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ORIGINAL ARTICLE

Synthesis and characterization of lightweight unmanned aerial vehicle composite building material for defense application

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Abstract

In this study, a lightweight unmanned aerial vehicle composite material for defense purpose was prepared using green pea pods (*Pisum sativum*) lignin macromolecule, industrial hemp fiber, and polyester resin. The primary objective of this research was to investigate how the addition of lignin improves the load bearing, wear, and flammability properties of hemp fiber–reinforced polyester composite. The lignin was synthesized from recycled green pea pod wastes via modified thermochemical process and utilized for composite making. The results indicated that the addition of lignin shows improvement in mechanical properties. Similarly, a significant improvement in wear resistance occurred at an increase of lignin volume up to 4.0, which is equal to 0.103 mm^3/Nm of sp. wear rate and 0.35 of COF. However, the maximum fatigue life counts of composite containing 2.0 vol.% of lignin records 36,972 at 25% of UTS. Moreover, inclusion of lignin up to 4.0 vol.% retains higher hydrophobicity as neat resin with the lowest propagation flame speed of 11.90 mm/min. This load bearing, wear, and flammability properties improved lightweight composites which could be used as a building material for unmanned aerial vehicles in defense, morphing wing, and surveillance drones.

Keywords Composites · Lignin · Mechanical properties · Wear properties · Flammability

1 Introduction

Recently, unmanned aerial vehicle (UAV) development in domestic and defense sector got a boom to replace human beings where human operators would be inconvenient, dangerous, or unnecessary. The unmanned aerial vehicles currently have a wide range of uses and missions, from surveying natural disasters by collecting geophysical data and from small birds to helicopters in size (air taxis) [1]. The exact structure and dimensions of the UAV may further be dependent on the missions, but according to recent trends and findings the number of UAVs will likely rise by a few thousand for a variety of missions in the coming years. The UAV's ability to be manufactured highly depends on the material, and it is another crucial consideration during the designing stage. The selection of appropriate materials for UAV production remains a crucial challenge to maintain its efficiency [2]. As of now, these UAVs are manufactured using plastics and some of them are made using even lightweight metals. However, further weight reduction and increment of life span of UAVs may be significant in decision-making strategies by the end user [3]. In order to improve the strength by keeping the weight remaining less, the composite materials are the right choice, since they are cost-effective, high in strength-to-weight and size ratios, eco-friendly (biocomposite), and readily available [4]. However, utilizing polymeric composites with synthetic fillers and fibers may affect the environmental quality and human's quality of life [5]. To overcome these issues, researchers developed sustainable biocomposites using degradable natural fiber and fillers. Moreover, there are lot of previous studies showing the deployment of natural fiber–based polymeric composites in UAV applications. Natural fibers like jute, sisal, abaca, hemp, pineapple, flax, agave, and kenaf are some of the notable fibers [6]. Similarly, in particle, toughening biofillers like

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areca powder, wood saw dust, nanoclay, cow dung, cellulose, lignin, chitosan, chitin, biosilica, and biochar are some of the notable fillers. Among these, some of them are biopolymers, which could alter the matrix properties at micro level.

Sarmiento et al. [7] have done a numerical investigation on jute-based composites, which is aimed to make wing body of unmanned aerial vehicle. According to the results, the jute fiber epoxy composite had a capability to handle the wind and mechanical loads, which can be acted on the UAV possibly. Moreover, due to less weight, the energy consumed by the UAV was also less compared with previous versions. Similarly, evaluation of the possible use of salago fiber composite as an alternative material in drone airframe was investigated by Lopean et al. [8]. Salago fiber composites nonetheless managed to achieve a lower density of 1.19 g/cm^3 and a greater heat deflection temperature of 58.6 °C, even though the glass fiber composite continues to be stronger in terms of flexural and impact strengths. Similarly, Zaghloul et al. [9] reviewed the possible new biomaterials in fiber and filler which are used in UAV applications. According to the author, the drones and UAVs are manufactured with natural fiber and filler encapsulated with polyester resins as high environmental concerns. These fibers and fillers are also capable of handling wind load and structural rigidity, according to the author. Thus, it is clear that natural fiber and fillers are predominantly used in UAVs these days.

