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ORIGINAL PAPER

Extraction of Lignin from Fluorescent Perianths of Jack Fruit and it's Mechanical, Wear, Creep and Flammability Behaviour of Abaca-Polyester Composites

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Abstract
This study investigates the mechanical, thermal, and morphological properties of abaca-polyester composites made using lignin from fluorescent perianths of jack fruit. The primary scope of this research is to study the viability of producing lignin from waste jack fruit fluorescent perianths and how it influence the mechanical, wear, creep and flammability properties of abaca-polyester composite. The lignin biopolymer was extracted via thermo-chemical method and composites were prepared using hand layup method. The produced composites were evaluated based on American society of testing and materials (ASTM) standards and the results revealed significant improvements in tensile and flexural strength. The addition of abaca fiber and 3.0 vol% of lignin in PA2 composite shows the highest tensile strength, while the PA3 at 5.0 vol% of lignin shows slight shortfall due to clustering of particle. However the PA3 outperform in impact strength, hardness, and wear resistance. The Flammability test reveals effective self-extinguishing properties for PA3 exhibiting superior performance due to lignin's char-forming capabilities. Moreover, creep and TGA analysis demonstrated that the incorporation of abaca fiber and lignin of 5 vol% contributed to reduced creep strain and mass loss at initial, middle and final stages. SEM analysis confirms the effective interaction of lignin particle with resin matrix and ensured effective toughening. The study concludes the optimization potential of abaca-polyester composites, with 3.0% lignin identified as an optimal concentration for balanced improvements across various properties, providing valuable insights for composite material design and applications.

Keywords Polymer composites · Fibre · Wear · Flammability · Creep properties

Introduction

Composite materials have created a potential impact in the world of material science, and it is mainly due to their composition of two or more materials having distinct physical and chemical properties [1]. These distinct features of composite materials are classified based on matrix which going to reinforcement, such as metal matrix, ceramics matrix and polymer matrix composite. Among those types, thepolymer matrix composite are used widely across various application, and it is because of their chemical resistant, corrosion resistant, high stiffness, light weight nature [2, 3]. Generally, polymer matrix composite is prepared by reinforcing the matrix substances with fiber or particulate matter. The fiber reinforcement within matrix has increases the stability, superior flexibility and strength to the composite, which will promote high load withstanding capacity to the material

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[4]. These fibers can be either in the form of natural or synthetic one. Growing attention on utilizing environmentally friendly, biodegradable compounds has creates to produce natural fiber reinforced biocomposite material. Further, the natural fiber has certain specific characteristics such as, less density, renewable, accessible, affordable, good specific modulus, reduced carbon footprints, non-toxicity, bio compatibility, good thermal insulation and damping properties, etc. [5, 6]. This natural fiber can be obtained from various plant and animal sources. Plant source of natural fibers are used predominantly in recent research study and it is obtained from various part of the plant partssuch as leaf part of pineapple, abaca, stem part of kenaf, hemp fruit part of areca, coir, bast part of flax, jute and stalk part of bamboo, etc.Numerous research works are done on natural fiber under various properties. Among different fibers, the abaca fiber is rich in cellulosic content and resistant to salinity, wear and tear, good thermal insulating, and durability property [7, 8].

According to FAO report 2021, the world production of abaca is valued around 60 bn dollar per year. This huge production and high cellulose content, the abaca fiber from leaf sheath is utilized in most researches. The abaca fiber along with sandstone filler reinforced polymer composite material and their mechanical strength was evaluated by Girisha et al. [9]. Author reported that addition of 40 – 32 wt% of abaca fiber and 0-8wt.% of filler content has increased tensile, flexural, impact and hardness property of the composite material. Furthermore, Sivasankar et al. [10] conducted a comparative study on abaca and hemp fiber reinforced epoxy composite and their mechanical strength. The study concluded that addition of 30 vol% of abaca fiber with zero wt% of hemp fiber shows maximum tensile strength. Further, the addition of 40:10 ratio of abaca and hemp fiber shows maximum flexural strength. Similar such studies are done on abaca fiber reinforced polymer composite, due to their potentiality in enhancing the thermal, mechanical properties of the material. [11, 12].

However, during fiber reinforcement the composite material has some internal defects void formation, gap, poor interfacial adhesion, and these will create delamination between the matrix and fiber, low load bearing capacity [13]. To provide effective interfacial bonding and to filling of micro-voids the filler particles are added into the composite material. Recent years, the biofillers are creating innovation in composite material under various automobile, aerospace, marine, structural and non-structural applications, etc [14]. The most widely used biofillers such as cellulose, lignin, chitin, biosilica, biochar, etc. Among those biofillers, Ligninisderived from different plant sources, waste biomass, paper industry which are not only eco-friendly in nature, but also significantly improve the bio compatibility, mechanical, physical, thermal, wear properties of the material [15]. Further, this lignin compound as some features which makes to utilize as filler material in composite rather than using petroleum-based material. In addition, the lignin compound has inherently having some level of natural flame retardancy properties, which will increase the flammability properties of the material. There are more testimonials available to prove the effectiveness of lignin addition in the composite as well as in properties [16–20].

