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ORIGINAL ARTICLE

Characterization of vinyl silane-treated biomass cellulose and banana fiber on reinforced unsaturated polyester composite

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Abstract

This study examined the biocomposites consisting of unsaturated polyester (UP) reinforced with twill-woven banana fiber (TBF) and cassava root cellulose (CRC). The main objective of this study is to synthesize cellulosic particle from waste biomass and treat them with triethoxy-vinyl silane in order to examine the load-bearing properties of the composites. The cellulose is synthesized from the biomass via the thermo-chemical method and extracted cellulose and fiber-reinforced composites were fabricated using the hand layup method. The composites were allowed to cure sufficiently (24 h) and post-cured for 48 h. The results of the research demonstrated that the polyester matrix (61 vol.%) along with cellulose particle (4 vol.%) and banana fiber (35 vol.%) reinforced composite (PCB3) exhibited a maximum tensile strength of 130.5 MPa, a flexural strength of 155.2 MPa, an interlaminar shear strength of 5.52 GPa, an Izod impact toughness of 6.03 J, and a hardness of 83 Shore-D. Similarly, the same composite sample (PCB3) showed the lowest specific wear rate of 0.009 mm^3/Nm. Furthermore, it was discovered that all of the composite fabricated plates exhibited a better water absorption and contact angle behavior exceeding 70°, which suggests that their hydrophobic nature is still preserved. Further, the scanning electron microscopy (SEM) images revealed improved particle dispersion and reacted phases of fiber and particle with matrix. Thus, the present research study highlights the crucial need of establishing a robust link between the matrix and reinforcing fibers and how the inclusion of cellulose particles has been demonstrated to have advantageous impacts on improving mechanical characteristics. In addition, due to their improved strength, biodegradable, less dense, corrosive resistance nature, they could potentially be utilized in several specific applications, including automobile panels, drones, defense products, structural products, and sporting goods.

Keywords Composites · Polymer · Natural fiber · Biofiller · Mechanical properties · Wear · Hydrophobicity

1 Introduction

The recent climate change has threatened the living beings in the world. It is very important to make environmentally friendly and biodegradable materials [1, 2]. Consequently, most corporations globally, such as those in the automotive, energy, defense, and medical industries, are presently endorsing sustainable development [3]. In the present era, many car manufacturers are using biocomposite materials into their products due to their cost-effectiveness, absence of toxicity, environmental advantages, ability to decompose naturally, and contribution to the circular economy [4, 5]. There are numerous testimonials regarding the load-bearing capacities of composites made with eco-friendly components. Neher et al. [6] conducted a study to examine the physical, mechanical, and thermal characteristics of a composite material made from banana fiber and HDPE. The composite material in this study is created by adding 5%, 10%, 15%, and 20% of banana fiber to the matrix. The author's research states that the inclusion of 5% banana fiber reinforced composite results in improved flexural capabilities.

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Furthermore, increasing the weight percentage of the fiber up to 20% boosts the thermal stability property of the composite. Nguyen et al. [7] assessed the mechanical and flammability properties of a composite material made from epoxy reinforced with banana fiber. This study utilizes banana fiber, which comprises up to 25% of the material, and undergoes pretreatment with a NaOH solution. The study's findings indicate that the inclusion of fiber up to 20 wt% combined with silane treatment improves the tensile, compressive, impact, and flammability properties. Moreover, other researchers have conducted similar studies including the use of banana fiber mat-reinforced polymer composites. Moreover, Hossain et al. [8] investigated the strength properties of banana fiber-reinforced polyester composite. Based on their investigation, the addition of 20 wt% of fiber into the composite shows excellent mechanical and bending strength properties of the composite material. Furthermore, the carbon fiber, banana fiber possesses the qualities of being lightweight, robust, and environmentally advantageous.

Therefore, banana fiber mats were used for this experiment. In addition, scientists are investigating the use of biofillers as a feasible substitute for enhancing composites composed of natural fibers [9]. Cellulose offers several advantages, including thermal stability, outstanding tensile and modulus strength, a high tensile strength to weight ratio, and excellent mechanical characteristics. Research has shown that processed cassava cellulose has the capability to function as a natural substance that fills gaps and enhances the physical characteristics of polymer composites. Previous research on this topic has been limited [10]. The cassava roots were used as a cellulose source due to their common occurrence as biowaste. Cassava is considered one of the top three important crops due to its roots' high starch content. While both humans and animals use the tubers of cassava, the roots are specifically used for planting. Regrettably, a significant proportion of the roots end up being discarded, either by being incinerated in public or left abandoned in the fields, posing a potential threat to the environment [11].

As a result of this, Jagadeesan et al. [12] performed a study on a composite material made of cellulose particles derived from biomass and reinforced with basalt and banana fibers. The cellulose utilized in this research is derived from the residual biomass of waste sesame oil cake, with a weight percentage ranging from 0 to 10%. The author's conclusion states that the composite plate produced with a cellulose particle content of 5 wt% exhibits the highest tensile, flexural, and impact qualities. Alshahrani et al. [13] conducted a study where they studied the impact of using microcrystalline cellulose extracted from waste green pea pod biomass and hemp fiber to reinforce polyester composite. They specifically focused on analyzing the changes in mechanical characteristics. In addition, the author stated that the inclusion of 2 vol.% of silane-treated microcrystalline cellulose, coupled with silane-treated natural hemp fiber reinforcement, results in the highest levels of tensile strength and impact strength. Furthermore, this combination improves the adhesion between the composite materials by enhancing the interfacial bonding.

Furthermore, Gugulothu et al. [14] studied a composited fabricated using microcrystalline cellulose and bamboo fiber-reinforced polyester composite. The author reported that the inclusion of 40 vol.% of bamboo fiber and 4 vol.% of cellulose particle shows a 39% and 42% increase in tensile and flexural strength, as well as shows the lowest specific wear rate of 0.011 mm^3/Nm. Thus, the aforementioned research studies have demonstrated that chemically treated filler and fiber particles exhibit superior bonding adhesion and mechanical qualities in comparison to untreated fiber and filler particle reinforcement. Various treatment methods were applied, including acid treatment, base therapy, amine silane treatment, and vinyl silane treatment. Among these, vinyl silane functions as a coupling agent, adhesion promoter, and cross-linking agent. The vinyl groups on the silane molecule have the ability to undergo reactions with functional groups that are found on the surface of the fiber or filler, as well as with the polymer matrix, during the production of the composite material [15]. Kanimozhi et al. [16] examined the impact of vinyl silane functionalized rice husk ash-reinforced unsaturated polyester nanocomposite by analyzing its characteristics. The effects of vinyl silane treatment on the fillers are analyzed using FTIR, SEM, XRD, and Goniometry techniques. The findings from the aforementioned observations demonstrate that the use of vinyl silane-functionalized rice husk ash as a reinforcement in the resin matrix leads to significant improvements in morphological characteristics, as well as increased tensile, flexural, impact, and hardness strength. Additionally, it exhibits a favorable water contact angle characteristic. Shaniba et al. [17] conducted an assessment of the mechanical and thermal characteristics of a composite material made from styrene-butadiene rubber reinforced with peanut shell powder treated with vinyl silane. The author concluded their research based on the acquired findings, which demonstrate that surface changes on peanut shell powder enhance the interfacial bonding adhesion and thermal stability qualities of the composite material.

