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ORIGINAL PAPER

Production and characterization of epoxy based biocomposites using pectin biopolymer derived from Passiflora edulis husk and areca fibre

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Abstract

Composites' many desirable qualities—including low density, high rigidity, light weight, and improved mechanical performance—have prompted much research into composite manufacturing. Because of these qualities, composites have become the material of choice in many other industries, such as the automotive, building, sports, consumer goods, and engineering fields. Reinforcing epoxy-based composites with 30 vol. % areca nut fibre and pectin made from the husks of Passiflora edulis in different volume percentages for filler. In order to enhance interfacial bonding, the fibre and filler were surface modified before production with 3-Aminopropyltrimethoxysilane (3-APTMS), a silane coupling agent. The water absorption, mechanical, fatigue, and creep tests were carried out in compliance with the applicable ASTM standards. According to the results, composite produced with 30 vol. % of fibre and 3 vol.% of pectin outperformed in mechanical properties. Similarly, the same composite demonstrated improved fatigue resistance in terms of life counts. The scanning electron microscopy (SEM) analysis of the failure mechanisms verified the efficient connection between the fibres and the matrix, as well as the uniform distribution of the filler. On the other hand, the RAP2 composite with 5 vol. % filler, showed marginally higher water absorption (4.9%), and the highest hardness up to 92 Shore-D. Moreover the same composite outperformed in creep resistance with a lowest strain rate of 0.0256 at 15,000 s. These positive outcomes by the addition of pectin in the composite may lead high performance applications in automotives, defence, infrastructure and sports.

Keywords Composites · Natural fiber · Biopolymer · Silane treatment · Water absorption

Abbreviations

3-APTMS	3-Aminopropyltrimethoxysilane
ASTM	American Society for Testing and Materials

Extended author information available on the last page of the article

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SEM	Scanning electron microscopy
MPa	Mega Pascal
Shore-d	Shore-durometer
UTS	Ultimate tensile stress
R	Resin
RA	Resin + areca nut fiber
RAP0	Resin + areca nut fiber + pectin biofiller
RAP1	Resin + areca nut fiber + pectin biofiller
RAP2	Resin + areca nut fiber + pectin biofiller

Introduction

Natural fiber-reinforced composites are gaining popularity as a solution to environmental pollution and sustainability concerns. These composites use renewable resources, cut down on petrochemical use, and make waste valuable again, making them a better option than traditional composites [1, 2]. Incorporating natural fibres has been more common in recent decades, thanks to the worldwide demand for sustainable and eco-friendly products. On the other hand, polymer composites made with natural fibres instead of synthetic reinforcements are a renewable, inexpensive, and environmentally conscious material innovation [3–5]. They found use in several fields, including packaging, construction, and automobiles, because of their low density, biodegradability, and excellent mechanical qualities [6, 7]. Natural fibres such as areca, kenaf, hemp, bamboo, pineapple, banana, and kenaf fibre are also used to reinforce the composite material [8–10]. The areca nut fibre is used in this study to enhance its characteristics. The fibre from the areca nut is also known as areca palm, and it comes from the nut's outer husk. Areca nut fibre is an excellent reinforcement material for composites since it is mainly made of lignocellulosic components; it is extracted from the betel nut husk. Typical chemical makeup includes cellulose (33–40%), hemicellulose (20–26%), and lignin (35–45%), the latter of which gives the material its inherent stiffness and durability [11]. Also included are ash (1–2%), pectin (3–4%), and moisture (8–12%). Especially after being surface-treated to improve matrix compatibility, areca nut fibers moderate cellulose and high lignin content make it an attractive structural material. Many studies have improved the mechanical properties of composites by reinforcing them with natural fibres. As an example, the properties of the areca nut fibre reinforced composite were investigated by Hasan et al. [12]. The author found that by adding 2 vol., the material attained a tensile strength of 18.16% and a compressive strength of 2.89%. by weight of areca fibre. Similarly, Sakib et al. [13] demonstrated a betel nut fibre reinforced epoxy composite with a tensile strength of 20.38 MPa. They added 10 vol. 20 vol.% fibre content and 16.82 J/cm^2 impact strength were achieved. % of fibre from betel nuts. Analogously, Natarajan et al. [14] studied the mechanical parameters of epoxy composites reinforced with almond fibre and found that they achieved a hardness of 93 shore-D, an impact strength of 4.31 kJ/m^2, a flexural strength of 109 MPa, and a tensile strength of 77 MPa.

Fibres have a number of disadvantages, such as the creation of voids and poor interfacial bonding with the matrix [15–17], despite the fact that they primarily produce the load-bearing and structurally improving properties. It is crucial to incorporate fillers into the composite material in order to overcome these difficulties. This study makes use of pectin, a filler obtained from the husk of the Passiflora edulis fruit (a member of the Passifloraceae family) [18]. The husk has a pectin content of about 10–20%, which helps with adhesion between surfaces, makes the dispersion more uniform, and improves the thermal insulation. Biopolymers are environmentally benign and have practical uses, hence they are being investigated more and more by researchers as potential sustainable fillers for composite materials. One study that looked into PLA and pectin composites plasticised using polyoxyethylene sorbitan monopalmitate was Ivorra-Martinez et al. [19]. The author found that a break elongation of 23.6% was accomplished. Same goes for the chitin reinforced vinyl ester composite; Baskaran et al. [20] investigated its effects. After adding 20 vol.%, the author found that the tensile strength reached 99 MPa. Similarly, Lavoratti et al. [21] studied cellulose reinforced epoxy composites and their creep properties; they found that the composites' creep strains rose by as much as 60%.