Thus, the present research study contributes to fill the research gap, by analyses the strength of lignin macromolecule from jackfruit perianth. Further, this kinds of bio mass extracted filler particle research, also creates a path to academicians, scientists, industrial professionals to explore more on this route.Thus, this research study aims is to investigate the mechanical, creep, wear and flammability behaviour of jackfruit perianth extracted lignin particle and abaca fiber reinforced polyester composite. Further, these cellulose abaca fabric and lignin particle has certain unique features like thermal stability, wear resistance, corrosion resistance, enhanced mechanical properties, and less dense, biodegradable, etc., which make it to utilized in various engineering, bio medical, marine, food industrial and pharmaceutical, domestic application, etc.

Experimental Procedure

Materials

In this study, the polyester resin developed using maleic anhydride with a molecular weight of 6000 g/mol, a viscosity of 600cps, and a density of 1.13 g/cm^3. Further, for curing purpose the hardener MEKP (Methyl-Ethyl-Ketone-Peroxide) was used, which has a molar mass of 210.1 g/mol and density of 0.95 g/cm^3. The polyester resin and the hardener were purchased from Herenba Instruments, Chennai, India. The abaca fiber was purchased from Metro Composite, Chennai, India. The Jackfruit was procured from local fruit shop.

Preparation of Lignin Biopolymer

The lignin particle from Jackfruit perianth is extracted via thermo-chemical method as shown in Fig. 1. First, the jack fruit perianth, which is covered outer seed coat, was purchased from local fruit shop. Then it is washed and dried out for 24 h, to eliminate the moisture content. Further, the dried sample is crushed by using a mechanical grinder. In the first step, 2 g of sample powder was taken in a beaker, subsequently added 12 ml of H_2SO_4 and 3 ml of distilled water within it. Now, the mixture is continuously stirred with the

Fig. 1 Preparation of lignin from Jackfruit perianth

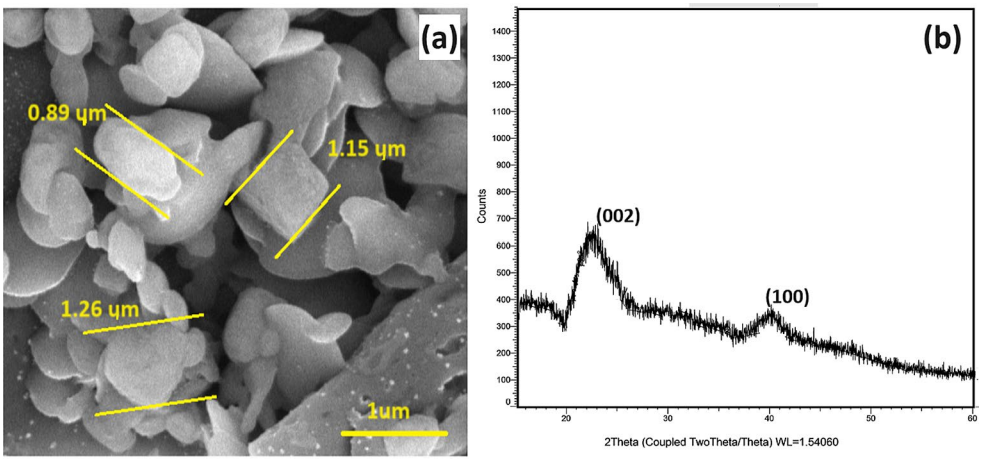

Fig. 2 Images of (**a**) FESEM of particle prepared, (**b**) XRD plot of lignin biopolymer

help of hot plate magnetic stirrer for 3 h and temperature is maintained around 25 °C by immersing in a water bath. After 3 h of stirring the solution was filtered by using a filter paper and dried for 24 h. In the second stage, same dried powder mixed with the same solution and stirred with magnetic stirrer at room temperature for 2 h. After completion of 2 h of stirring the solution was filtered with distilled water until the pH of drained water will comes to the neutral [21].

Finally the pH treated lignin biopolymer is powdered using mortaring process for 2 h. Figure 2 (a) shows the SEM image of lignin prepared and 2(b) shows the XRD structure of lignin particle. The particles are in non-uniform manner with average particle size of 1 µm. This indicates that the particles are in non-crystalline form. The presence of hydrogen bridge linkages in the produced lignin is confirmed by peaks at 22.4◦ (002) and 40.3◦ (100).

Composite Development Using Reinforcements

The lignin particle and abaca fiber reinforced polyester composite was prepared under various compositions which are mentioned in Table 1. First the polyester matrix was mixed with obtained lignin particle and stirred continuously under magnetic stirrer at room temperature. Now the lignin added polyester matrix was then mixed with hardener Methyl ethyl ketone peroxide and stirred continuously for

Table 1 Composite designation for various combinations

Composite Designation	Polyester Resin Vol (%)	Abaca Fibre Vol. (%)	Lignin particle Vol. (%)
P	100	-	-
PA0	60	40	-
PA1	59	40	1.0
PA2	57	40	3.0
PA3	55	40	5.0

