (MPa)	Dielectric / Q-Factor	Key Observation	Reference
1	Epoxy + Coir + Luffa fiber + $CaCO_3$ filler	81	95	–	Moderate strength; fillers increased brittleness	Mohana Krishnudu et al., 2022
2	Epoxy + Kenaf fiber + Graphene filler	51.7	–	–	Nanofiller improved stiffness, limited strength	Natrayan L. et al., 2022
3	$CoFe_2O_4$/$NiFe_2O_4$/Carbon fiber/PP composite	–	–	$\varepsilon' \approx 11$–13, $Q \approx 6$–8	Good EMI absorption, weak structural properties	Sadeghi R. et al., 2020
4	Epoxy + Coir + $NiFe_2O_4$ (C1)	160.2	131.0	1.39 pF, Q = 13.39	Highest tensile strength & lowest dielectric loss; efficient energy storage	Present work
5	Epoxy + Coir + $CoFe_2O_4$ (C2)	144.1	173.9	2.03 pF, Q = 6.91	Highest flexural	Present work

					strength & dielectric constant; excellent EMI absorption	

4 Conclusion

The mechanical characteristics of epoxy-based composites supplemented with metallic fillers (NiFe and CoFe) and natural fibers (coir and sugarcane) are examined in this work. To evaluate the impact of fiber type and metallic filler composition on the structural performance of the composites, tensile and flexural tests were conducted.NiFe reinforcement improves load-bearing capability, as demonstrated by C1's greatest tensile strength of 160.215 N/mm². With a tensile modulus of 2859.09 N/mm², S1 achieved the highest value, indicating that sugarcane fibers contribute to increased stiffness. Sugarcane fiber had the highest crystallinity of 81.24%, contributing to greater stiffness and load resistance. Coir fiber had the lowest crystallinity of 53.04%, indicating higher amorphous content, which enhances energy dissipation and impact resistance.
CoFe obtained a higher dielectric constant that suits in high-frequency absorption. NiFe stores energy more efficiently with lower loss. Higher impedance in NiFe may mean better attenuation of low-frequency EM waves. The results indicate that NiFe-filled composites, C1 & S1 offer superior mechanical and dielectric properties suits for structural materials. These findings contribute to the growing field of sustainable and high-performance polymer composites.

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