Despite the many advantages, the areca nut fibre and pectin filler have poor interfacial bonding, quick degradation, and reduced mechanical performance because their naturally hydrophilic surfaces do not adhere effectively to hydrophobic epoxy matrix. In addition, the adhesion and mechanical properties of the composites are improved with silane treatment [22]. The treatment also includes the use of 3-Aminopropyltrimethoxysilane (3-APTMS), a silane coupling agent that is well-known for improving adhesion between surfaces. In order to maximise the composite's performance, researchers have delved deeply into the fibre and filler with surface treatments. Balguri et al. [23] typically investigated vinyl ester composites reinforced with areca nut weave fibre and bronze filler. Incorporating 40 vol.% of the material improved its tensile strength 37.2%, flexural strength 22.4%, and izod impact strength 36.6%, according to the author's findings. Similar to that, Anžlovar et al. [24] examined melt-processed nanocomposites with LLDPE and cellulose nanocrystals treated with silane. They demonstrated that the addition of 1–2 wt enhanced the tensile strength by 30% and the young's modulus by 20%. Analogously, the assessment of Phoenix sp. Rajeshkumar et al. [25] investigated modified fibre surfaces for use in composite reinforcing. The tensile modulus was 9.26 GPa and the tensile strength was 466.35 MPa, as noted by the author.

Hence, a novel method is introduced in this study to enhance the epoxy matrix's compatibility with areca nut fibre and pectin filler derived from Passiflora edulis husks. Using mechanical, creep, fatigue, and water absorption properties, the research aims to produce a sustainable composite material and assess its structural stability. In addition, the natural fibre and filler are treated with silane, which improves the composite's performance by strengthening the link between the two materials. Herein lies the originality of the current investigation. These newly created composites show great potential as eco-friendly building materials, marine-grade items, high-performance biodegradable car parts, and other similar uses.

Novelty of the study

Polymer composites made from biopolymers extracted from agricultural waste are the subject of active investigation due to the rising need for environmentally friendly and technically advanced materials. One of the most common agricultural waste products, the husk of the passion fruit plant (Passiflora edulis) contains a high concentration of pectin, a biodegradable biopolymer that forms a film and has outstanding binding capabilities. The mechanical, fatigue, creep, and water absorption properties of epoxy composites made from areca nut fibres and pectin from Passiflora edulis husk are improved by adding silane to the mixture. A innovative approach that improves structural performance while being environmentally benign is the dual reinforcement that uses natural fibre and a biopolymer generated from plants. This method advances sustainable composite technology while also encouraging the value addition of agro-waste.

Materials and methodology

Base materials used

Table 1 presents the raw materials utilized in the composite manufacturing process.

Extraction of fiber from areca nut

The following stages outline the technique for extracting areca nut fibre, which was used in this research. Figure 1 depicts the many steps of the extraction process. In order to begin, gather the areca nut fruit from the previously stated source and wash them thoroughly with distilled water to eliminate any dirt or other contaminants. To remove any remaining moisture, the areca nut fruit that had been cleaned was dried in a hot air oven set at 70 ℃ for one hour [26]. To further isolate the fibrous material from the lignocellulosic matrix, the dehydrated shells were ground in a hammer mill fibre extractor (model: HM-FE-5). To ensure that no residual contaminants

Table 1 details of source materials used in composite fabrication

Material	Source	Form	Dimensions	Density (g/cm^3)
Areca nut fiber	Srinidi trading, Chennai	Chopped (CSM: 245 g/m^2)	5–8 mm length	~1.2–1.4
Passiflora edulis pectin	Adithya chemicals, Chennai	Fine powder	< 100 µm	~1.5–1.6
Epoxy resin (LY556)	Shield solutions, Chennai	Liquid	—	~1.15–1.20
Hardener (HY951)			—	~0.97–1.00
3-APTMS (Silane agent)	Triveni chemicals, Chennai	Liquid (solution)	—	~0.78
Ethanol (Solvent)			—	—

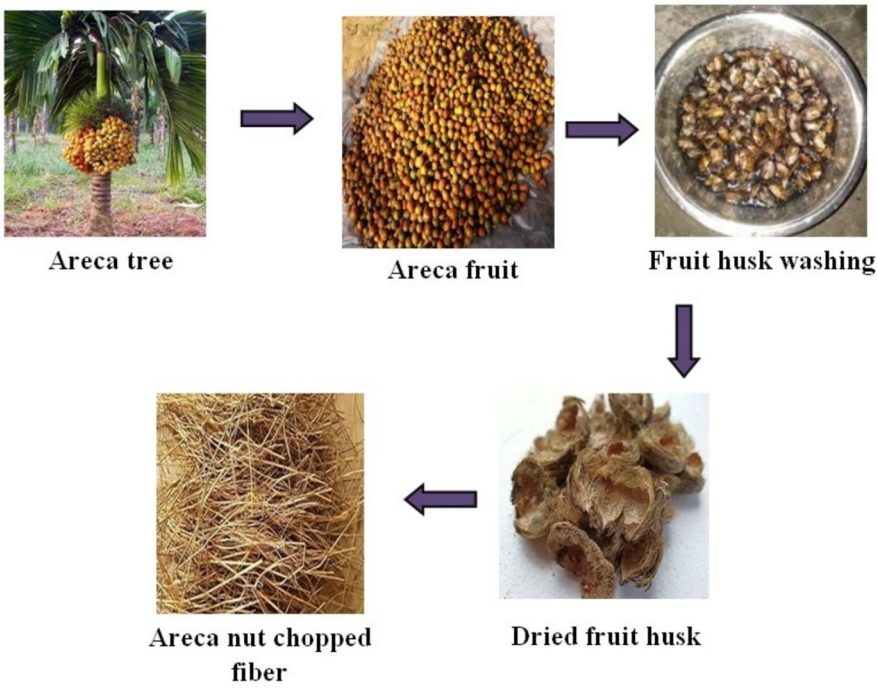

Fig. 1 Stages of areca nut fiber extraction from husk

remained, the separated fibres were rinsed with distilled water once more. The last step was to dry the fibres in a hot air oven set at 60 ℃ for four hours after they were cleaned.