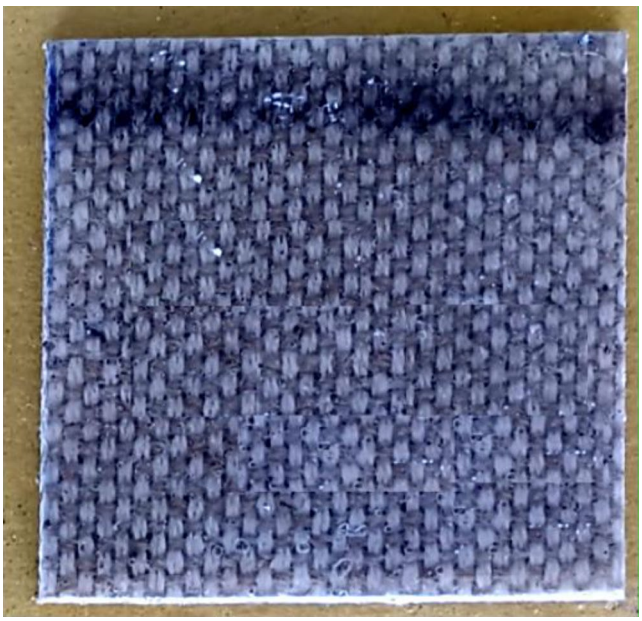

Fig. 3 Photographic view of composite PA1

20 min at room temperature in order to obtain homogenous solution. Before pouring the resin mixture into the mold, the molten wax is applied on to the surface of the mold. Now, by using hand layup process, the fiber is layered on to the surface of the mold. After layered, the using the cotton roller the excess resin was scrapped off [22]. Now, the fabricated composite are allowed to cure at room temperature for 24 h. after that the developed composite was placed in hot air oven at 110°C for 2 h. Figure 3 shows the prepared composite PA1 and Fig. 4 shows the FTIR spectra of PA3. It is observed that the peaks at 3482 cm^{-1} and 3308 cm^{-1} indicates the lignin and cellulose content of the composite since it is reinforced with cellulosic abaca fibre as well as the lignin biopolymer. Similar other peaks at 2988 cm^{-1} and 1710 cm^{-1} indicate the polyester's compounds such as C-C, C-O and C-OH stretches at the IR vibration. Thus the FTIR spectra study confirms the effective adhesion and blending of lignin biopolymer and cellulosic biopolymer.

Characterizations

The post cured lignin particle and abaca fiber reinforced polyester composite material are tested, in order identify their performance of the composite [23]. As per the ASTM standard the testing specimen were cut by using a abrasive water jet machine (Maxieum, 1515 KENT, USA. The testing such as tensile, flexural, impact, hardness, creep, wear and flammability are carried out in this research study. The testing specimen and their machine specification along with the ASTM standards are represented in Table 2; Fig. 5.

Results and Discussions

Mechanical Properties

The mechanical properties of abaca-polyester composites, specifically focusing on mechanical properties, were comprehensively investigated in comparison to the composite (P) in Fig. 6. In terms of tensile strength conducted based on ASTM D-3039 [24], the polyester resin (P) exhibited a value of 63 ± 2.8 MPa with a std. deviation of 1.7. The reduced values are caused by the brittle matrix, which is incapable of supporting the higher level of load applied. The introduction of abaca fibers in PA0 resulted in a 36.94% increase, showcasing the initial reinforcing impact of natural fibers on tensile strength. The incorporation of abaca fibers

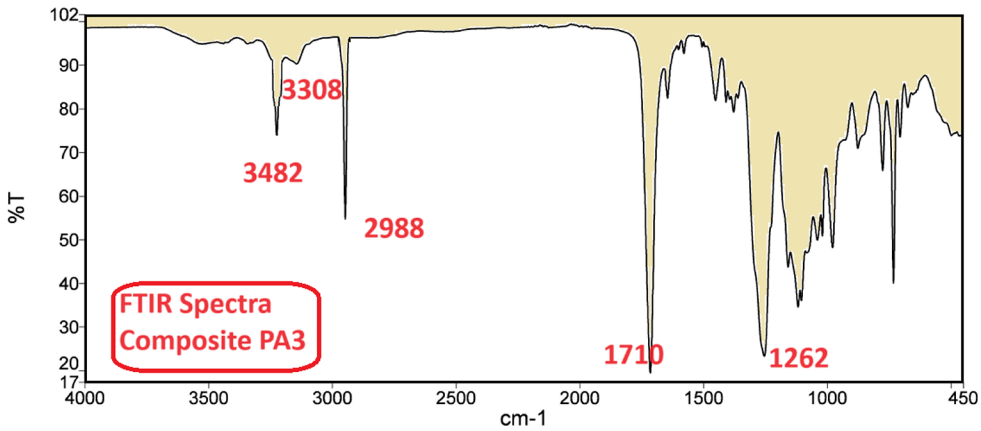

Fig. 4 FTIR spectra of composite PA3

Table 2 ASTM standards for various tests and their machine specification

Tests	ASTM	Machines
Tensile	D-3039	Ultimate Tensile Strength (UTM).
Flexural	D-790-17	INSTRON 4855, UK Traverse speed of 1.5 mm/min
Izod impact	D256–10	Krystal equipment Ltd., India Maximum load capacity of 20 J.
Hardness	D 2240	Durometer (shore-D), Blue steel, India.
Wear	G 99–17	Pin-on-disc setup (Novus Tribo solutions Pvt. Ltd), Load of 10 N, rpm of 500 and track distance of 1000 m set as process variables.
Flammability	D 635	UL-94 H & V, the evaluation covered both horizontal and vertical modes, and a Bunsen burner was used as the ignition source for the testing process.
Creep	D 7337	Metro Precision Machine Tools India, Pvt. Ltd, Load of 30% UTS, time of 10000s and temperature of 50°C was set as process parameters
TGA		
SEM	-	HITACHI, S-1500, JAPAN

