# Mechanical and Sound Absorption Performance of Cashew Apple Bagasse and Mahogany Fruit-based Hybrid Composites

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Mechanical and acoustic properties were studied for hybrid composites developed from Cashew Apple Bagasse (CAB) fibers and Mahogany tree Fruit Filler (MFF) in an epoxy matrix. The effect of alkali treatment (5% and 10% NaOH solutions) on CAB fiber composites at different weight fractions of MFF (0 to 25 wt%) was studied. The composites including 15 to 20 wt% MFF and treated with 5% NaOH offered the highest performance. Tensile, flexural, and impact strengths were improved by 40%, 50%, and 45.7%, respectively, when compared to untreated ones; also, a 56.7% increase in noise reduction coefficient (NRC) was measured. These enhancements can be attributed to the removal of surface impurities on the fiber surface, improving fiber-matrix bonding, and achieving even dispersion of filler in the matrix. Using alkali treatment with NaOH concentration exceeding 10% and with a higher filler content (> 20 wt%) embrittled the fibers, at the same time allowing them to clump together, which decreased both mechanical and acoustic performance. The best approach was to combine CAB and MFF in appropriate quantities into a hybrid composite, striking a good balance between reinforcement and load transfer efficiency. These composites are intended to be used in car interiors, soundproof panels, and lightweight structural parts.

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## INTRODUCTION

Natural fiber composites (NFCs) are being increasingly used, taking advantage of their sustainability (Khalid *et al*. 2021) and increased availability of vegetable waste (Divya *et al*. 2022). They are also defined as "biomass-based composites" (Iwuozor *et al*. 2024). Their growing diffusion and application appear closely related to the wealth and variety of biomass available. According to Tahir *et al.* (2023), the world production of biomass amounted to 220 billion tons in 2020, which offers an extensive potential for its use in materials. On the other hand, the market of NFCs is steadily growing in the last few years (by 8.2% from 2015 to 2020), though most of the successful applications concern the use of a few fiber species, such as hemp, flax, jute, sisal, kenaf, pineapple, bamboo, banana, *etc.* (Jagadeesh *et al.* 2022). The trend towards their employment in various sectors suggests diversification of properties and their more thorough evaluation in the future (Khan *et al.* 2024).

Along these lines, improvements in the performance of NFCs is being pursued in various aspects, not limited to their mechanical properties alone (Lotfi *et al*. 2021; Palanisamy *et al*. 2024). Interest in the sound absorption coefficient (SAC) of natural fiber composites is an example of the wide-ranging applications. Due to their larger diameter and high porosity and consequently their lower compactness, the SAC in NFCs can be considerably high, even approaching a value of 1 at some frequencies (Nordin *et al.* 2016). Path tortuosity is enhanced by placing various fillers in different forms, which is defined as producing "fibrogranular composites" (Mamtaz *et al.* 2016).

It is noteworthy that the combination of diverse lignocellulosic materials in the same composite, thereby creating a hybrid material, is a common practice (Islam *et al*. 2024). In particular, given the variable amount of lignin and cellulose contents in lignocellulosic biomass, an option leading to the enhancement of the performance of NFCs can be the insertion of more cellulosic fibers, to provide structural strength, together with more ligneous fillers, to improve hardness. Examples of this procedure are reported (Babu *et al*. 2021; Palanisamy *et al*. 2021), where luffa fiber composites incorporating almond shell powder, or composites in which coir fibers and ligneous fillers obtained from the same production system *i.e.*, coconut, have been employed with appreciable synergetic effect (Kumar and Saha 2024). However, preserving if not enhancing the initial strength of composites after employment of a hybrid combination of reinforcing natural fibers with a harder material is a possibility not to be neglected, as it has been in the case of hemp shives (Scardecchia *et al*. 2020). In a future perspective, this knowledge will be useful for obtaining seed-filled NFCs, which may also be recommended due to the wide presence of secondary raw matter of this nature (Fragassa *et al*. 2024).

In this sense, a recent trend is represented by exploring the use for NFCs of minor parts of some plants, which are heavily exploited for other applications: this will be inherently sustainable, by reducing biomass waste and the depletion of resources. This can be the case for example for pineapple crown leaves, which are a by-product of pineapple fruits, largely used in industry for the production of canned flesh or fruit juices (Johny *et al*. 2023). Another example is mahogany (*Swietenia macrophylla*) wood, which is one of the largest products in this industry, even threatened by illegal logging. Mahogany fruit seeds have also some applications, especially in view of their antidiabetic properties (Lin and Mon 2020): on the other hand, the applications of mahogany tree fruit shells as fillers (MFF) are still poorly investigated (Snook *et al*. 2005). A composite of mahogany fruit shells in a natural rubber matrix has also been proposed for potential application in pavements (Jaroenta *et al*. 2020).