Nevertheless, there have been a restricted number of investigations conducted on composite materials treated with vinyl silane. Further, there was no such study found on vinyl silane-treated cellulose particle and banana fiber-reinforced composite material. Therefore, in order to fill such research gaps, the present study aims to investigate a composite material using chemically modified cellulose from banana and cassava tuber roots. Consequently, the research has investigated the mechanical, wear, and hydrophobic characteristics of composites reinforced with silane-treated fibers and filler particles. The laminates were subsequently characterized according to the relevant ASTM criteria by a manual layup process. These environmentally friendly composites have the potential to be utilized in several specific applications, including automobile panels, drones, defense products, structural products, and sporting goods.

2 Materials and methodology

2.1 Raw materials used

The unsaturated polyester resin with a density of 1.43 g/cm^3, and the catalysts of Methyl ethyl ketone peroxide of density 1.16 g/cm^3 and this resin and catalysts were procured from Herenba chemical instruments, Chennai, India. The 1.1 g/cm^3 density twill-woven banana fiber mat with each fiber diameter of 200–250 μm and thickness of 0.8 mm, which was supplied by Metro Composites, Chennai, India. Similarly, the vinyl silane called triethoxyvinylsilane has a density of 0.903 g/ml at 25 ℃, and it was used for the surface treatment of fiber and cellulose. This vinyl silane was purchased from Sigma Aldrich, USA. The cellulose particle is prepared from cassava root and it was purchased from a local market.

2.2 Synthesis of cellulose particle

The excavated cassava roots were repeatedly washed with water to get rid of the dirt and sand particles. After that, the roots are divided into tiny pieces and left to dry for 10 h in a hot air oven. Next, a mechanical grinder is used to powder the dried roots for roughly 30 min at a higher rpm of 1500. Next, 88 cm^3 of pure water and 12 ml of 1 mol NaOH were combined with the powder.

After that, the suspension was heated to 80 °C for 2 h on a hot plate and left to dry for 24 h. To make the solution in relation to this, 50 cm^3 of distilled water was combined with sodium hypochlorite (NaOCl). After that, the mixture was heated to 80 °C for 1 h in a magnetic stirrer [18]. The solution can be poured onto filter paper to remove the particulates. This powder is cleaned with distilled water to return it to a pH of neutral. After the powder was created, 3 h of drying in a hot air oven was used to extract the cellulose. The extracted cellulose particle has a size of 1–3 μm. Figure 1 illustrates the cellulose preparation processes.

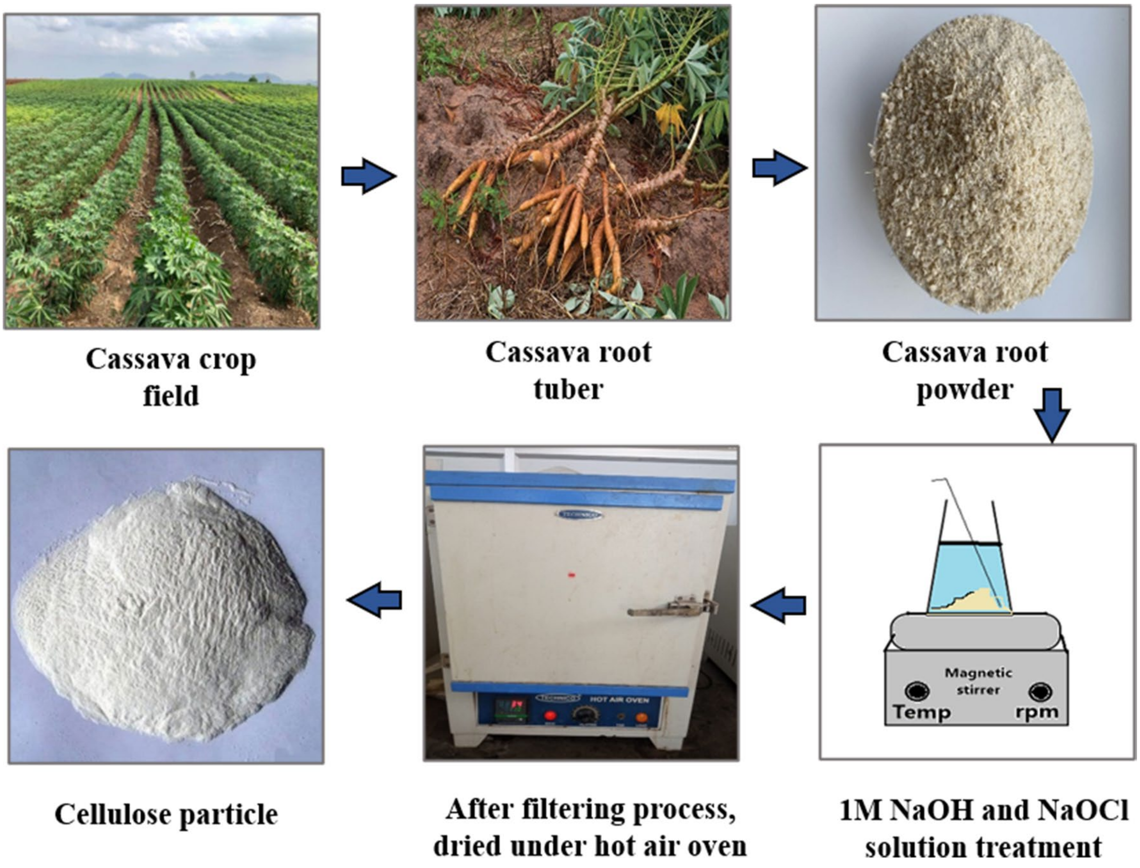

Fig. 1 Cassava root extracted cellulose particle

2.3 Silane treatment on *fiber* and filler substances

In addition, the cellulose particles and fiber undergo surface treatment using triethoxy vinyl silane. The fiber and filler were initially treated with a solution of triethoxy vinyl silane (1%, w/w) and dicumyl peroxide (0.5%, w/w) in a 90% methanol (250 ml) solution. The acidity level of the solution was modified to a pH range of 3.5–4 by adding acetic acid [19]. The solution was agitated incessantly for 2 h. The fibers and fillers were rinsed with distilled water and then dehydrated in the air oven at a temperature of 60 °C for a duration of 24 h.