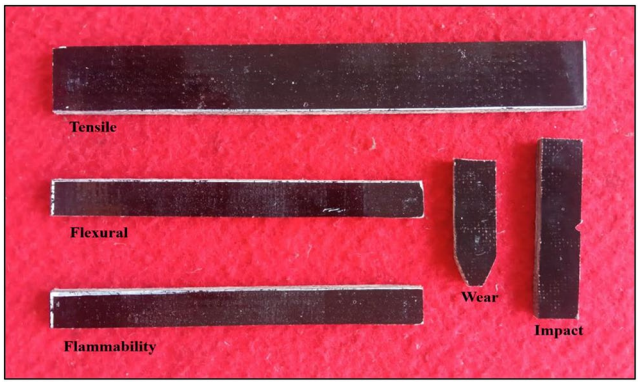

Fig. 5 ASTM standard testing specimen for lignin and abaca polyester composite

helps distribute applied loads more effectively, preventing crack propagation and improving the composite's ability to withstand tensile stress, the inclusion of fiber improves the mechanical properties of the composite by acting as a load bearing system within the composite and ensuring uniform fiber distribution throughout the matrix [25].

Moving to PA1, where 1.0% lignin particles were incorporated, and a substantial 81.9% enhancement in tensile strength was observed, emphasizing the positive influence of lignin as a reinforcing agent. Lignin particles enhance the adhesion between the abaca fibers and the polyester resin matrix. This improved adhesion helps in better load transfer between the fibers and the matrix, preventing the occurrence of weak interfaces and promoting a more cohesive material structure. PA2, containing 3.0% lignin particles, demonstrated the most significant improvement in tensile strength, the combination of abaca fibers and lignin in PA2 leads to a synergistic effect. Lignin particles, with their rigid and complex structure, act as effective fillers and reinforce the matrix. The interaction between lignin and abaca fibers creates a cohesive and strengthened structure, resulting in the remarkable 109.52% increase in tensile strength. Furthermore, in PA3, with 5.0% lignin content, a substantial 94.29% increase in tensile strength was achieved compared to P, underlining the reinforcing capabilities of lignin within the composite matrix.Excessive lignin does not integrate as effectively with the matrix, leading to potential agglomeration with the fiber-matrix interaction.

Moving to flexural strength measured based on ASTM D-790-17 [26], the composite (P) exhibited a value of 92 ± 3.4 MPa. The addition of abaca fibers in PA0 led to a 65.22% increase in flexural strength, indicating the positive impact of natural fibers on structural integrity. Abaca fibers, being strong and stiff, enhance the ability of the composite to resist bending forces. The fibrous structure created by abaca fibers contributes to improved load distribution and structural integrity. In PA1, where 1.0% lignin particles were introduced, a 47.83% improvement in flexural strength was observed, highlighting the reinforcing effect of lignin on the composite's bending properties. Lignin, with its rigid

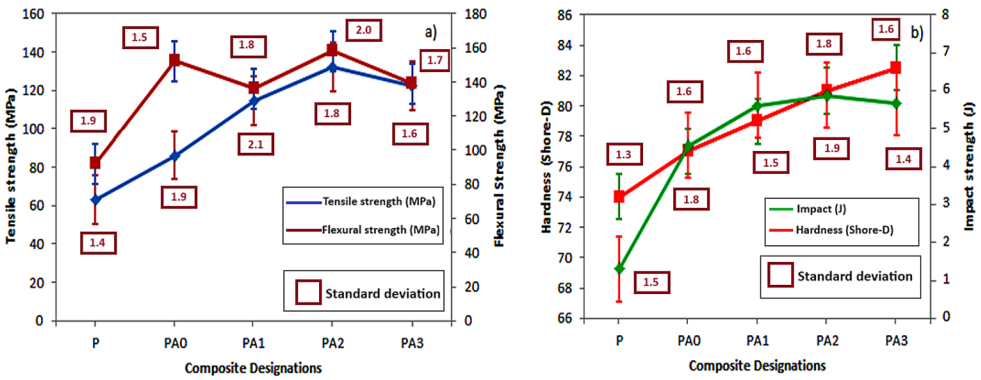

Fig. 6 Mechanical properties for various composite designations

and complex structure, acts as reinforcing filler within the composite matrix. The enhanced adhesion between lignin, abaca fibers, and the polyester resin contributes to improved resistance against bending stresses. PA2, with 3.0% lignin particles, displayed the highest increase in flexural strength at 71.74%, emphasizing the effectiveness of the combined abaca and lignin reinforcement. This suggests that the 3.0% lignin content in PA2 is optimal for maximizing flexural strength. The combination of abaca fibers and an optimal concentration of lignin results in a synergistic effect, leading to enhanced structural integrity and the ability to withstand bending forces.Finally, in PA3, with 5.0% lignin content, a 50.0% enhancement in flexural strength was achieved, further illustrating the positive contribution of lignin to the overall mechanical performance of the composite. There is a decrease in flexural strength compared to PA2, suggesting that there is diminishing return with higher lignin content. However, mentioned in their study increasing the filler vol% up to 3.0 vol% results in lower mechanical values due to the lignin toughening the composite but making it brittle in nature [27].