On the other hand, bagasse from liquor extraction offers a fibrous and consistent material to be used in NFCs: the most common one is the one from sugarcane, which obtained considerable attention in materials applications (Loh *et al.* 2013). Bagasse from cashew apple (*Anacardium occidentale* L.) is similarly a by-product of a broad agrifood system, which can used as a source of cellulose (Bamgbola *et al*. 2020). Beyond this, *Anacardium* liquid resins have been proposed *e.g.*, also as a suitable replacement for phenolics (Telascrêa *et al*. 2014). This breadth of application suggests the possibility to approach a no-waste concept, by exploiting also further the remaining material from cashew apples. Moreover, the concept of hybridization (simultaneously using two kinds of reinforcement in a composite) can also offer other possibilities: for example, composites with cashew apple bagasse showed sound absorption coefficients (SAC) of 0.8 at 3000 Hz and 0.7 at 6400 Hz, therefore highlighting their possible use for acoustic panels aimed at sound reduction (Lawan *et al*. 2023).

More specifically, this study is aimed at investigating the mechanical and acoustic properties of CAB/MFF hybrid composites and determining the effect of various concentrations of alkali on them, namely performed by sodium hydroxide (NaOH). The objectives include the study of the effect of 5% and 10% NaOH treatments on the interfacial bonding and mechanical strength of CAB fibers, while assessing the influence of varying MFF weight fractions on mechanical and sound absorption properties. This will enable establishing which combined content of the two fillers offers the highest performance.

## EXPERIMENTAL

### Materials

The CAB fibers were agricultural waste obtained from local processing facilities of cashew nut around Panruti, Neyveli District, Tamil Nadu, India. The bagasse was washed carefully with water for impurities eradication, left drying in natural conditions (open air, therefore subjected to day-night cycles) for 48 h, and subsequently decorticated removing by stripping and subsequent manual selection the bark residues to obtain the fibers to be used for composite manufacturing. The fibers were subsequently chopped down to a length of 10 (±0.5) mm.

The MFF was prepared from mahogany tree fruits harvested from Arasur, Tamil Nadu, India. The fruit shells, deprived of their seeds previously marketed for pharmacological purposes, were dehydrated, then ball milling was used to obtain a fine powder. Sieving was carried out with the resultant filler to have similar particle size diameter for uniform strengthening in the matrix. Particles between 50 and 100 µm were retained.

The resin used for forming the matrix material was a two-part epoxy system (Epoxy LY 556) bought from a supplier in Coimbatore, Tamil Nadu, India together with its curing agent (Hardener HY 951).

### Fiber Treatment

Cashew apple bagasse fibers were treated at two concentrations of sodium hydroxide, namely 5% and 10%, to improve their interfacial compatibility with the epoxy matrix. These concentrations are largely suggested in literature to be effective to treat quite hard and ligneous fibers, as it is in the case of raw matter considered in the present study (see, for example, Raju *et al.* 2021), on *Symphorema involucratum* stem. Treatment methodology involved immersion for 4 h at ambient temperatures with periodic stirring to ensure the complete exposure of fibers to NaOH solutions. After the immersion period, distilled water was used to thoroughly rinse the fibers several times to remove the residual alkali: washing was continued until the pH of the effluent water reached. Following treatment, the fibers were dried in a hot-air oven at 80 °C for 24 h in order to remove residual moisture and to prime them for composite fabrication.

## Composite Manufacturing

The hybrid composites were prepared using CAB fibers. MFF was then introduced in different proportions into the epoxy resin to create six different compositions. The compositions were prepared with CAB fibers from 15% to 40%, MFF from 0% to 25%, and epoxy resin fixed at 60 wt%. The treated CAB fibers and MFF were well mixed with epoxy resin and hardener (in a weight ratio of 10:1) for 10 min to achieve homogeneous dispersion. The mixture was then poured into a preheated steel mold, and compression molding was conducted at 10 MPa and 120 °C for 30 min. Subsequently, the composites were cured at room temperature for 24 h to allow complete polymerization of the epoxy resin. Upon curing, the composites were cut into appropriate dimensions according to ASTM standards, as detailed further down, for mechanical and acoustic testing. The compression molding process makes it possible to produce composites with uniform density and excellent surface finish, thus making them ideal for complete property studies. A scheme of the work performed and of the six categories of samples produced and characterized is reported in Fig. 1.

## Mechanical Testing

The mechanical properties of the hybrid composites were evaluated in accordance with standards for American Society for Testing and Materials (ASTM) intended for accuracy and consistency.