Among all natural fiber, the industrial hemp (*Cannabis sativa*) is one of the most accessible and extensively manufactured bast fiber with significant cellulose content [10]. Consideration of this fiber is supported because of environmental protection as well as their intrinsic characteristics like as low density, high specific strength, and stiffness [11]. For these reasons, the industrial hemp fiber is often chosen as the reinforcing material for high load bearing properties. There are lot of testimonials available to prove the effectiveness of adding hemp fiber in the composite manufacturing [12–14]. Thus, using hemp fiber as primary reinforcement in composite making is a wise decision. Similarly, as particle toughening, lots of bio and ceramic fillers are available and this could be used in treated or untreated way in composites. In the past decades, researchers used particles such as nanosilica, nanoclay, carbonaceous materials like CNTs, carbon dots, and biochar as toughening agents for polymer composites [15]. However, these materials are altering the polymer's properties as macroscopic level and no intermolecular level of changes is done. But to enhance maximum property change in the polymer, molecular level changes are required, thus researchers recommending usage of biopolymers in the form of liquid or powders. Cellulose, lignin, chitosan, and chitin are few of popular biopolymers usually added into the polymers at the time of making biocomposites [16]. There are more proven studies available on composite platform, which uses the above said biopolymers as toughening agents [17–19]. Among various biopolymers, lignin has garnered the most interest because of its high carbon content, low cost, and biorenewability. Lignin, an aromatic polymer found in nature, coexists with cellulose and hemicellulose to create the primary structure of the majority of terrestrial plants [20]. Its long continuous chain structure would improve the cross-linking density and make the base polymer rigid. Due to its substantial carbon composition and multi-reactive structural groups, the lignin has emerged as a potential and environmentally friendly source of flame retardants [21]. Researchers derived this lignin from many plant sources and reported so far in composite development but the extraction from waste plant sources such as spinach root waste, pea pods, grape stalk, and other organic waste are yet to report.

Throughout the world, especially in metropolitan cities, the current waste issue has grown beyond control and is now a very serious health problem for the world population. As the inhabitants grow, consumption patterns influence, and people's lives start changing, and garbage production also rises [22]. There are many different types of biowaste which contains lignin sources and that can be used as filler materials for strengthening of the natural fiber composites. Pea peel waste is one of the undervalued sources of energy that has the ability to produce cellulose, lignin, and biochar [23]. There are tons and tons of pea waste dumped as organic waste landfill, even these wastes are not used as animal feed. There are very few studies reporting to date the utilization of pea pod waste to useful subsidies like cellulose, lignin, and biochar. Converting these wastes as useful material may create a path to make sustainable material development as well as provide solution to solid waste management. Mohammadalipour et al. [24] developed and studied the polyhydroxybutyrate/lignin electrospun scaffolds. The addition of lignin also increased (up to twice) the mechanical characteristics of polyhydroxybutyrate, such as elongation at break, toughness, young modulus, and tensile strength. Similarly, another related study was done by Li et al. [25] on the development of eco-friendly packaging film using waste pea pod cellulose. The authors developed needle-like cellulose in the size range 81–286 nm (length) via chemical route. The authors concluded that inclusion of cellulose nanocrystals into the carboxymethyl cellulose film decreased the water vapor permeability and increased the tensile strength of about 50% on compare with the plain films.

However, there is a lack of research found for the utilization of green pea pods as a lignin filler source with any resin system. Moreover, combination of industrial hemp fiber and green pea pod lignin in polyester resin for lightweight application also was not studied by any researcher. Therefore, the present investigation aims to develop a lightweight polyester composite using industrial

hemp fiber with green pea pod lignin. Moreover, the study focuses on the mechanical, fatigue, contact angle, and flammability behavior of fiber and varying vol.% of lignin in polyester composites. The composites could fabricate by hand layup method and characterized in accordance with American Society of Testing and Material (ASTM) standards. Such highly strengthened, lightweight, and thermally stable composite materials could be used for unmanned aerial vehicle and aerospace uses.