2.4 Composite fabrication

In this investigation, a two-stage composite preparation method was employed. First, the vinyl silane is used to silane treat the fiber and cellulose particles. The second phase was using the hand layup method to combine fiber and cellulose to make a composite. To make a homogenous mixture, first combine the cellulose and polyester resin and stir gently for 20 min. Then the Methyl ethyl ketone peroxide (MEKP) and cobalt were added to the polyester resin as a hardener and catalyst. Following that, the composite was placed within a wax-coated silica rubber mold. Lastly, a 35 vol.% twill-weaved banana fiber mat was laid in a 0–90° angle form and pressed firmly [20]. Using a cotton roller, the excess resin and trapped air bubbles were removed, and the mixture was then left to cure for 24 h at room temperature. In addition, the composites are cured in a hot air oven for 4 h at 120 °C. Table 1 is a list of the composites and their components, and Fig. 2 shows the composite fabrication flowchart.

Table 1 Composites and compositions

Composite designations	Polyester resin (vol.%)	Twill-woven banana fiber (vol.%)	Cellulose (vol.%)
P	100	0	0
PB	65	35	0
PCB1	64	35	1
PCB2	63	35	2
PCB3	61	35	4

3 Characterizations of composites

The post-cured silane-treated composite material was tested further to identify the performance of the material. The testing specimen is cut under an abrasive water jet machine, Maxieum KENT 1515, USA. The process variables for the abrasive water jet machine were a standard deviation of 0.3, a particle size range of 10 to 30 microns, and a water-impinging pressure of 170 psi. In order to obtain well-finished specimens, a 0.3 mm diameter nozzle was used. The testing is done based on ASTM standard. The testing specimen as per ASTM standard is mentioned in Fig. 3, and the testing standards and machine specification for testing are represented in Table 2.

4 Results and discussion

4.1 Mechanical properties

The tensile and flexural test results (Fig. 4) reveal remarkable enhancements in mechanical properties across various composite designations compared to the base specimen, denoted as P. Starting with P, the tensile strength

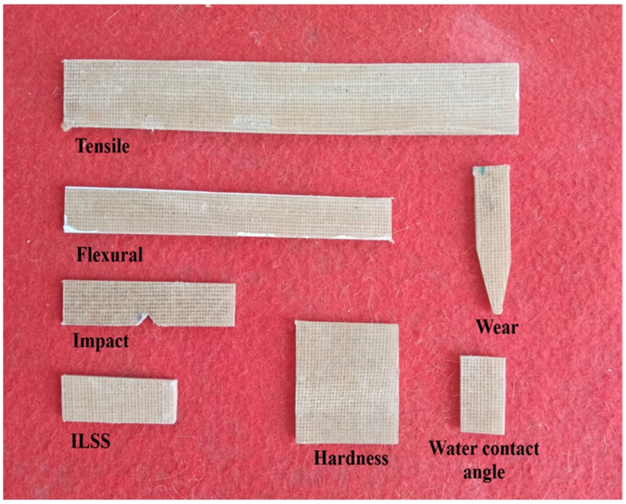

Fig. 3 ASTM standard testing specimen of the composite

Fig. 2 Composite fabrication procedure flowchart

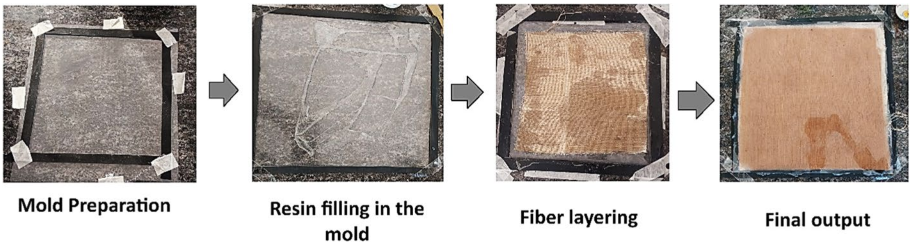

Table 2 ASTM and specification standards for various tests

Tests	ASTM standards	Machines specifications
Tensile strength	D-3039	FIE Universal testing machine, having ball screw driven mechanism. The samples were end-tapped and gripped using hydraulic grippers. The traverse speed followed for all samples is 1.5 mm/min
Flexural strength	D-790–17	
ILSS	D-2344	
Izod impact	D256–10	A mini-impactor of 25 J capacity, Metro Precision Testing Equipment's, India
Hardness	D 2240	Surface hardness of the material is tested under Shore-d (Durometer)
Wear	G 99–17	Pin on disc method, Novus Tribological Solutions Private. Ltd. Load of 10N, speed of 800 rpm at dry condition, and sliding distance 1000 m were taken as process variables [21]
Hydrophobicity	-	Contact angle meter, Holmarc-01, India
Scanning electron microscope (SEM)	-	TESCAN, MIRA III, UK
TGA	-	E1131-NETZSCH STA Jupiter, 409 PL luxx, Germany