The investigation of impact strength and hardness were done in the abaca-polyester composites via ASTM D 256 and D 2240 [28] reveals substantial enhancements compared to the composite (P). In terms of impact strength, the introduction of abaca fibers in PA0 results in a remarkable 1091.68% increase, showcasing the energy-absorbing properties of these fibers. Abaca fibers possess excellent energy-absorbing properties due to their strong and flexible nature. When subjected to impact, these fibers distribute and dissipate energy throughout the composite, preventing crack propagation and resulting in a significant improvement in impact resistance.Further, in PA1, where 1.0% lignin particles are introduced, a significant 1444.68% improvement is observed, underlining the reinforcing effect of lignin on impact resistance. Lignin, with its rigid and complex structure, acts as a filler and reinforcement within the composite matrix. This addition enhances the composite's ability to absorb and dissipate energy during impact events, contributing to the observed significant improvement. PA2, containing 3.0% lignin particles, demonstrates the highest increase at 1527.85%, suggesting a synergistic effect between abaca fibers and lignin, contributing to enhance impact strength. The combined effects of abaca fibers and an optimal concentration of lignin result in a composite with enhanced impact strength [29].

The lignin particles contribute to a more cohesive matrix, preventing crack propagation and promoting energy dissipation. In PA3, with 5.0% lignin content, a substantial 1459.54% increase is achieved compared to P, highlighting the reinforcing capabilities of lignin within the composite matrix. Lignin, being a rigid and brittle material, imparts increased brittleness to the composite at higher concentrations. An excessively brittle matrix is more prone to fracture upon impact, leading to decreased impact strength. Additionally, higher lignin content contributes to increased stiffness, affecting the material's ability to absorb and dissipate energy during impact events. Moving to hardness, the addition of abaca fibers in PA0 results in a 4.05% increase, demonstrating a moderate improvement. Abaca fibres, being inherently rigid and strong, contribute to the composite's hardness by reinforcing the polymer matrix [30]. While the improvement is moderate, it demonstrates the initial reinforcing impact of abaca fibers on the hardness of the composite. PA1, with 1.0% lignin, exhibits a 6.76% increase in hardness, emphasizing the contribution of lignin to the composite's hardness. Lignin particles contribute to cross-linking within the polymer matrix. Cross-linking increases the intermolecular forces and overall cohesion of the material, resulting in improved hardness. The cross-linking network helps maintain the integrity of the material and prevents it from easily yielding to external pressure. PA2, containing 3.0% lignin particles, displays a 9.46% increase in hardness, showcasing the combined effects of abaca fibers and lignin.

Lignin is a complex and rigid polymer found in plant cell walls. Its intricate and branched structure provides additional strength and stiffness to the composite material. When incorporated into a polymer matrix, lignin acts as reinforcing filler, contributing to the overall hardness of the composite. Finally, in PA3, with 5.0% lignin content, an 11.49% increase in hardness is achieved, indicating the positive impact of higher lignin content on the composite's resistance to indentation. There is often a point of diminishing returns when adding reinforcing agents to a composite. Beyond a certain concentration, the incremental improvements in mechanical properties become less significant. The law of diminishing returns suggests that increasing lignin content does not linearly correlate with increased impact strength. However, increasing the filler vol% up to 5.0 vol% results in improved hardness values due to the lignin toughening the composite [31].

Wear Properties

Investigating the wear behavior based on G-99 [32] (Fig. 7) of abaca-polyester composites in comparison to the polyester resin (P) reveals distinctive trends in specific wear rates and coefficients of friction (COF) specimen P has the highest specific wear rate and COF because the impoverished wear resistance are due to the pure polyester resin's increased abrasion on the wear disc due to its soft nature [33]. The introduction of abaca fibers in PA0 results in a notable reduction in the specific wear rate, indicating enhanced wear resistance compared to P. The fibrous structure of abaca

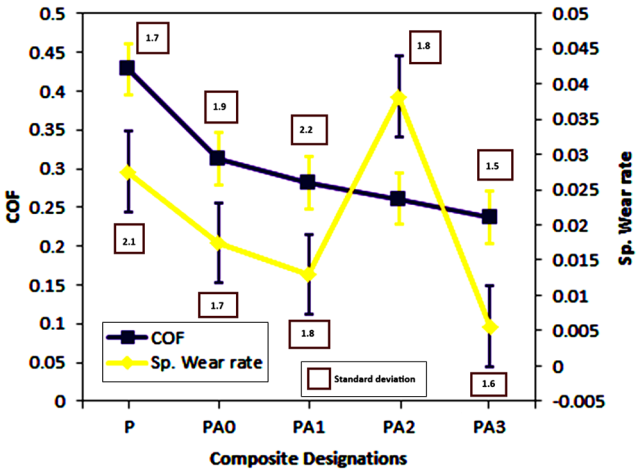

Fig. 7 Wear properties for various composites

fibers acts as a reinforcing element within the composite matrix, mitigating wear and preventing material loss during sliding or abrasive contact. Furthermore, the lower coefficient of friction (COF) suggests improved sliding behavior in PA0. Abaca fibers act as effective lubricants or offer smoother interfaces during sliding, resulting in reduced frictional resistance. This attributes to the flexibility and fibrous nature of abaca fibers, allowing them to deform and absorb energy during contact, leading to a smoother sliding motion. In PA1, where 1.0% lignin particles are incorporated, both specific wear rate and COF decrease, highlighting the positive impact of lignin on wear performance and frictional behavior. Lignin, with its rigid and complex structure, enhances the overall structural integrity of the composite. This reinforcement reduces the susceptibility of the material to wear-related deformations, resulting in improved wear resistance. Lignin particles act as lubricating agents, reducing the frictional resistance during sliding. Additionally, the incorporation of lignin strengthens the intermolecular interactions within the composite matrix, leading to smoother sliding interfaces and a decrease in COF [33].