Pectin extraction from passion fruit husk

After collecting the passion fruit husks, they were washed twice with distilled water, chopped into small pieces, blanched for five minutes in hot water to kill any pectin-degrading enzymes, and then dried in an oven at 80 ℃ for five hours. Afterwards, a high-speed grinder was used to break the dry husks into powder. In order to aid in the breakdown of cell walls and the release of pectin, the husk powder was combined with hydrochloric acid while stirring continuously to maintain a pH of about 4 [27]. Vacuum filtering was used to separate the liquid extract after heating the mixture at 75 ℃ for 80 min in a water bath to extract pectin. Centrifugation at 500 rpm for 15 min helped recover the pectin that had precipitated after being left undisturbed for 5 h after adding an equivalent amount of ethanol to the filtrate. Ultimately, the pectin filler that had precipitated was left to dry for three hours in a laboratory oven set at 70 ℃. Figure 2 shows the process of extracting pectin from Passiflora edulis, and Fig. 3 shows the biopolymer of synthesised pectin. The particles are rough-surfaced and abundant in pores.

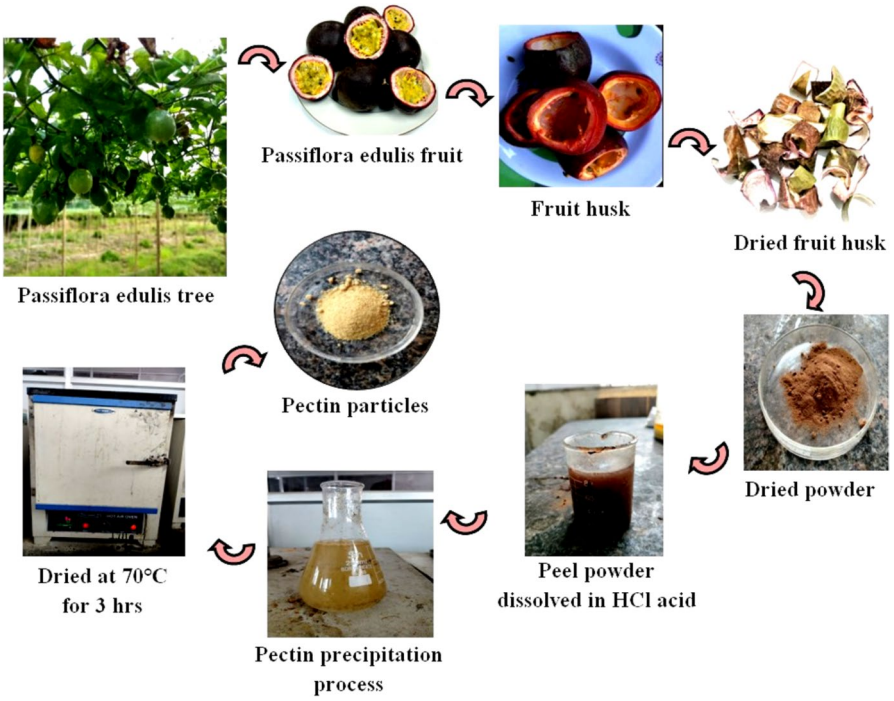

Fig. 2 *Passiflora edulis* pectin preparation

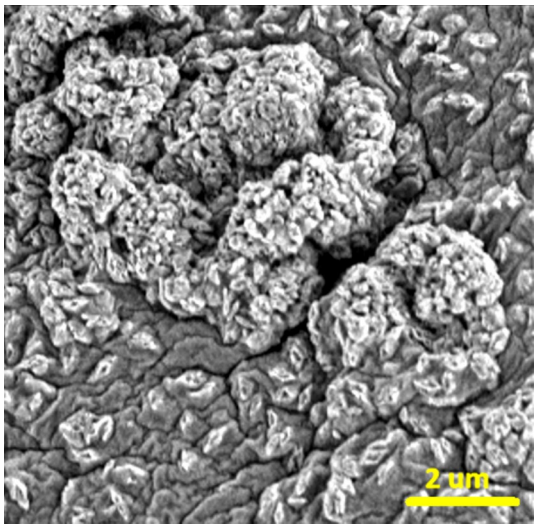

Fig. 3 Morphology of pectin biopolymer prepared

Surface treatment process

To perform silane surface treatment process a silane solution was made by combining 2 weight percent with water before the treatment. % 3-APTMS with ethanol, and acetic acid was used to reduce the pH to 4. The filler and fibre were immersed independently in beakers containing the silane solution while the mixture was constantly agitated [28]. For optimal silane coating, the soaked reinforcements were allowed to sit at room temperature for a duration of six hours. The fibre and filler were washed with clean water to remove any excess silane after soaking. Finally, a hot air oven was used to dry the treated fibres and fillers for 2.5 h at 60 ℃. Figure 4 depicted the silane method used for the reinforcements.