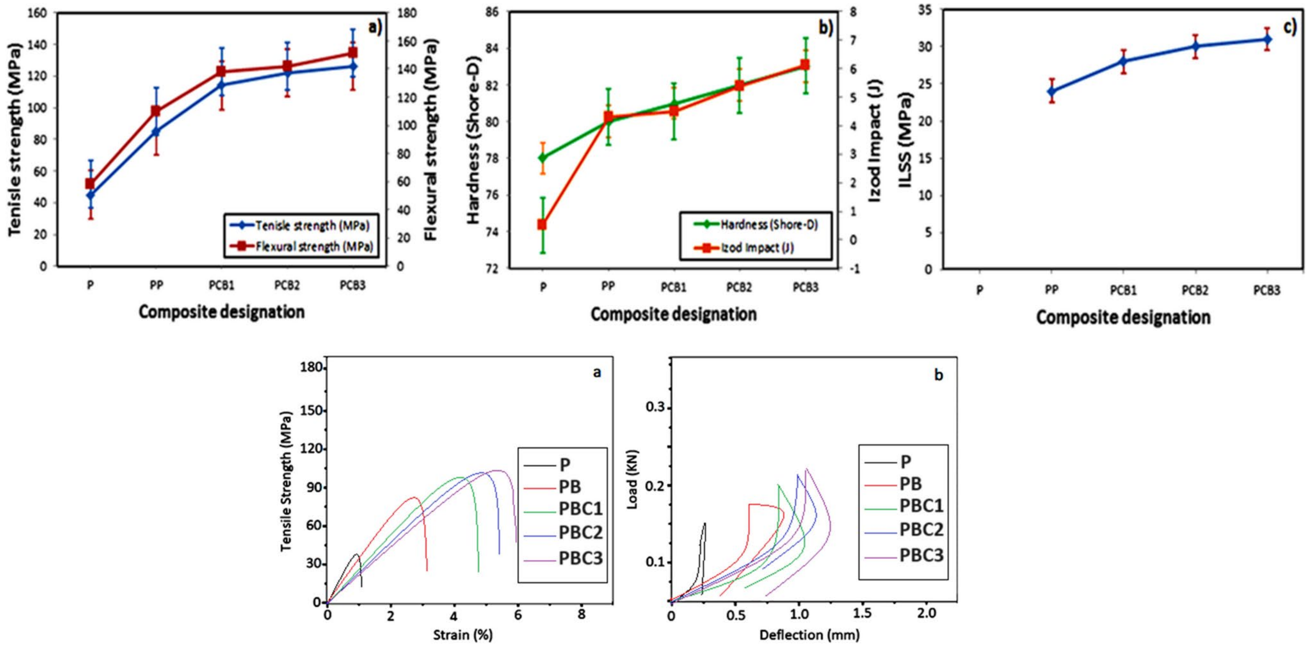

Fig. 4 Mechanical properties of various composite designations

was measured at 45 MPa, while the flexural strength stood at 58 MPa.Strength and stiffness are usually provided by reinforcements, but pure polyester resin causes a noticeable decrease in composite P's mechanical performance since it lacks the performance and durability of other matrix materials [22]. However, composite PP exhibited significant improvements, with its tensile strength soaring to 85 MPa and flexural strength to 110 MPa, representing percentage increases of approximately 89% and 90%, respectively, over the base specimen. The twill weave structure of banana fibers provides alignment in specific directions, enhancing load-bearing capacity. Aligned fibers contribute to increased tensile and flexural strengths, particularly in the direction of the weave. Moving to PCB1, further notable enhancements were observed, with the tensile strength reaching 114 MPa and flexural strength 138 MPa, indicating percentage increases of approximately 153% and 138%, respectively, compared to P. The combination of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber increases the composite's toughness.

Toughness refers to the ability of a material to absorb energy and deform without fracturing, contributing to improved mechanical properties. PCB2 showcased similar trends, demonstrating a tensile strength increase to 122 MPa and flexural strength to 142 MPa, corresponding to percentage increases of approximately 171% and 145%, respectively, over P. Composite PCB2 contains a higher volume fraction of reinforcing fibers, specifically vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber. Higher filler content results in more effective load transfer and distribution within the composite matrix, leading to enhanced mechanical properties. The extracted cellulose is integrated in the resin matrix to improve overall mechanical strength, distribute stresses uniformly, and strengthen the structure [23]. Most notably, PCB3 exhibited extraordinary enhancements, with its tensile strength surging to 126 MPa and flexural strength to 151 MPa, indicating percentage increases of approximately 180% and 160%, respectively, relative to the base specimen. The combination of cellulose and banana fibers increases the toughness of the composite, allowing it to withstand higher loads and deformations without failure. Enhanced toughness contributes to the overall improvement in mechanical properties, including tensile and flexural strengths.

Venkatesh et al. [24] investigated the effect of submicron pore-sized waste coffee emesis biochar on glass–epoxy composite thermal interface material. The author reported that the addition of glass fiber along with biochar increased the load-bearing effect. The authors reported a maximum tensile strength of 158 MPa; however, it is almost close to the current research value. Since the glass fibers used in the literature achieved 158 MPa. But for natural fiber, the achieved tensile strength is better. Similarly, Ahmad et al. [25] studied the water-soaking effect and influence of nanoclay on the mechanical properties of bamboo/glass fiber-reinforced epoxy hybrid composites. According to the author, the water soaking affects the mechanical properties.

The izod impact and hardness (Shore-D) test results unveil remarkable improvements in mechanical properties across various composite designations compared to the base specimen, designated as P. Initially, specimen P exhibited a hardness of 78 Shore-D and izod impact strength of 0.5 J. Subsequently, the composite PP demonstrated significant enhancements, with its hardness escalating to 80 Shore-D and izod impact strength to 4.3 J, translating to percentage increases of approximately 2.6% and 760%, respectively, over the base specimen. These improvements suggest not only augmented material hardness but also a substantial boost in its capacity to withstand impact forces.

In this, the fibers serve a major role in composite's reinforcing phase. Generally, the fiber reinforcement enhances the tensile strength of the material in order to maintain a substantial portion when force is applied, and thereby preventing or limiting the crack. This prevention of fiber results in energy absorption; by reducing the fibers' stiffness and tension in the direction of the applied load, this energy is helpful. This results in an increase in impact strength. Moving to PCB1, further noteworthy enhancements were evident, with the hardness reaching 81 Shore-D and the izod impact strength at 4.5 J, marking percentage increases of approximately 3.8% and 800%, respectively, relative to P. The amalgamation of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber fostered these enhancements by enhancing the material's resistance to indentation and deformation, as well as its ability to absorb impact energy. PCB2 exhibited analogous trends, showcasing an increase in hardness to 82 Shore-D and izod impact strength to 5.4 J, corresponding to percentage increases of approximately 5.1% and 980%, respectively, over P.