However, PA2, with 3.0% lignin content, exhibits a higher specific wear rate compared to PA0 and PA1, indicating a potential correlation between wear resistance and COF, there is diminishing return on wear resistance. Excessive lignin content could lead to suboptimal interactions within the composite matrix, potentially resulting in increased wear. The coefficient of friction in PA2 remains lower than in P, suggesting some improvement in frictional characteristics when fiber and particle comes into contact with a wear disc, which exhibits abrasion resistance and reduces the exposure of resin molecules to the wear in the disc, which increases fiber-matrix adhesion [34]. Notably, PA3, with 5.0% lignin content, stands out with a significantly reduced specific wear rate, indicating superior wear resistance, there seems to be an optimal concentration where the reinforcing effects of lignin are maximized without compromising wear resistance. The lower COF in PA3 further signifies improved frictional behavior compared to both P and PA2. This is due to the effective reinforcement provided by 5.0% lignin, leading to a well-balanced composite with enhanced wear resistance and improved sliding characteristics.

Flammability Behaviour

Table 3 shows the flammability properties of composites tested using flammability tester in accordance to ASTM D 635 [35]. The plain resin (P) demonstrated a moderate propagation speed of 6.7 ± 1.4 mm/min, with an HB rating in horizontal burning. Notably, it achieved a V-0 rating in the vertical position, indicating effective self-extinguishing without the production of flaming drips. No falling drops or cotton lightening were observed, emphasizing its promising flammability characteristics. PA0 exhibited a higher propagation speed of 12.5 ± 3.1 mm/min, maintaining an HB rating horizontally. Although achieving a V-1 rating vertically, indicating limited flaming drips, PA0 showcased effective self-extinguishing properties. No falling drops or cotton lightening were noted during testing. The incorporation of fibers alters the thermal properties of the composite. Fibers have different heat absorption and dissipation characteristics compared to the polymer matrix. These changes can influence the material's response to heat and flame. However, adding fibre reduces fire retardancy due to the presence of cellulosic components on the fiber's surface [36]. PA1 demonstrated a moderate propagation speed of 8.05 ± 1.8 mm/min, with an HB rating in horizontal burning. In the vertical position, it achieved a V-0 rating, highlighting effective

Table 3 Flammability test values for various composite designations

Composite designation	Propagation speed (mm/min)	Propagation speed (Standard Deviation)	UL 94 Rating (Horizontal)	Falling drops	Cotton lightens	UL-94 Rating (Vertical)
P	6.7 ± 1.4	1.6	HB	No	No	V-0
PA0	12.5 ± 3.1	2.2	HB	No	No	V-1
PA1	8.05 ± 1.8	1.9	HB	No	No	V-0
PA2	6.65 ± 2.1	1.6	HB	No	No	V-0
PA3	5.19 ± 1.9	1.8	HB	No	No	V-0

self-extinguishing without flaming drips. No falling drops or cotton lightening were observed, showcasing favourable flammability characteristics. The interaction between fibers, possibly abaca, and the polymer matrix influences the material's ability to form a protective char layer during combustion. This char layer act as a barrier, preventing further flame spread and contributing to self-extinguishing properties.The addition of lignin to the resin reduced the flame propagation speed [37], emphasizing its role as a flame retardant. PA2 displayed a relatively low propagation speed of 6.659 ± 2.1 mm/min, with an HB rating horizontally. In the vertical position, it achieved a V-0 rating, emphasizing effective self-extinguishing without the generation of flaming drips. No falling drops or cotton lightening were observed, indicating robust flammability performance.Lignin has a tendency to form a stable and protective char layer when exposed to heat or flames. This char layer acts as a barrier, inhibiting the further spread of flames and contributing to the self-extinguishing properties observed in PA2. The char layer reduces the availability of combustible material, enhancing fire resistance.PA3 demonstrated a relatively low propagation speed of 5.192 ± 1.9 mm/min, with an HB rating horizontally. Achieving a V-0 rating vertically, PA3 exhibited effective self-extinguishing without the presence of flaming drips. No falling drops or cotton lightening were noted, underscoring its commendable flammability characteristics.The charred structure formed by lignin during combustion creates a physical barrier that hinders the transfer of heat and slows down the progression of flames. This barrier effect is more pronounced with higher lignin content [38].

Creep Behaviour

Table 4 shows the creep behaviour of plain resin as well as composites tested based on ASTM D 7337 [39]. In resin (P), a gradual increase in creep strain is observed, indicating its inherent viscoelastic nature and susceptibility to deformation over time. This behavior underscores the inherent viscoelastic properties of polyester, allowing for time-dependent deformation under prolonged loading [40]. In contrast, the introduction of abaca fibers in PA0 results in a notable reduction in creep strain at 2000 s, suggesting enhanced resistance to initial deformation. This trend continues at 4000 s, emphasizing the potential reinforcing effect of abaca fibers in mitigating the material's long-term deformation.The alignment and orientation of abaca fibers within the polymer matrix play a crucial role in enhancing the material's resistance to deformation. The fibers act as reinforcing elements, providing structural support and preventing excessive creep under sustained loads. Also, abaca fibers aid in distributing the applied load more evenly throughout the composite. This even distribution helps in transferring stress across the material, minimizing localized areas of strain that could lead to deformation. The effective stress transfer between the fibers and the polymer matrix contributes to the reduction in creep strain.The fibre finally diffused the load over the composite via its fibril nature and enhanced toughness by branching employing with filler, resulting in higher creep strain, suggesting brittleness reduction and toughness enhancement [41].