Fabrication of composites

A homogeneous mixture was achieved by carefully combining the epoxy resin and its matching hardener, triethylenetetramine, in a 10:1 (w/w) ratio. To avoid lumps and uneven distribution, the produced mixture was slowly added to the chopped areca nuts and pectin while being constantly stirred with a mechanical stirrer that had been coated with silane. A releasing agent was applied to a clean mould before the slurry was poured into it, making demolding after curing much easier [29]. In order to achieve

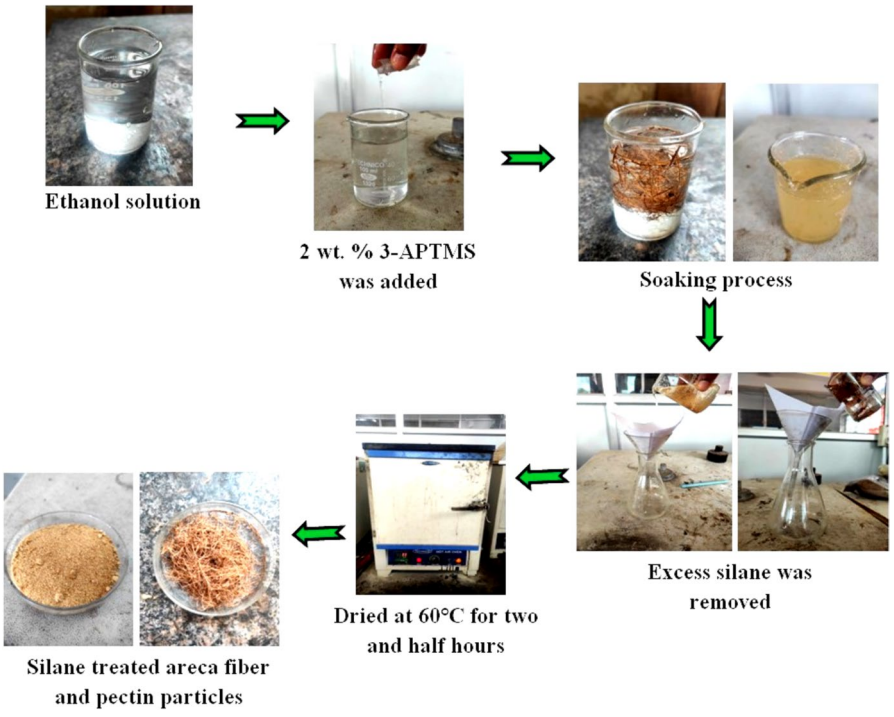

Fig. 4 Schematic representation of silane treatment process

Table 2 Proposed composite designations

Composite Designation	Epoxy resin (Vol. %)	Areca nut fiber (Vol. %)	Pectin (Vol. %)
R	100	–	–
RA	70	30	
RAP0	69	30	1
RAP1	67	30	3
RAP2	65	30	5

R, resin; A, areca nut fiber; P, pectin biofiller

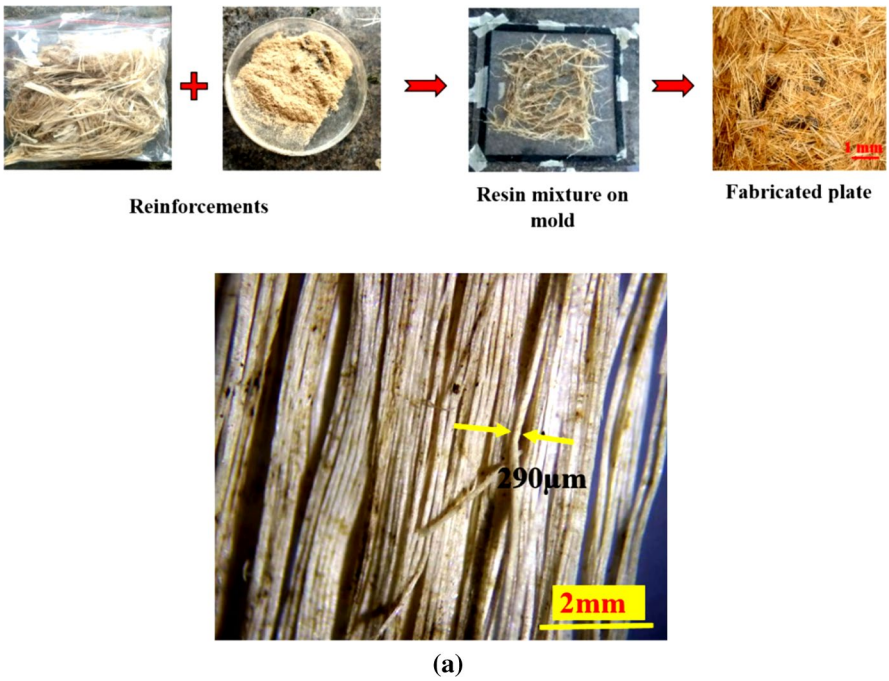

Fig. 5 Step by step procedure of composite plate fabrication process **a** Optical microscopic view of chopped areca nut fiber

better surface smoothness and consolidation, the composite panels were made utilising a manual lay-up technique. The composites were first cured for 23 h at room temperature after manufacture, and then for three hours they were post-cured in a hot air oven set at 70 °C to increase their mechanical strength. Table 2 displayed the reinforcing concentration. Figure 5 depicts the composite plate.