Tensile, flexural and interlaminar shear strength (ILSS) tests were carried out using a computerized universal testing machine (UTM) by Instron 3400 Series (Norwood, MA, USA) equipped with a 50 kN load cell. Impact strength was measured by using a 15 Joules Izod instrumented pendulum by Noselab ATS (Nova Milanese, Italy). Shore D durometer used for hardness test was obtained from Sauter (Sesto San Giovanni, Italy). For each category and test, five samples were measured. Further details are offered in Table 1.

**Table 1.** Test Types and Details

| Test | ASTM Standard | Samples Dimensions (mm) | Further Details |
|---|---|---|---|
| Tensile | D3039/D3039M-14 | 250×25×3 | Crosshead speed 2 mm/min<br>Grip length 60 mm |
| Three-point flexural | D790-17 | 127×12.7×3 | Span length 50 mm |
| Interlaminar shear strength (ILSS) | D2344/D2344M-22 | 20×6×3 | Span length 12 mm |
| Izod impact | D256-24 | 63.5×12.7×3 | V-notched samples |
| Shore D hardness | D2240-15 | 75×25×3 | Five measurements each sample. The average was taken. |

## Sound Absorption Properties

For the determination of acoustic properties of the prepared hybrid NFCs, six specimens from each composite formulation were tested to ascertain the consistency and reliability of results. The noise reduction coefficient (NRC) was measured with an impedance tube apparatus model SW470 produced by BSWA, Beijing, China, based on ASTM E1050-24 standard. A circular specimen of diameter 100 mm and thickness of 3 mm was used for measuring the sound absorption coefficients over a frequency range from

125 to 4000 Hz. NRC is defined as the arithmetic mean of the absorption coefficients measured at the standard frequencies of 250, 500, 1000, and 2000 Hz.

### Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) (JEOL JSM-6360, JEOL Ltd., Akishima, Tokyo, Japan) was used to analyze the surface morphology and interfacial characteristics of the hybrid composites and to determine the effects of the fiber treatment and filler distribution. The fractured surfaces of the tensile test specimens were selected for SEM analysis in order to study fiber pull-out, matrix adherence, and void formation. Before imaging, samples were prepared to be electrically conductive by depositing a layer of gold by means of sputter coater (Quorum Q150RS, Quorum Technologies, Edinburgh, UK). The SEM images were obtained using a potential difference of 15 kV between its high-tension stage and earth stage; the captured micrographs vary according to their magnifications while revealing fiber-matrix interfacial bonding and the distribution of MFF in the epoxy matrix. A minimum of three specimens per composite formulation were analyzed to ensure the analysis captured the representative morphological features of the composites.

## RESULTS AND DISCUSSION

The analysis of the results obtained emphasized the effect of the introduction of MFF fillers in combination with the cellulose bagasse obtained from cashew apples (CAB). It is expected that the two fillers would behave differently: while the fibrous bagasse might provide higher mechanical (tensile and flexural) strength, the introduction of quasi-spherical fillers, such as in the case of MFF, can also exert some effect on the rigidity of the composite. Previous studies indicated that MFF contains, beyond holocellulose and extractives, around 13.5% lignin (Colares *et al*. 2015), while for CAB the lignin content was larger, amounting to 23.9% (dos Santos Lima *et al*. 2012). The considerable presence of lignin suggests that alkali treatment, even in not very diluted solutions, can be adapted to improve the mechanical properties of the material, by the removal of the loose parts of the lignocellulosic matter while also regularizing its surface and improving composite functioning. Two concentrations for the NaOH solution were selected for this purpose, and pretreatment was performed by considering other works with fibers with similar lignin content, such as bamboo (20 to 30% lignin) (Liu and Hu 2008), palms of the *Phoenix* sp. (15-35% lignin) (Rajeshkumar *et al*. 2016), or residues of hemp core (Serra-Parareda *et al*. 2020), while for hemp fibers the lignin content is significantly lower, such as 8-9% (Alaru *et al*. 2011), and so the treatment can be lighter. In the reported studies (Liu and Hu 2008; Rajeshkumar *et al*. 2016; Serra-Parareda *et al*. 2020), the concentration of NaOH has been centered on a 5% to 10% interval, which is considered suitable also in the present case.

A global observation of the mechanical results from Figs. 2a and 2b (tensile strength and stiffness), Figs. 3a and 3b (flexural strength and stiffness), Fig. 4 (Izod impact strength), and Fig. 5 (interlaminar shear strength), indicates that out of the eighteen sets of samples (six compositions, per three conditions, untreated, 5% NaOH treated, and 10% treated), a clear superiority in performance was observed in the C25M15 5% NaOH treated sample.