These elevated hardness values signify improved material durability and stiffness, while the substantial increase in izod impact strength underscores the composite's heightened capacity to dissipate impact energy without fracture. The enhanced resistance to impact forces was caused by the silane treatment of the fiber and cellulose as well as the significant toughening effect of cellulose in the matrix [26]. Remarkably, PCB3 demonstrated extraordinary improvements, with hardness surging to 83 Shore-D and izod impact strength to 6.1 J, reflecting percentage increases of approximately 6.4% and 1120%, respectively, relative to the base specimen. Generally, fillers are composed of harder materials and have a greater volume fraction. They also introduce surface roughness and texture, which increases hardness. When fillers with high hardness and abrasion resistance are dispersed properly, they make a better connection with the matrix. Therefore, compared to fiber-reinforced composites, these filler-reinforced composites exhibit higher hardness. The introduction of cellulose and banana fibers into the composite matrix not only elevated the material's hardness but also significantly enhanced its resilience against impact forces. This enhancement in material toughness positions PCB3 as particularly well-suited for applications necessitating both hardness and impact resistance. Further, uneven or varying-sized fillers have the ability to deflect cracks and generate stress, both of which cause energy to dissipate. Thus, the type of filler and volume percent of fillers increase the stiffness and flexibility of the composites, which generate energy that helps to stop fracture propagation and improve toughness. Therefore, compared to fiber-reinforced composites, an increase in silane-treated cellulose filler-reinforced composites has higher impact strength.

The interlaminar shear strength (ILSS) test results illustrate a significant improvement in mechanical properties across various composite designations compared to the base specimen, denoted as PP. Initially, fiber-reinforced PP composite has exhibited an ILSS of 24 MPa. In addition, the fiber is naturally rigid and robust. They have high mechanical properties as a result. The way that the fibers typically lay down improves their ability to tolerate shear forces between the layers, which increases stress transfer and improves the bonding between the fiber and matrix, improving the overall strength, stiffness, and ILSS. Moving to PCB1, notable enhancements were observed, with the ILSS increasing to 28 MPa, indicating a percentage increase of approximately 16.7% compared to PP. The incorporation of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber in PCB1 increases the toughness of the composite [27]. Enhanced toughness allows the composite to withstand higher loads and deformations without failure, contributing to the observed increase in ILSS. Similarly, PCB2 demonstrated a further increase in ILSS to 30 MPa, corresponding to a percentage increase of approximately 25% over PP. Most notably, PCB3 showcased extraordinary enhancements, with its ILSS surging to 31 MPa, marking a percentage increase of approximately 29.2% relative to PP. PCB2 and PCB3 benefit from enhanced interfacial bonding between the reinforcing fiber, filler, and the resin matrix.

Silane-treated fillers are usually uniformly dispersed tiny particles that enhance the toughness, strength, and stiffness properties of the composites. Additionally, fillers work in concert with fiber and matrix to create frictional resistance between the layers, which raises ILSS and overall strength. The shape of the fillers and their volume percentage and bonding nature in composite improved the ILSS property. Further, the improved bonding facilitates efficient stress transfer from the matrix to the filler, fibers, leading to increased ILSS values [28, 29]. Rajabipour et al. [30] researched on interlaminar shear properties of bamboo composite for structural applications. According to the author, the shear capacity decreased from 20.4 to 14 MPa as the humidity increased from 60 to 90%. However, in this present study, the composites achieved ILSS value more than the reported literature.

4.2 Wear properties

The specific wear rate and coefficient of friction (COF) test results in Fig. 5 demonstrate a progressive improvement in wear resistance and reduction in frictional forces across various composite designations compared to the base specimen, denoted as P. Initially, composite P exhibited a specific wear rate of 0.03 mm^3/Nm and a COF of 0.7. This large wear loss and COF is the reason for the brittle nature of resin, which could break when the continuous shear forces (force acting on the plane surface) are applied. The same is evident in the SEM image denoted in Fig. 6a. The worn surface shows a flat surface along with some erosive material removed part.

Moving to PP, notable enhancements were observed, with the specific wear rate decreasing to 0.02 mm^3/Nm and the COF reducing to 0.6, representing percentage reductions of approximately 33.3% and 14.3%, respectively, compared to P. These improvements suggest a decrease in material loss due to wear and a reduction in frictional forces, contributing to enhanced durability and smoother operation. The reason behind such improvement in wear resistance is due to the inclusion of fiber, which aids in more evenly dispersing the applied load across the composite material (Fig. 6b). Because of the homogeneous distribution, there are less localized stress concentrations, which leads to preventing microcrack formation and propagation, which eventually enhance the wear resistance property of the composite.

Subsequent composite designations, PCB1, PCB2, and PCB3, showcased further remarkable improvements in both specific wear rate and COF values. PCB1 demonstrated a specific wear rate of 0.015 mm^3/Nm and a COF of 0.55,