Test methods

A water abrasive jet cutting machine was used to cut the manufactured laminates to standard dimensions in order to prepare the specimen for testing. Mechanical, fatigue, creep, and water absorption testing were all a part of this investigation. The produced composite was tested according to the arrangement shown in Fig. 6 (a, b and c).

Mechanical test

Using industry-standard testing procedures, we determined the composite's mechanical properties, including its strength, stiffness, and deformation resistance. The following standards were used: ASTM D3039-17 for tensile testing, ASTM D790-17 for flexural testing, ASTM D2240-15e1 for hardness testing, and ASTM D256-10e1 for impact testing. Specimens shaped like dumbbells were subjected to a universal testing machine for tensile strength and elongation at break evaluations. The flexural strength and modulus were determined by subjecting rectangular specimens to three-point bending tests. The digital shore-D hardness tester was used to measure the hardness, which shed light on the material's resistance to localised surface deformation. The energy absorbed during rapid fracture was measured using a Charpy impact tester in order to assess impact resistance.

Fatigue test

The composite's low fatigue analysis is performed using a tension-tension electromagnetic power assisted fatigue testing machine (MTS, Bionic, USA). Dog boned test samples are used do for testing with a young's modulus of 5GPa, stress ratio of -1, frequency of 5 Hz in accordance to ASTM D3479-19. The results are plotted stress vs. no of cycles and the causes of failure are reported.

Creep test

The creep test was conducted using the protocols laid out by ASTM D2990-17. The elongation of specimens was measured as a function of time under a constant tensile force. An important aspect of assessing a computer's long-term performance is learning how it deforms over time when subjected to persistent stress, and our test did just that.

Water absorption

Following the procedures outlined in ASTM D570-98 (2018), we performed the water absorption analysis. Weighting and immersion in room-temperature distilled water were the first steps in preparation for the test. The samples were

(a)

(b)

(c)

Fig. 6 **a** Mechanical test setup **b** fatigue test setup of prepared composite **c** creep test setup of prepared composite

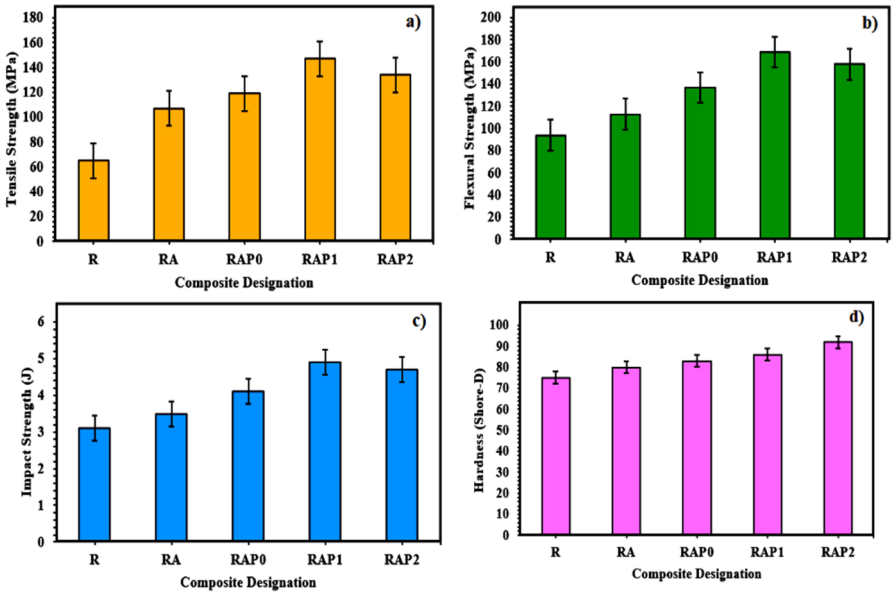

Fig. 7 Mechanical characteristics of the composites

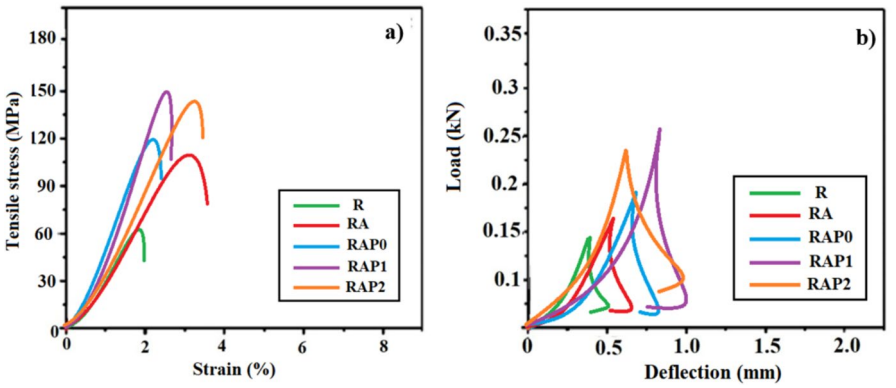

Fig. 8 **a** and **b** stress strain curve and load deflection curve of tensile and flexural test respectively

taken out, rinsed of any surface water, and then weighed again at predetermined intervals. In order to determine the hydrophilicity of the composite, the percentage of water absorption was computed. The endurance of the composite in situations prone to moisture or with high humidity could not be determined without this test.