A statistical analysis was carried out on tensile and flexural strengths and the results are reported below. In particular, the ANOVA analysis (Table 2) confirmed that the tensile strength differences across untreated, 5% NaOH-treated, and 10% NaOH-treated fibers were statistically significant, with an F-statistic of 7.91 and a p-value of 0.0045 ($p < 0.05$). Tukey's HSD post-hoc analysis (Table 3) revealed significant differences between the untreated and 5% NaOH-treated composites and between the untreated and 10% NaOH-treated composites. However, no significant difference was observed between the 5% and 10% NaOH-treated composites, indicating that excessive chemical treatment did not yield additional benefits. This suggests that 5% NaOH treatment is optimal for enhancing the tensile properties.

**Table 2.** ANOVA for Tensile Properties

| Source | Sum of Squares | Degrees of Freedom (df) | F-Statistic | p-Value | |
|---|---|---|---|---|---|
| Chemical treatment | 20.6 | 2 | 7.91 | 0.0045 | Significant |
| Residual | 98.9 | 15 | | | |

**Table 3.** Pairwise Comparison for Tensile Properties

| Group 1 | Group 2 | Mean Difference | Lower CI | Upper CI | p-Value | Significant |
|---|---|---|---|---|---|---|
| Untreated | 5% Treated | 11.52 | 3.75 | 19.29 | 0.003 | Yes |
| Untreated | 10% Treated | 9.91 | 2.14 | 17.68 | 0.01 | Yes |
| 5% Treated | 10% Treated | -1.61 | -9.38 | 6.16 | 0.807 | No |

In addition, pairwise comparisons, mean differences, confidence intervals, and p-values are shown in Table 2. A significant improvement in tensile strength was observed when comparing untreated composites to those treated with 5% NaOH. The tensile strength increased substantially, indicating that the 5% treatment effectively removed surface impurities and enhanced the interfacial bonding between the CAB fibers and the epoxy matrix. Similarly, untreated composites also showed a significant improvement in tensile strength when compared to composites treated with 10% NaOH, confirming that chemical treatment at higher levels also enhances the fiber-matrix interaction. However, the comparison between the 5% and 10% NaOH-treated composites demonstrated no statistically significant difference in tensile strength, suggesting that both treatment levels offer similar effectiveness in improving the mechanical properties. These findings highlight 5% NaOH as the optimal treatment condition to achieve the desired mechanical improvements without the risk of fiber degradation associated with excessive treatment.

The ANOVA results (Table 4) for flexural properties clearly indicated that there was a statically significant effect on the flexural strength and modulus of the tested specimens due to treatment and MFF weight fractions. The F-values for the two parameters were calculated as 8.12 for flexural strength and 7.56 for flexural modulus at p-values 0.0035 and 0.0041, respectively ($p < 0.05$).

**Table 4.** ANOVA for Flexural Properties

| Source | Sum of Squares | Degrees of Freedom (df) | F-Statistic | p-Value | |
|---|---|---|---|---|---|
| Chemical Treatment | 312.84 | 2 | 8.12 | 0.0035 | Significant |
| Residual | 576.32 | 15 | - | - | |

From the results, the observed differences between the treatments in the flexural properties were clearly not random effects but were caused by a combination of variables depending on treatment concentration and filler amounts.

The statistically significant p-values point toward the presence of chemical treatment and weight fraction effect on flexural properties that warrants further probing with pairwise differences. In fact, Tukey's HSD post-hoc (Table 4) also revealed important aspects of this specific difference based on treatments considered in the analyses. The comparative analyses indicated that flexural strength had been significantly increased with average mean difference amounting to 25 MPa, whereas modulus got an average of mean difference in magnitude of 2.5 GPa. This supports the fact that 5% NaOH treatment improves interfacial bonding and enhances stress transfer. In addition, there were also significant improvements in flexural properties, though slightly lower than those of the 5% NaOH-treated composites.

The mean difference was 20 MPa for strength and 2.2 GPa for modulus, showing that 10% NaOH treatment also improved performance, though to a lesser extent. However, no statistical significance was seen in these groups and it is confirmed that the two treatments are equally effective to improve flexural properties. Yet, 5% showed continuously marginally superior performance than all other groups, indicating that it may be an optimum condition.