The incorporation of 1.0% lignin particles in PA1 further contributes to a lowered creep strain at both 2000 s and 4000 s, showcasing the positive impact of lignin on the composite's resistance to sustained loads. PA2, containing 3.0% lignin particles, displays consistently low creep strain values, indicating a potential synergistic effect between abaca fibers and lignin in minimizing deformation over time.Lignin, as a rigid and high-molecular-weight polymer, contributes to the overall stiffness and strength of the composite. The incorporation of lignin in both PA1 and PA2 reinforces the matrix, reducing the susceptibility of the material to deformation over time under sustained loads [42]. Also, lignin enhances the bonding and adhesion between the abaca fibers and the polymer matrix. This improved interfacial interaction contributes to better load transfer and stress distribution within the composite [43]. As a result, the material experiences reduced localized deformation, leading to lower creep strain. Remarkably, PA3, with a higher lignin content of 5.0%, exhibits the lowest creep strain among the composites at both 2000 s and 4000 s, highlighting the reinforcing capabilities of lignin in significantly reducing time-dependent deformation [44]. The higher content of lignin in PA3 contributes to increased rigidity and stiffness within the composite. Lignin, being a rigid polymer, reinforces the polymer matrix, resulting in a material that is more resistant to deformation under sustained loads. So, limiting lignin to 3.0% is more efficient.

Table 4 Creep behaviour for various composite combinations

Composite designations	Creep Strain				
	2000 S	4000 S	6000 S	8000 S	10,000 S
P	0.0081 ± 0.0035	0.0088 ± 0.0062	0.0115 ± 0.0025	0.0224 ± 0.0063	0.0329 ± 0.0036
PA0	0.0177 ± 0.0026	0.0191 ± 0.0022	0.0251 ± 0.0043	0.0346 ± 0.0024	0.0488 ± 0.0032
PA1	0.0138 ± 0.0043	0.0169 ± 0.0053	0.0197 ± 0.0016	0.0252 ± 0.0026	0.0485 ± 0.0026
PA2	0.0124 ± 0.0014	0.0180 ± 0.0016	0.0215 ± 0.0033	0.0295 ± 0.0031	0.0519 ± 0.0038
PA3	0.0107 ± 0.0025	0.0126 ± 0.0042	0.0144 ± 0.0042	0.0238 ± 0.0036	0.0441 ± 0.0031

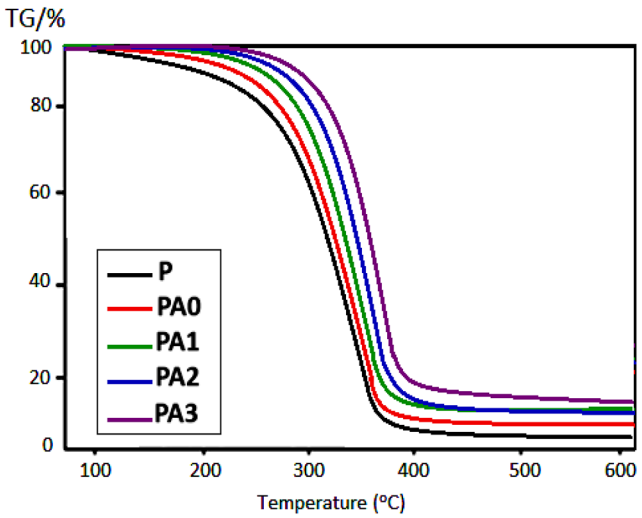

Fig. 8 TGA graphs of composites prepared

Thermogravimetry Analysis

The thermogravimetry analysis of polyester resin and composites is depicted in Fig. 8. The plain resin exhibits a moderate mass loss of 3.78% during the first decomposition, followed by a 66% loss during the intermediate stage, and a final mass loss of 28.32%. The high cross-linked molecules and their high entangled form is their moderate stability against temperature [45]. Nevertheless, the incorporation of glass fiber results in an enhancement of thermal stability. The use of natural fiber enhanced the capacity for heat retention and absorption due to the composition of the cellulosic fiber, which consists entirely of hydrocarbons and small quantities of lignin. Hence, a greater amount of thermal energy is necessary to induce vibrations in the fiber molecules, so facilitating further decomposition [46]. The observed values indicate that the early mass loss decreased to 3.24%, the middle mass loss decreased to 22.5%, and the ultimate mass loss decreased to 5.88%. The value of this is considerably lower compared to that of normal resin. Additionally, it is worth mentioning that the incorporation of lignin into the resin resulted in a further decrease in mass loss throughout the heating process. The composite material, which consists of 5 vol% lignin, exhibits superior thermal stability compared to the plain resin. The early mass loss experienced a decrease of 2.38%, followed by a reduction of 19.04% in the middle mass loss, and ultimately resulting in a final mass loss of 4.68%. This demonstrates the strong link between lignin and natural fibre. Due to the presence of long molecular structure and improved cross linking as well as interpenetrating polymer networks exhibits a notable degree of thermal stability. Therefore, the thermal stability is enhanced when lignin is added [47].