Results & discussions

Analysis on mechanical characteristics

Figure 7 shows the relationship between the mechanical properties of the areca nut fibre and the strength, stability, stiffness, toughness, and durability of pectin reinforced epoxy composites under varying loading situations. The stress strain curve for the tensile test and the load deflection curve for the flexural test are shown in Fig. 8 a and b. The 100-volume matrix R is simple. With tensile strength of 65 MPa, flexural strength of 94 MPa, impact energy of 3.1 J, and shore-D hardness of 75, epoxy exhibited minimum mechanical behaviour. They have minimal behaviour because they are intrinsically brittle and have a low elongation at break, making them susceptible to breaking under stress [30]. The 30 vol. RA reinforced with areca nut fibres has excellent mechanical properties, including a tensile strength of 107 MPa (64.6% of the total), a flexural strength of 113 MPa (20.2% of the whole), an impact strength of 3.5 J (12.9%), and a shore-D hardness of 80 (6.66%). The improved mechanical properties are due to the fibres' ability to bridge cracks, limit deformation, and distribute stress more effectively than pure epoxy resin [31]. A combination of improved stress transfer and matrix adherence also increases toughness.

Not to mention volumes 1 and 3. The RAP0 and RAP1 pectin reinforced composites achieved tensile strengths of 119(83%) and 147(126%) MPa, flexural strengths of 137(45.7%) and 169(79.7%) MPa, impact strengths of 4.1(32.2%) and 4.9(58.7%) J, and shore-D hardnesses of 83(10.6%) and 86(14.6%), respectively. By making the matrix more continuous and encouraging better stress distribution across the composite, an increase in pectin content enhances mechanical behaviour [32]. The natural polymer chains of pectin have the ability to create hydrogen bonds with fibres, which enhances the adhesion between surfaces. Both the tensile strength and the flexibility are enhanced as a result. Furthermore, pectin has the capacity to lessen brittleness, which in turn enhances toughness and durability [33]. However, composite RAP2 with higher pectin content up to 5% vol. % produced lower result outcomes duet to the agglomeration [34]. As a result of the inherent stiffness of the fillers, the surface of the composites becomes harder, leading to an improvement in hardness to 92 Shore-D, a 22.6% improvement above R.

Scanning electron microscopy (SEM) was used to analyse the surface morphology of the epoxy composites that were reinforced with areca nut fibre and pectin. Figure 9a shows micro voids and fibre pull outs, which point to localised debonding of the fibres and interfacial failure as a result of insufficient stress transfer. There is no noticeable micro-cracking or detachment in Fig. 9b, which indicates that the pectin particle is properly encapsulated and that there is robust adhesion between the particle and matrix. Figure 9c further shows that the silane treatment resulted in a consistent distribution of pectin particles throughout the matrix, with minimum voids. This indicates that the filler was well-interacted with the resin [35, 36]. Figure 9d shows that at greater concentrations, the morphology becomes more densely packed and roughened, with clusters of areca fibre and fillers. This suggests that agglomeration could happen.

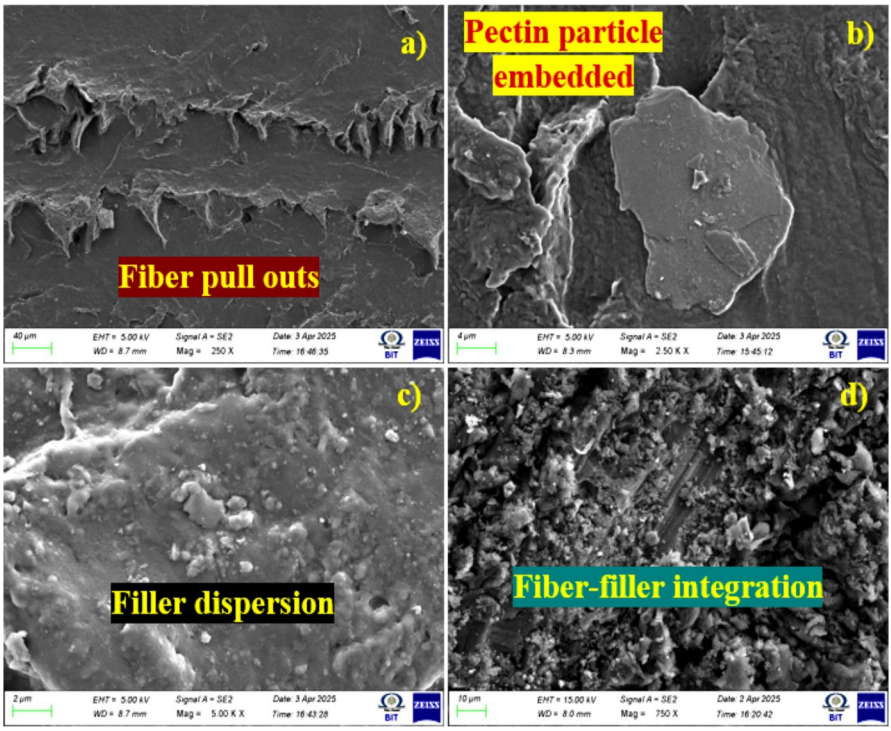

Fig. 9 **a** fibre pullout, **b** Toughness improved matrix, **c** filler dispersion and **d** fibre-filler interface

Low cycle fatigue failure analysis

At 25% Ultimate Tensile Strength (UTS), the base specimen failed after 17,981 cycles; at 50% UTS, it was 16,551 cycles; and at 75% UTS, it was 15,515 cycles. These are the lowest fatigue life counts observed. Due to micro-voids and a lack of reinforcing agents, the material's capacity to absorb and dissipate cyclic stress is reduced, leading to poor performance [37]. Alternatively, the fatigue life of the composites reinforced with areca nut fibres and treated with silane was significantly improved. The failure cycles for these composites were 18,316 (25% UTS), 17,958 (50% UTS), and 16,851 (75% UTS), respectively. Improved interfacial adhesion is the result of functional groups introduced to the fibre surface during silane treatment. These groups form chemical bonds with the matrix. There will be less chance of microcrack formation and interfacial debonding because of this stronger link, which allows for more effective stress transmission during cyclic loading. Composites made with RAP0 (1 vol. %) and RAP1 (3 vol. %), which are silane-treated fillers, also showed markedly better fatigue performance. The enhanced performance is because the silane-treated fillers are distributed evenly throughout the composite, which reduces the likelihood of failure due to localised