**Table 5.** Pairwise Comparison of Flexural Properties

| Group 1 vs. Group 2 | Avg. Difference (MPa) | Lower CI | Upper CI | p-Value | Significant |
|---|---|---|---|---|---|
| Untreated vs. 5% Treated | 25 | 15 | 35 | 0.002 | Yes |
| Untreated vs. 10% Treated | 20 | 10 | 30 | 0.010 | Yes |
| 5% Treated vs. 10% Treated | -5 | -15 | 5 | 0.786 | No |

To better assess how this material compares with similar NFCs composites, this most performing configuration was put alongside other data from literature according to its mechanical characteristics. The requirements of the potential competitors are short fibers, typically from Musaceae, palms, or agave, contained in an epoxy matrix, which have been treated with sodium hydroxide, even if not necessarily with the same concentration as in this work. For each study, the highest results obtained for this fiber fraction, *i.e.*, a total of 40 wt% (in case for example of the use of different fiber varieties or lengths) have been reported. In our case, the result obtained for C25M15 5% NaOH treated fibers is given in Table 6.

From data reported in Table 6, the highest values obtained for tensile stiffness and flexural properties in this study indicated favorable results. In contrast, the impact tests outcomes were quite deceiving: this was attributed to the combination of the two fillers that is not able to hinder crack propagation during the abrupt fracture event. Further studies over the effect of fiber length would need to be carried out though to better put into context the data obtained.

**Table 6.** Comparison of C25M15 Results with Other Data in Literature

| Filler | TS (MPa) | TM (GPa) | FS (MPa) | FM (GPa) | IS (kJ/m²) | Reference |
|---|---|---|---|---|---|---|
| C25M15 | 48.5 | 8.75 | 84.3 | 16.8 | 7.75 | This work |
| Banana | 108.4 | 1.82 | 72.3 | - | 86.2 | Ramesh *et al*. 2014 |
| Banana | 62.3 | 8.72 | - | - | - | Irawan and Sukania 2015 |
| Abaca | 21.4 | - | - | - | 6.2 | Punyamurthy *et al*. 2014 |
| Agave | 25 | 0.27 | 57.5 | 3.5 | 20 | Mylsamy and Rajendran 2011 |
| Agave cantala | 108 | 5.13 | 136 | 12.01 | - | Ramesh *et al*. 2023 |
| A. angustifolia | 17.84 | - | 72.7 | - | 74.4 | Ramakrishnan and Sampath 2017 |
| Coir | 21.1 | - | | - | 23.5 | Obele and Ishidi 2015 |
| OPEFB | 27.4 | 1.5 | - | - | - | Faizi *et al*. 2022 |
| Piassava | 89.3 | 2.87 | - | - | - | (Nascimento *et al*. 2012) |
| Date palm | 47.3 | 1.07 | 83.2 | - | - | (Saba *et al*. 2019) |
| Date palm | - | - | 28.6 | 2.3 | - | (Gheith *et al*. 2019) |
| Sugar palm | 27.1 | 3.09 | 54.4 | 2.62 | - | (Sapuan and Harussani 2022) |