SEM Analysis

Figure 9 shows the SEM fractograph analysis of plain resin as well as composites prepared. In Fig. 9a, representing the plain resin, the SEM micrograph reveals a smooth surface typical of the polyester resin. The absence of reinforcing

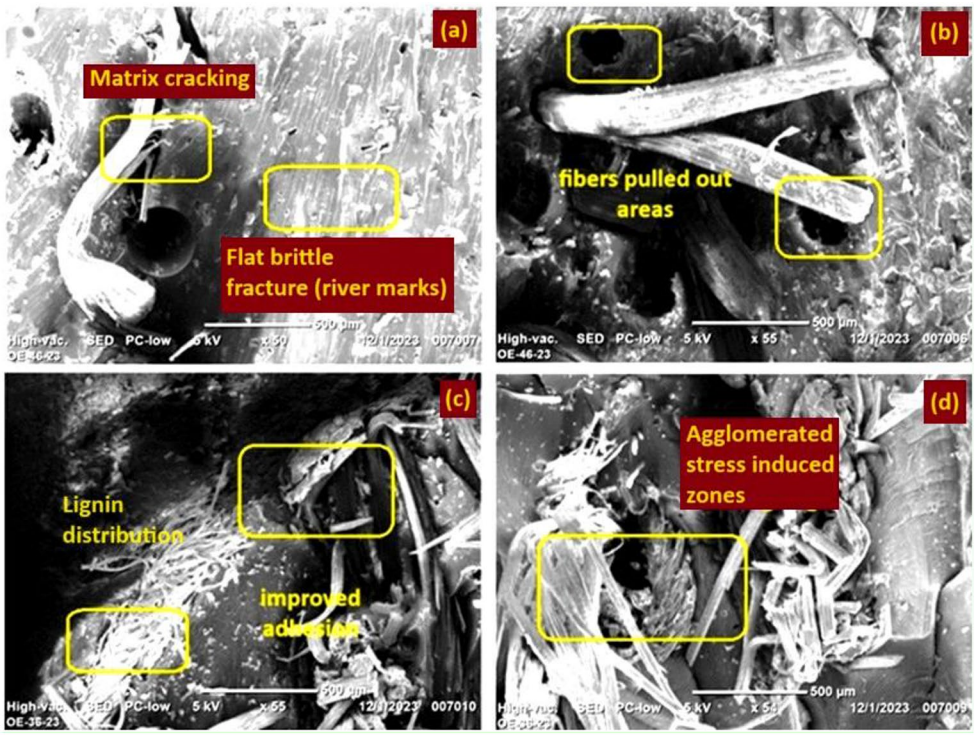

Fig. 9 SEM fractography of composite samples

fillers or fibers results in a homogeneous matrix without notable surface features. However, flat fracture is evidenced due to the retained brittleness of the matrix. Moving to Fig. 9b, where the composite lacks sufficient filler content, visible cracks in the polymer matrix indicate compromised structural integrity [48]. The absence of reinforcing fillers leads to increased susceptibility to mechanical stresses, resulting in crack formation and potential failure points. Figure 9c showcases the presence of lignin and abaca fibers within the composite. Darker areas representing lignin particles are observed in conjunction with evidence of fiber breakage. This micrograph highlights the reinforcing effect of lignin but also indicates localized areas of stress and deformation where fibers have experienced breakage. In Fig. 9d, agglomerated stress concentration areas are evident. The clustering of particles or regions with varying electron density suggests non-uniform mechanical properties and localized stress concentrations. This observation underscores the importance of achieving a uniform distribution of fillers within the composite to avoid areas of potential weakness [49].

Conclusions

In conclusion, the comprehensive investigation of abaca-polyester composites, denoted as P, PA0, PA1, PA2, and PA3, has provided valuable insights into their mechanical, thermal, and morphological properties. Tensile and flexural strength analyses revealed that the introduction of abaca fibers significantly enhanced the composites' mechanical performance. PA2, containing 3.0% lignin, exhibited the most significant improvement in tensile strength, suggesting a synergistic effect between abaca fibers and lignin. However, PA3, with 5.0% lignin, demonstrated diminishing returns, indicating that excessive lignin content might lead to suboptimal integration within the matrix. The impact strength and hardness assessments demonstrated substantial enhancements in PA0, PA1, PA2, and PA3, emphasizing the reinforcing effects of both abaca fibers and lignin. However, the impact strength decrease at 5.0% lignin in PA3 suggests a potential trade-off, possibly due to increased brittleness associated with higher lignin content. Wear properties showed that PA0 and PA1 exhibited reduced specific wear rates, highlighting the positive influence of abaca fibers and 1.0% lignin on wear resistance. The flammability tests indicated that all composites maintained effective self-extinguishing properties, with PA2 and PA3 showcasing superior performance due to the char-forming capabilities of lignin. Moreover, creep and TGA analysis demonstrated that the incorporation of abaca fibers and lignin of 5 vol% contributed to reduced creep strain and mass loss at initial, middle and final stages. Finally, SEM analysis provided evidence of toughness improvement by using fibre and lignin biopolymer. The wavy fracture surface shows toughness improvement in the matrix. These load bearing, time dependent and thermally stable composites could be used in engineering applications such as automotive door panels, structural members, drones, food packaging and defence sector, where lightweight and high strength is required.

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