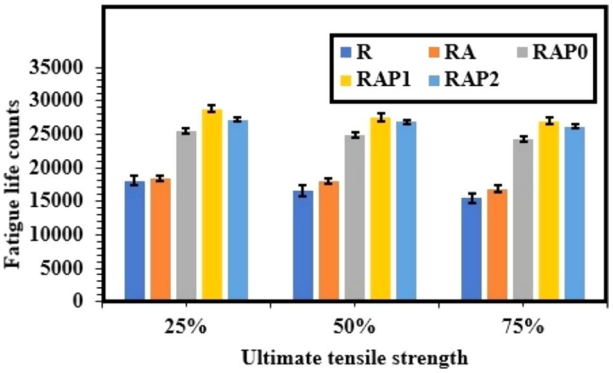

Fig. 10 Fatigue life counts of the prepared composites

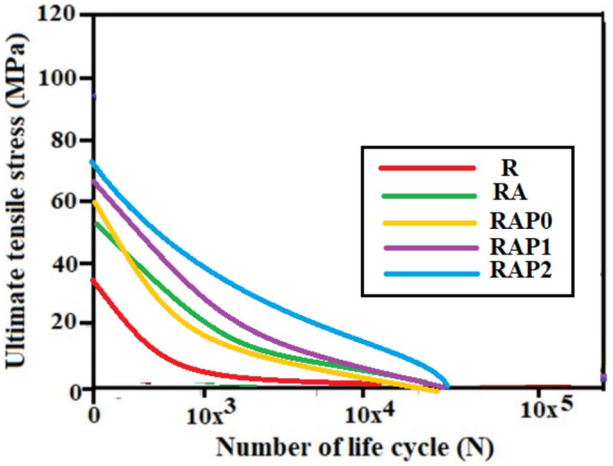

Fig. 11 SN curve of fatigue test conducted composite specimen

stress concentrations [38]. The RAP2 composite, on the other hand, showed a little reduction in fatigue life, with 2,7135 cycles at 75% UTS, 26,885 at 50% UTS, and 27,184 at 25% UTS. The high filler content probably causes the performance drop because it encourages agglomeration and breaks the polymer matrix's continuity. The material's deformability and cyclic energy absorption capabilities are diminished due to these agglomerates, which make the material more brittle and prone to fatigue failure. An RAP1 composite including three volumes stood out among the other samples. The fillers that were treated with silane had the most impressive fatigue performance. By striking the right mix of filler content and interfacial compatibility, it allows for improved energy absorption, longer fatigue life under repeated loading circumstances, and effective stress distribution.

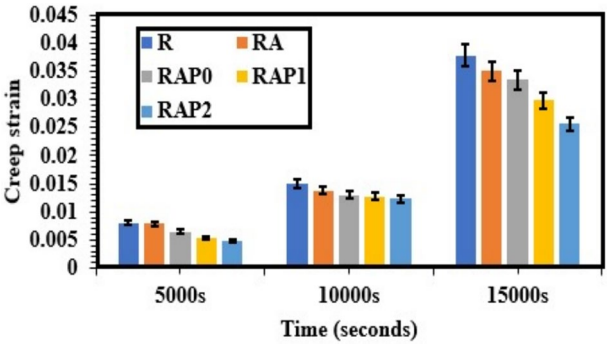

Fig. 12 Creep strain vs. time of the composites

Counts of fatigue life for the prepared composites are shown in Fig. 10. The composite specimen's SN curve from the fatigue test is shown in Fig. 11.

Low temperature creep failure analysis

Figure 12 displays the creep behaviour of the composites. At5000,10,000, and 15,000 s, the creep strain values for the base resin sample (R) are 0.0081, 0.0150, and 0.0378, respectively. The polymer's amorphous structure is responsible for this behaviour; when subjected to high temperatures or prolonged stress, the molecular chains relax, causing deformation that varies with time [39]. The composite RA's creep resistance is somewhat better after fibre integration; after 5000, 10,000, and 15,000 s, the corresponding values are 0.0079, 0.0138, and 0.0350. Polymer chains are able to move more slowly due to the relaxation process that causes creep when fibres are present in the matrix [40]. The addition of filler content to composites RAP0, RAP1, and RAP2 further enhances their properties. The samples show reduced creep strain values at various time intervals: 5000 s: 0.0065, 0.0054, and 0.0048; 10,000 s: 0.0130, 0.0128, and 0.0123; and 15,000 s: 0.0335, 0.0298, and 0.0256. Because pectin strengthens the matrix and limits molecular mobility under long-term loading, creep strain reduces as pectin content increases. Deformation that is reliant on time is decreased as a result of improved stiffness and load transmission. Better fiber-matrix bonding also reduces structural relaxation and slippage [41].