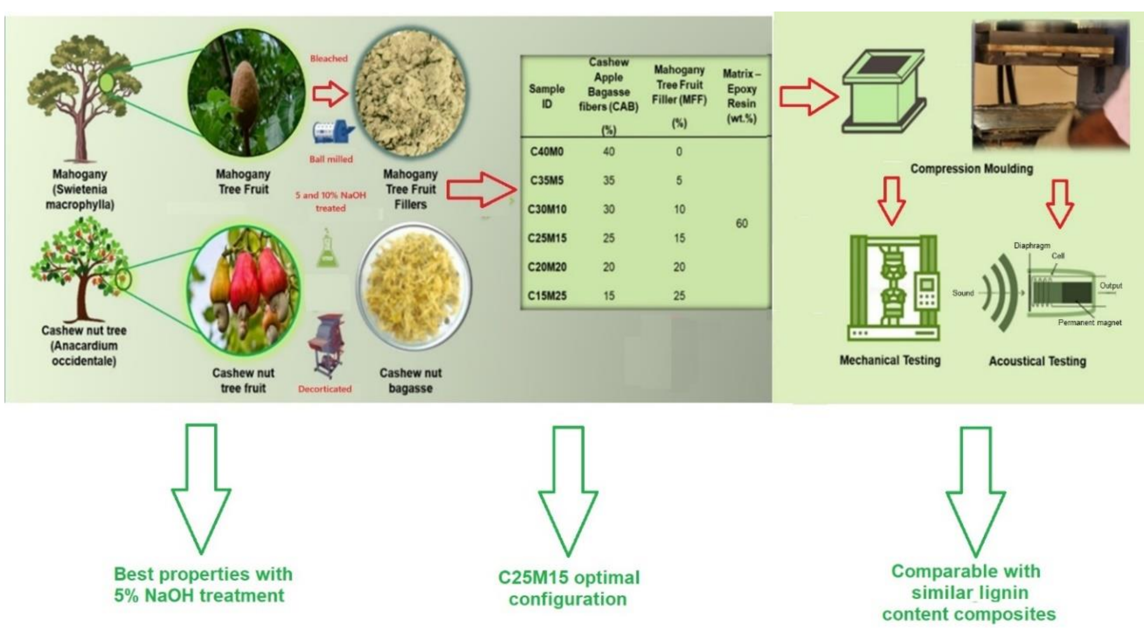


**Fig. 1.** Raw materials, composite categories, production method, and characterization

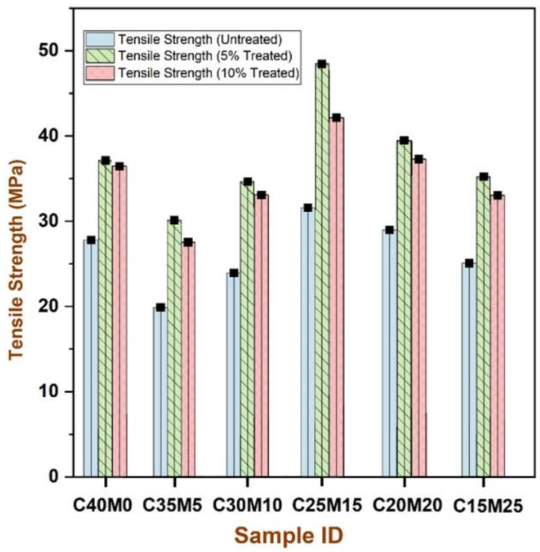


**Fig. 2a.** Tensile strength results

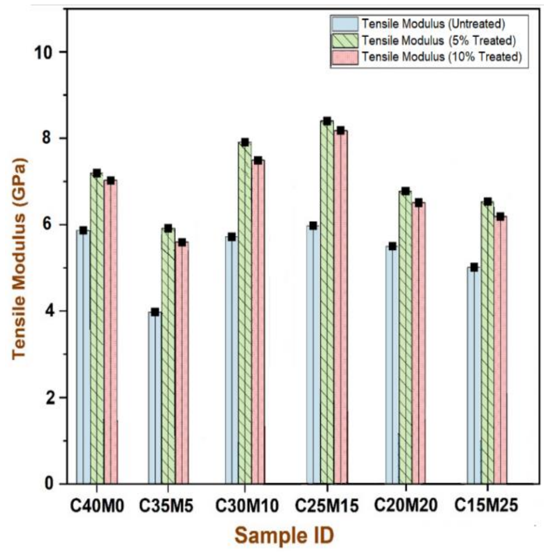


**Fig. 2b.** Tensile modulus results

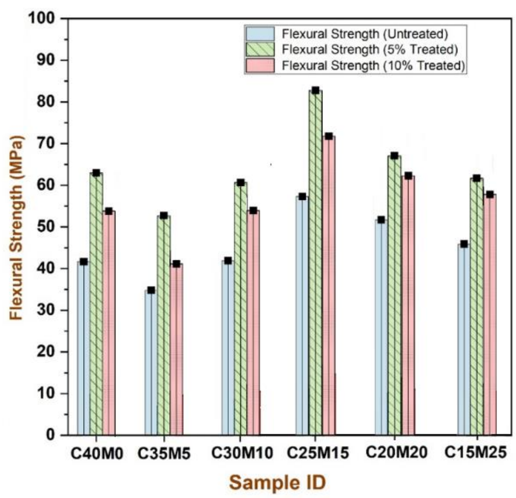


**Fig. 3a.** Flexural strength results

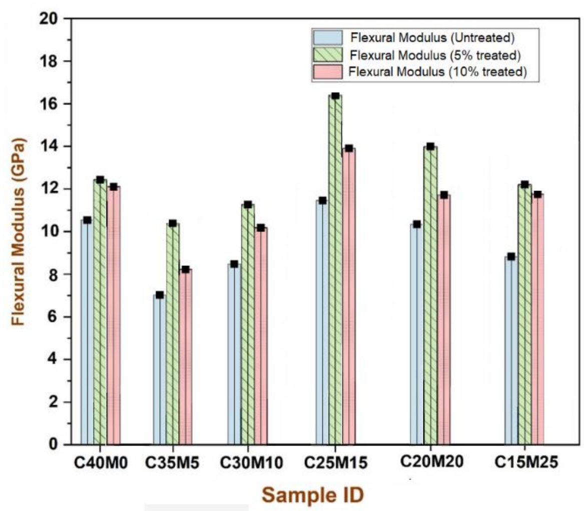


**Fig. 3b.** Flexural modulus results

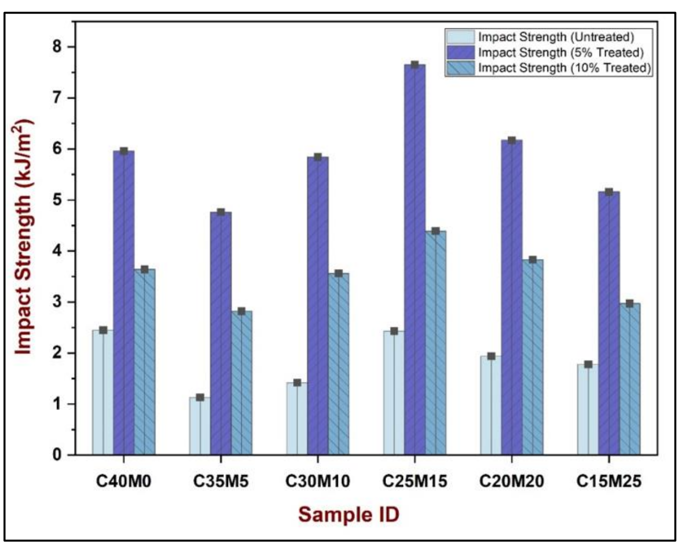


**Fig. 4.** Izod impact tests results

The effect of alkali treatment appeared very high also when considering ILSS properties. In the specific case of the highest performing composite *i.e.*, C25M15, an over 30% improvement was demonstrated in the case of 5% NaOH treatment. It needs to be noticed that ILSS properties are not always increased by the insertion of fibers, such as *e.g.*, palm rachis ones, though the values obtained are in the order of what revealed in the present study (Pinto-Flórez *et al*. 2019).

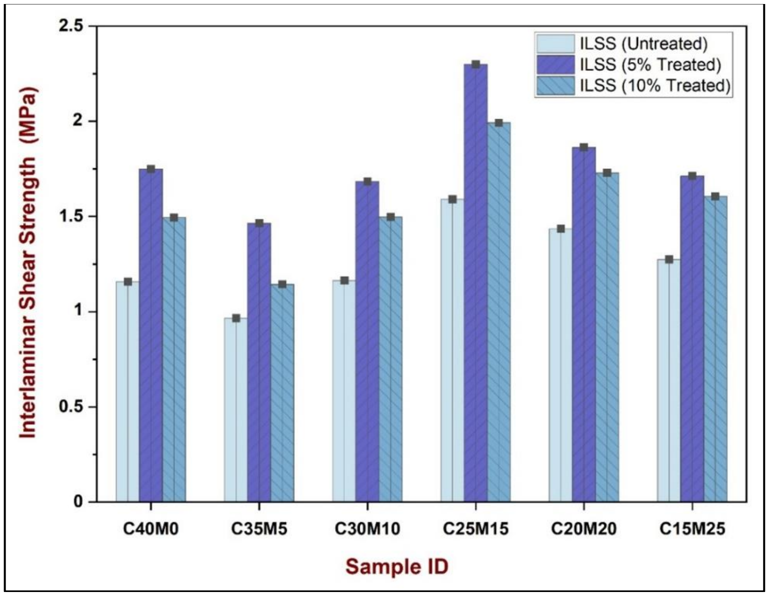


**Fig. 5.** Interlaminar shear strength (ILSS) results

As far as hardness results are concerned, again the C25M15 leads to one amongst the best results, although in absence of the mahogany filler (C40M0) for 5% NaOH treatment, hardness is even higher. The effect of NaOH concentration appears to be very limited, if any (Fig. 6). As for noise reduction coefficient, the application of the optimal treatment concentration *i.e.*, 5% NaOH, led to optimal results, though NRC was progressively higher with the increase of mahogany filler content in the composite (Fig. 7). It is noteworthy though that the results were, even in the best case, were somewhat inferior with those obtained on jute, flax, and ramie (0.65, 0.65, and 0.6, respectively) in Yang and Li (2012), though clearly higher than those obtained on glass and carbon fibers. Also, considering that the sound absorption measurement has for highest frequency 2000 Hz, the results appear slightly more promising that those obtained with hemp waste fibers, which are 0.37 at 2000 Hz, as reported in Zhang *et al.* 2022, and therefore still inferior to NRC. Other studies on less uniform material, such as sugarcane bagasse (Zulkarnain *et al.* 2024) suggested that the combined presence of the two fillers, namely cashew apple bagasse and mahogany fruit, lead to superior results for NRC. Of course, further investigations are needed for a real acoustic characterization of the material, such as pointed out in the review by Moges *et al.* 2024.