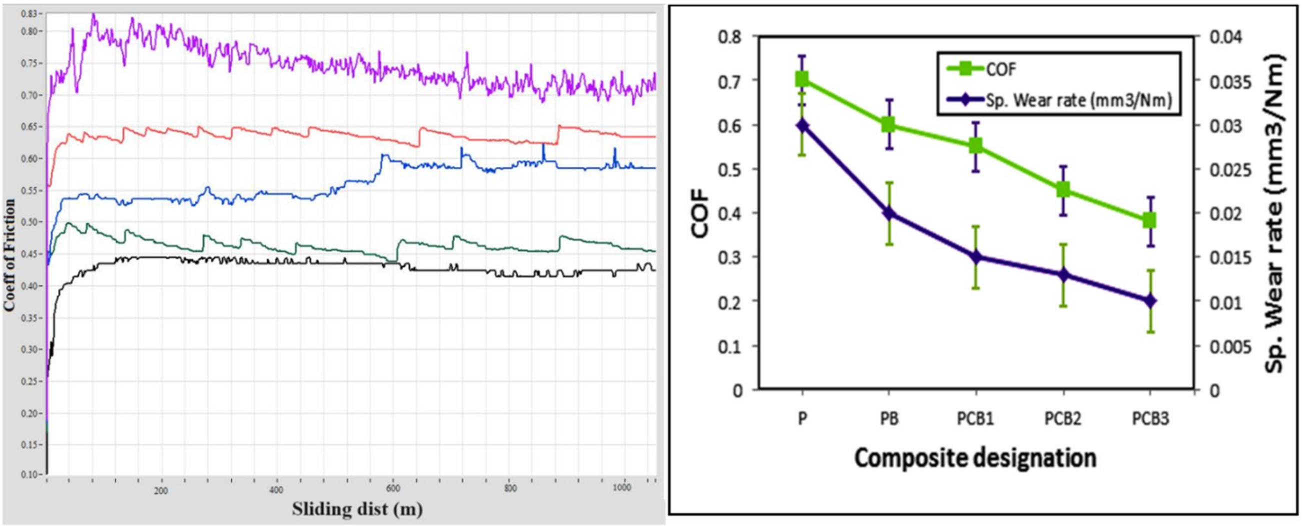

Fig. 5 Wear properties of various composite specimens

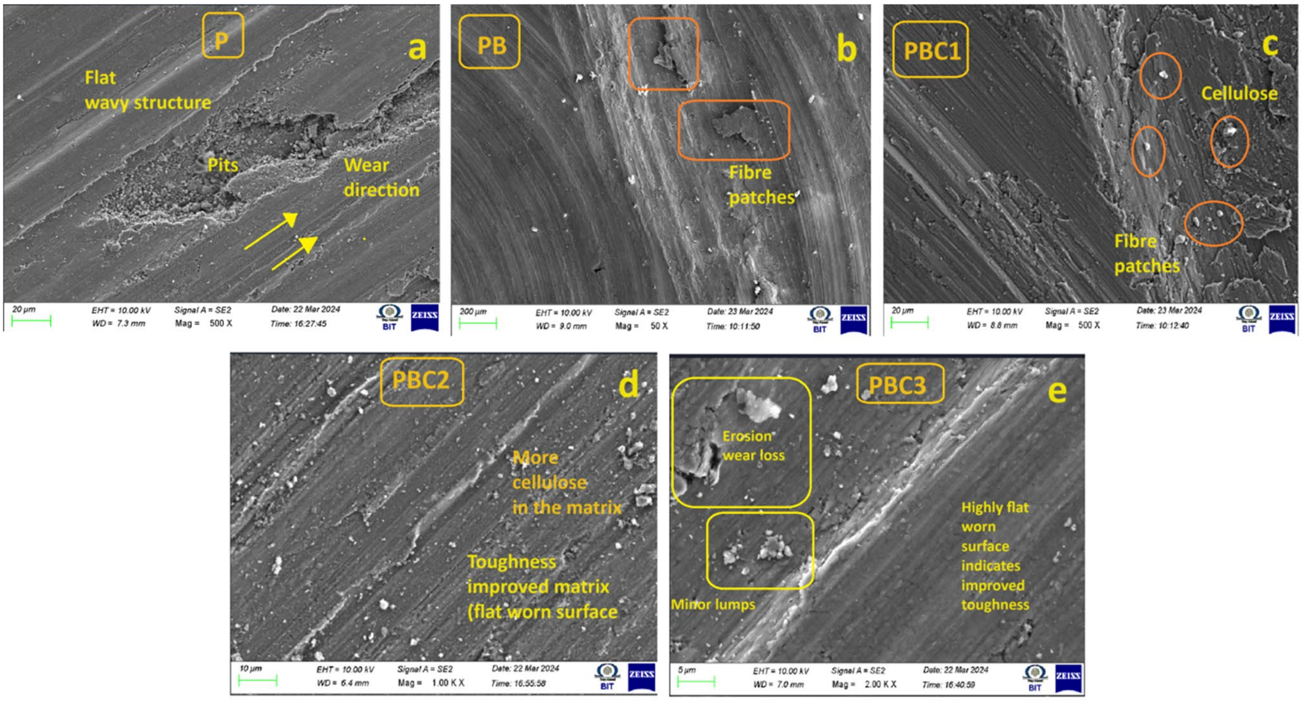

Fig. 6 SEM worn surfaces of resin and composites **a** P, **b** PB, **c** PBC1, **d** PBC2, and **e** PBC3

indicating percentage reductions of approximately 50% and 21.4% compared to P. Enhancing the material's resistance to wear is largely dependent on the addition of surface-treated fibers and cellulose particle into the matrix [31]. The addition of cellulose formed interpenetrating polymer networks and made rigid molecular structures. Thus the erosion and 3-body wear loss became less, which eventually reduced the overall wear volume. Figure 6c also ensures this claim and shows minor fiber patches and nor any material removed pits. The worn track is also flat indicating the toughness improvement.

Similarly, PCB2 exhibited a specific wear rate of 0.013 mm^3/Nm and a COF of 0.45, corresponding to percentage reductions of approximately 56.7% and 35.7%, respectively, compared to P. Most notably, PCB3 showcased extraordinary enhancements, with its specific wear rate reducing to 0.01 mm^3/Nm and its COF decreasing to 0.38, marking percentage reductions of approximately 66.7% and 45.7%, respectively, relative to P. The incorporation of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber in PCB1, PCB2, and PCB3 may increase the composite's toughness and resistance to surface deformation. Improved toughness helps the composite withstand abrasive forces and reduces material loss due to wear. PCB3 has a higher concentration of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber compared to the base specimen (P). Increased fiber reinforcement leads to improved mechanical properties, including enhanced wear resistance and reduced frictional forces.

The reason for this improvement is that the uniform distribution of silane-treated filler particles smooths the surface and creates strong connections with the molecules of polyester resin and enhances hardness by preventing deformation. These bonds together strengthen the material's resilience to wear and effectively minimize abrasion. Further, certain fillers function as solid lubricants, reducing friction between sliding surfaces and enhancing the composites' toughness and impact resistance. As a result, filler-reinforced composites outperform fiber-reinforced composites in terms of wear. Figure 6d and e also proves this phenomenon where the particles are dispersed well and reduced the material removal. However in Fig. 6e, in some places, the erosion wear loss is evident due to cellulose lumps. But overall the addition of fiber and cellulose particles into the resin firmly improved the wear resistance.

Keerthiveettil et al. [32] reported the wear properties of composites made using banana fly ash and sisal/pineapple hybrid fiber. According to the author, the addition of filler materials and hybrid fibers with the polymer matrix results in increased friction and reduced wear loss. However, the present study reported a much lower wear loss of 0.01 mm^3/Nm with a COF of 0.38. This is much lesser than that of the reported literature. Similarly, Reddy et al. [33] have done an evaluation of mechanical and wear performances of natural fiber-reinforced epoxy composites. The composites were fabricated for three different fibers with 20 wt% by hand layup method. According to results, the reported wear loss is higher than in the present study and it is because cellulose in the present study provided additional toughness.

4.3 Contact angle measurement

The contact angle test results (Fig. 7) unveil significant alterations in surface wettability across the composite designations, with notable changes compared to the base specimen, denoted as P. Initially, composite P exhibited a contact angle of 93°, suggesting a relatively hydrophobic surface. Upon transitioning to PP, there was a considerable decrease in the contact angle to 85°, indicating a shift towards increased hydrophilicity, and marking a percentage decrease of approximately 8.6% compared to P. Improved bonding between the reinforcing fibers and the matrix resin in composite PP results in a more homogeneous surface with fewer surface irregularities. Enhanced fiber-matrix interaction reduces the presence of air pockets or voids at the surface, promoting better wetting and a decrease in contact angle.