Hydrophobicity

Polymer composites are tested for their ability to absorb water in order to gauge their dimensional stability, performance in damp or damp settings, and overall longevity. As shown graphically in Fig. 13, the water absorption of the epoxy composites is taken note of. The firmly cross-linked molecular structure of pure epoxy prevents water molecules from penetrating the initial specimen R, which contained 3.5% water. Further, epoxy's hydrophobic properties limit its capacity to connect with water, which aids in preserving the material's dimensions and shields it from

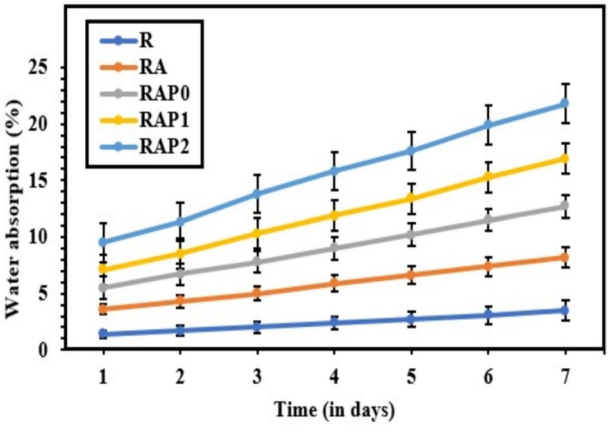

Fig. 13 Water absorption behaviour of the composites

degradation caused by moisture [42].Due to their hydrophilic character as a result of their cellulose content, which quickly absorbs moisture, the water absorption percentages in the composite RA rose to 4.7% with the addition of areca nut fibre [43]. The increase in water absorption is due to the fact that these natural fibres open up additional channels and spaces for water to enter.

At the same time, composites RAP0 and RAP1 had water absorption capabilities that decreased as the pectin content decreased from 4.5 and 4.2%, respectively, to 1 and 3 vol. %. Reason being, pectin increases matrix consistency by filling microvoids, which in turn limits water routes. Also, it makes the fibres and matrix stick together better, which means there are less spaces for water to get in. Without adding too much hydrophilic substance, the tiny amount of pectin creates a consistent barrier. Minimising moisture uptake is made easier with this balance.

On the flip side, water absorption increased by 4.9% due to the higher filler content of 5% pectin by volume. Because of its properties as a hydrophilic polysaccharide, pectin enhances water absorption when its concentration is high. The composite's water affinity increases when pectin content is high because it introduces more polar –OH groups [44]. Matrix homogeneity can be disturbed, leading to the formation of microvoids that facilitate water infiltration. The resistance of the composite to moisture is diminished as the pectin content increases.

Conclusions

This present study provided the comprehensive analysis of load bearing and time dependent properties of composites. The composites are made using areca nut fibre along with pectin. The composites are made via hand layup process and hot cured. According to the results, the load bearing properties are improved with fibre addition as well as pectin addition. A highest tensile strength of 147 MPa is recorded for composite RAP1, this indicates that the presence of pectin at 3 vol.% improved the

load bearing effect firmly. Moreover the same composite is outperformed in fatigue behaviour too. A highest fatigue cycle of 28,781 is observed at 50% of UTS without early failure. However, the composite that contained 5 vol. % of pectin showed an improved creep resistance with a the maximum hardness of 92 Shore-D. These findings point to improved dimensional stability and durability against deformation over time. On the other hand, due to filler agglomeration, which can cause microvoids and allow moisture entry, this composite had the greatest water absorption rate at 4.9%. Regardless, the fibre and pectin were treated with silane, which greatly improved their compatibility with the epoxy matrix, decreased their hydrophilicity, and increased their stress transmission efficiency. Taken together, the results show that bio-based composites can get a good mix of strength, durability, and resistance to environmental factors with the right amount of pectin and the right kind of surface modification. These materials are highly suitable for uses that require mechanical strength and resistance to moisture, including as building panels, automobile parts, and consumer goods.

Practical applications

The work offers specific applications where lightweight, durable and environmentally friendly composites are required. The advantages includes:

- Interior automotive components: Door panels, dashboard backing plates and trunk liners where moderate strength, fatigue resistance and low weight are critical.
- Construction applications: Ceiling boards, partition panels and wall claddings where moisture resistance and dimensional stability under load are required.
- Eco-friendly furniture components: Chair seats, backrests or armrests which benefit from both mechanical durability and biodegradability.

Industrial limitations and solutions

- Moisture sensitivity at high pectin content:
- Limitation: Increased water absorption may compromise dimensional stability and long-term performance in humid environments.
- Solution: Surface coatings or incorporation of hydrophobic additives reduces water uptake while retaining bio-based content.
- Filler agglomeration
- Limitation: Poor dispersion at high pectin levels lead to stress concentration and inconsistent mechanical performance.
- Solution: High shear mixing or ultrasonication during composite fabrication ensures uniform filler dispersion.
- Scalability and Process time
- Limitation: Manual fabrication methods may not suit high volume industrial production.

- Solution: Adapt processing to compression molding or resin transfer molding for faster and scalable production.

Future scope

- Hybrid reinforcement: Combining areca nut fiber with other natural or synthetic fibers to tailor performance for specific industrial needs.
- Thermal and Fire retardancy: Investigating thermal stability and flammability behaviour for application in electronics and transportation.
- Long term studies: Evaluating UV resistance, microbial degradation and moisture cycling performance for outdoor applications.
- Biodegradability and End of life analysis: Studying environmental impact, recycling potential and lifecycle performance for outdoor applications.
- Integration with bio resins: Replacing epoxy with bio-based resins to develop fully sustainable, petroleum free composite systems.

Conflict of interest

The authors declare no competing interests.

Author contribution All authors equally contributed.

Data availability No datasets were generated or analysed during the current study.

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