SEM observations on the mechanically strongest configuration C25M15, as from Fig. 8, suggest that treatment considerably reduces the occurrence of pull-out of the short fibers from the matrix. This might effectively explain the relative mechanical success of this material at this level of treatment.

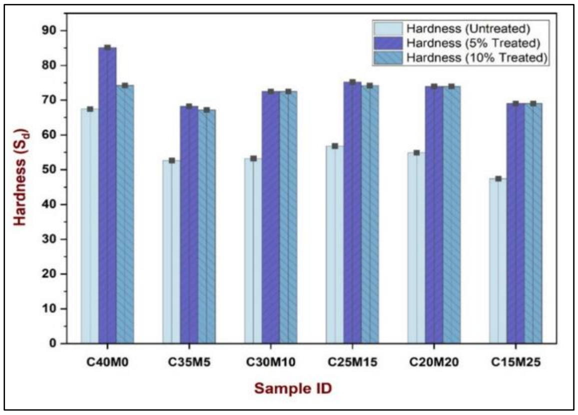


Fig. 6. Shore D hardness results

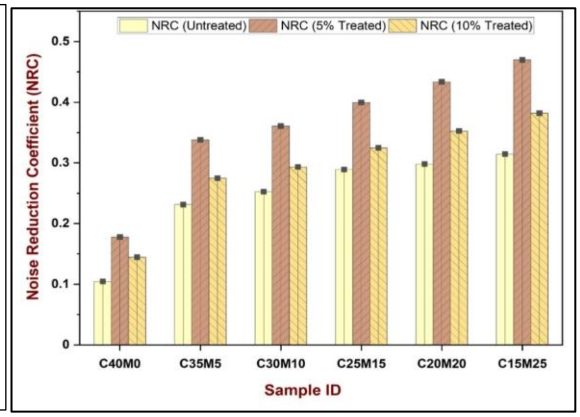


**Fig. 7.** NRC results

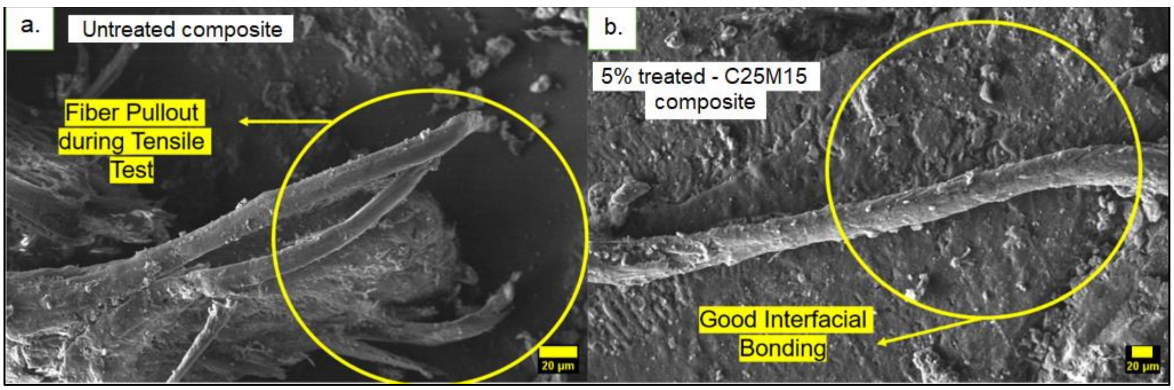


**Fig. 8.** SEM images of (a) Untreated C25M15 composite; and (b) 5% NaOH-treated C25M15 composite

## CONCLUSIONS

1. The introduction of a particulate filler obtained from mahogany tree fruit to a fibrous bagasse material from cashew apple improved the properties of the relevant epoxy matrix, when a respective 25:15 ratio of the two fillers was applied.
2. The mechanical results obtained were comparable with other similar types of fibers, with the advantage that this is achieved using waste materials, of scarce relevance for other uses.
3. A moderate sodium hydroxide treatment at 5 wt% concentration consistently improved the properties. By contrast, such treatment did not appear to be particularly beneficial for hardness.
4. Raising the level of chemical treatment (*i.e.*, exceeding 5 wt%) did possibly result in quite some damage to the composite.
5. Acoustical application of the material appears possible with respect to similar biomass waste composites, though it is not yet comparable with more structured and organized natural fiber products.
6. Use of bio-resins would also be recommended in view of further developments of the material.

According to the sound absorption properties obtained, it is suggested that sound absorption at 2000 Hz is not yet sufficient for potential use of these materials in interior applications, though it is comparable with other ones. Future developments will require more evaluations and considerations to bring the performance to the level of competitor materials, which are not yet in the purpose of this preliminary study.

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### Data Availability Statement

Data are available on request from the authors.

### Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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