Subsequent composite designations, PCB1, PCB2, and PCB3, showcased further reductions in contact angles, indicative of enhanced surface hydrophilicity. PCB1 demonstrated a contact angle of 83°, followed by PCB2 with a contact angle of 79°, and PCB3 with a contact angle of 76°. These values represent percentage decreases of approximately 10.8%, 15.1%, and 18.3%, respectively, relative to P. The combination of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber in PCB1, PCB2, and PCB3 results in improved interfacial bonding between the fibers and the resin matrix. Enhanced bonding minimizes surface irregularities and promotes better wetting, contributing to reduced contact angles. The observed decrease in contact angles is caused by the cellulose included in these composites, which draws and reacts with water [34]. Furthermore, water molecules are absorbed by fillers, and certain fillers have the tendency to form hydrogen bonds with water. Because fillers are porous, they increase surface area and give the composite a rougher surface, which changes its wettability. Additionally, hydrophilic nature is influenced by composition and processing conditions. Therefore the silane-treated filler-reinforced composites have a lower water contact angle and a high hydrophilic nature as a result. Nagaraj et al. [35] investigated the effects of loading date palm seed/vinyl ester composites with cellulosic filler on their mechanical and thermal characteristics. The author discovered that the percentages of water absorption increased with additional filler.

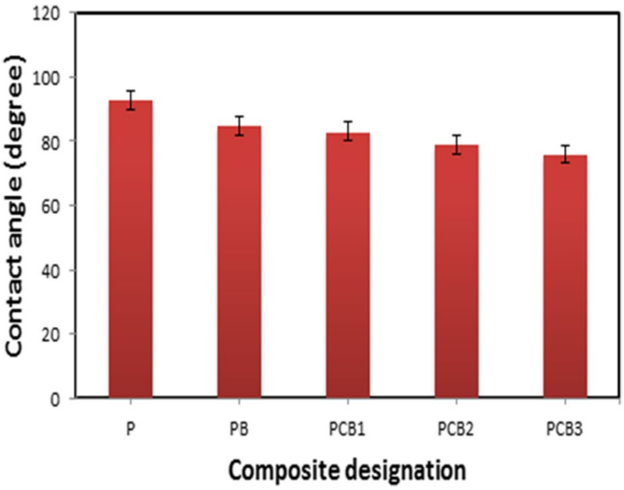

Fig. 7 Contact angle measurements of various composite specimens

4.4 SEM analysis

The SEM (scanning electron microscopy) analysis of tensile fractured composites is shown in Fig. 8. In Fig. 8a, the polyester resin mixture along with added cellulose particle are illustrated. And it demonstrates the uniform dispersion of filler particle along the matrix substance, which enhances the mechanical, bonding strength of the material. In Fig. 8b, the plain polyester surface was observed, revealing minor cracks and voids present within the matrix. These defects can weaken the overall structural integrity of the material. Figure 8c illustrates fiber pull-out, indicating low bonding between the matrix and fibers. This phenomenon can lead to reduced mechanical properties and compromised load-bearing capabilities of the composite. In contrast, Fig. 8d showcases reinforced bonding between the fibers and the matrix, along with the presence of cellulose particles. This indicates improved interfacial bonding, resulting in enhanced mechanical properties and increased toughness of the composite. Finally, Fig. 8e exhibits cluster particles of cellulose dispersed within the composite matrix. These clusters contribute to the reinforcement of the material, enhancing its overall strength and durability.

4.5 Thermogravimetric analysis

The TGA graphs in Fig. 9 illustrate the thermal stability of various composite materials derived from polyester resin, denoted as P, PP, PCB1, PCB2, and PCB3. Initially, the plain resin matrix, represented by P, exhibits a TGA% of 87% at a temperature of 421 °C. This relatively low TGA% is attributed to the susceptibility of polyester resins to thermal degradation, primarily due to the presence of ester functional groups. These ester linkages can undergo cleavage at lower temperatures, leading to the release of volatile compounds and consequent weight loss [36]. In contrast, the incorporation of banana fiber into the polyester resin matrix, denoted as PC, results in improved thermal stability,

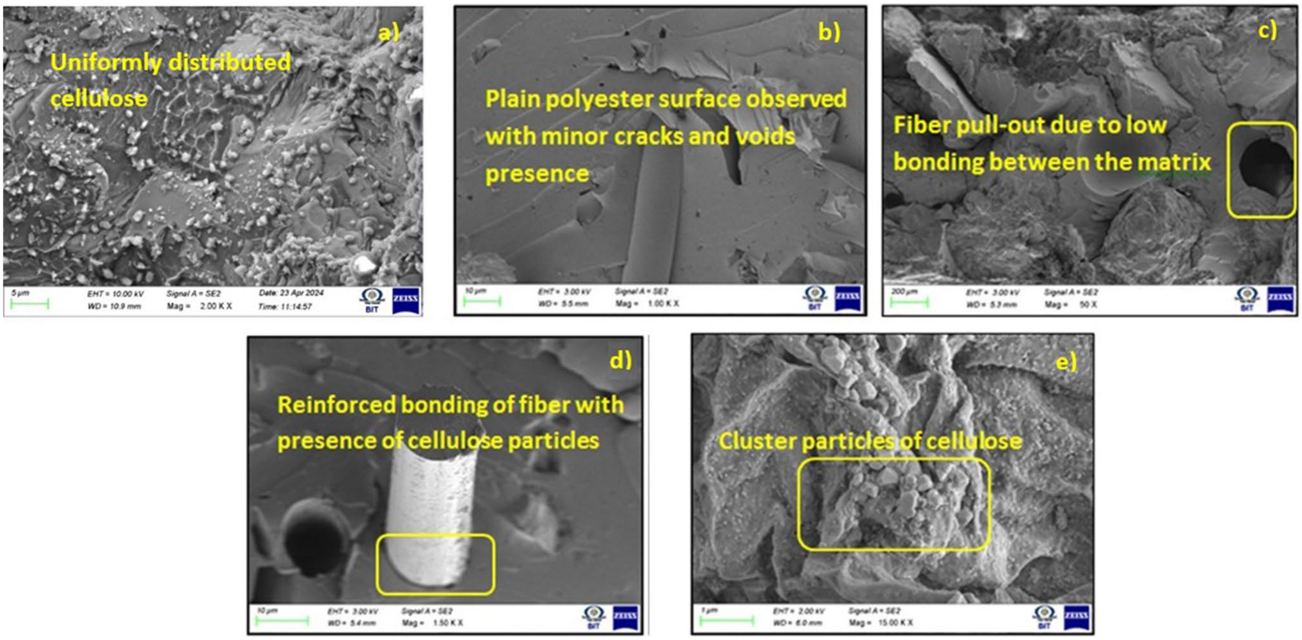

Fig. 8 SEM fractography of tensile tested samples

as evidenced by a TGA% of 92% at a temperature of 419 °C. Banana fiber, possessing inherent thermal stability owing to its chemical composition and structure, can elevate the decomposition temperature compared to the pure resin matrix. This delay in degradation onset contributes to the higher TGA% observed at lower temperatures [37].

Furthermore, the subsequent addition of cellulose to the composite, denoted as PCB1, PCB2, and PCB3, leads to progressive enhancements in thermal stability. These composites exhibit TGA% values of 94%, 97%, and 99%, respectively, at temperatures ranging from 430 to 456 °C. Cellulose, being a polysaccharide, is known for its capacity to form a stable char layer during thermal decomposition [38]. The inclusion of cellulose in the composite promotes additional char formation, thereby augmenting the protective barrier against thermal degradation. This increased char formation contributes to a further reduction in the rate of weight loss at elevated temperatures, consequently resulting in higher TGA% values. Overall, the sequential incorporation of banana fiber and cellulose into the polyester resin matrix progressively enhances the thermal stability of the composite materials, as evidenced by the increasing TGA% values and elevated decomposition temperatures. These improvements underscore the potential of natural fiber-reinforced polyester composites for applications requiring enhanced resistance to heat and thermal degradation.

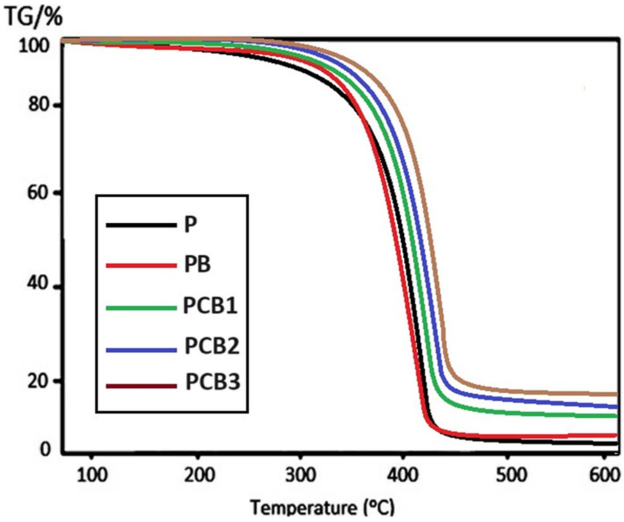

Fig. 9 TGA thermograms of composites

Wang et al. [39] studied the cellulose composites based on cellulose diacetate and nanofibrillated cellulose prepared by alkali treatment. According to the author, the treated fibers are better in thermal stability. Kumar et al. [40] studied thermal stability study on cotton pulp cellulose composite films with Napier grass cellulose fibrils. The author declared that the composites are degraded rapidly due to the cellulosic grass content. However, this present study the composite is withstanding for higher initial decomposition due to the presence of banana fiber.

5 Conclusions

In conclusion, the comprehensive evaluation of mechanical and surface properties across various composite designations demonstrates substantial enhancements compared to the base specimen, denoted as P. Starting with mechanical properties, the tensile and flexural strengths of the composites exhibited remarkable improvements. Composite PP exhibited significant enhancements with tensile strength increasing to 85 MPa and flexural strength to 110 MPa, marking percentage increases of approximately 89% and 90%, respectively, over P. Further enhancements were evident in PCB1, PCB2, and PCB3, with percentage increases ranging from approximately 153% to 180% in tensile strength and from approximately 138% to 160% in flexural strength compared to P. Additionally, the izod impact and hardness test results revealed substantial improvements across all composite designations. Composite PP demonstrated significant enhancements, with hardness increasing to 80 Shore-D and izod impact strength to 4.3 J, translating to percentage increases of approximately 2.6% and 760%, respectively, over P. Similar trends were observed in PCB1, PCB2, and PCB3, with percentage increases ranging from approximately 3.8% to 6.4% in hardness and from approximately 800% to 1120% in izod impact strength compared to P. Furthermore, the interlaminar shear strength (ILSS) test results demonstrated notable improvements in mechanical properties across PCB1, PCB2, and PCB3, with percentage increases ranging from approximately 16.7% to 29.2% compared to PP. Similarly, the specific wear rate and coefficient of friction (COF) test results showcased significant reductions across all composite designations, with percentage decreases ranging from approximately 33.3% to 66.7% in specific wear rate and from approximately 14.3% to 45.7% in COF compared to P. Lastly, the contact angle test results unveiled substantial decreases in contact angles across all composite designations, indicative of enhanced surface hydrophilicity, with percentage decreases ranging from approximately 8.6% to 18.3% compared to P. However, in the present study, certain limitations are there, due to hydrophilicity nature, it is not applicable in areas which are highly prone to water absorption such as housing applications, trains washtub cover material, marine engineering application, and some other water-prone domains. Overall, the combination of vinyl silane-treated waste cassava root cellulose and twill-weaved banana fiber in the composite matrix resulted in multifaceted enhancements in mechanical properties, wear resistance, and surface characteristics. These improvements position the composite materials as promising candidates for a wide range of applications requiring superior mechanical performance, durability, and surface functionality. Furthermore, SEM analysis provides valuable insights into the microstructure of the composites, highlighting the importance of proper bonding between the matrix and reinforcing fibers, as well as the beneficial effects of incorporating cellulose particles for improved mechanical properties. Thus, because of their less dense, low cost, and superior mechanical, wear, thermal stability, water absorption behavior, it is employed in door panels in the automobile sector, interior parts for housing, light-weight drone applications, and various recreational sectors, etc.

Author contribution Prabhu P and Gunaselvi Manohar — complete research; Karthikeyan T and Santhosh Kumar S — resting and manuscript drafting.

Data availability All data within manuscript.

Declarations

Ethical approval NA

Competing interests The authors declare no competing interets.

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