2 Experimental investigation

2.1 Materials

Maleic anhydride, an unsaturated polyester (UP) resin with a molecular weight of 6900 g/mol, a viscosity of 6000 cps, and a density of 1.17 g/cm^3, was obtained through Huntsman India Ltd. Methyl ethyl ketone peroxide (catalyst) was acquired by Merck India. Ltd. with a density of 0.85 g/cm^3 and a molar mass of 210.1 g/mol, as well as cobalt naphthenate with a density of 0.95 g/cm^3 and a molar mass of 401.2 g/mol. Industrial hemp fiber was purchased from Metro Composites, Chennai, India, which has GSM of 240 and a density of 1.28 g/cm^3. Finally, Sigma-Aldrich, USA, supplied the silane-surface-modifier 3-aminopropyletrimethoxylane having a density of 1.027 g/ml. Table 1 shows the physical and chemical properties of materials used.

2.2 Lignin preparation

To begin lignin preparation, firstly green pea pods were collected from food processing industries. They were then washed with distilled water and allowed to dry inside the hot air oven for 12 h to eliminate the residual moisture.

Then by utilizing the crusher, these dried green pea pods were further pulverized into a powder form. In the initial phase, a beaker containing 2 g of powdered green pea pod with 12 ml of H_2SO_4 and 3 ml of distilled water has been taken [26]. The mixture was continuously stirred for 3 h using a hot plate magnetic stirrer, and its temperature was kept at 25 °C using an ice bath. The solution was then filtered using filter paper and left to dry for 4 h in a drier. The dried powder was again proceeded for the second phase and stirred with a magnetic stirrer for 2 h at room temperature in the same H_2SO_4 solution prepared previously. The mixture was then stirred for 2 h after which it was filtered with distilled water until the drained water's pH reached 7 and then dried [27]. The procedure for extracting lignin from green pea pods is illustrated in Fig. 1. Figure 2a depicts an XRD plot of the prepared lignin. The presence of hydrogen bridge linkages in the produced lignin is confirmed by peaks at 22.6° (002) and 45.3° (100). Similarly, Fig. 2b depicts the FTIR plot of prepared lignin. The peaks indicates the presence of OH stretch, CH stretch, C = O bend, C–O rock, and C–C rock vibrations from the prepared lignin and confirmed the lignin synthesis is effective.

2.3 Composite preparation

In this study, composite fabrication is done by hand layup process but before fabrication of composites the silane surface treatment process was applied on industrial hemp fiber and green pea pod lignin to ensure better adhesion and dispersion [28]. To start fabrication, initially, mold was prepared by cleaning and applying the liberal coat of wax. The homogenous solution of epoxy-green pea pod lignin was prepared with the help of ultrasonicator. After the preparation of homogenous solution, the hardener was added and stirred for 15 min. The resin was then poured into the rubber mold along with the fiber mats and pressed firmly. The molded composite plates were then subjected for curing at room temperature for 24 h and post cured for 48 h at an elevated temperature of 120℃ [29]. Table 2 presents the composite designation with different composition of fiber and lignin used for composites.

Table 1 Physical and chemical properties of raw materials used

Properties	Polyester resin	Hemp fiber	Lignin
Density (g/cm^3)	1.17	1.25–1.3	1.3–1.5
Tensile strength (MPa)	45–55	3160–3240	40–55
Youngs modulus (GPa)	2–3.4	85–90	0.7–1.2
Elongation %	2	3.2	0.014
Poisson's ratio	0.64	0.32	0.15
Thermal expansion coefficient (10^{-6}/K)	12.2	5–7	2.2–3.0
Thermal conductivity (W/mK)	0.24	0.028	0.25–0.30
Sp. heat capacity (J/kg·K)	18.2	500–600	350 to 400
Melting point (K)	500–550	950–1100	280–320

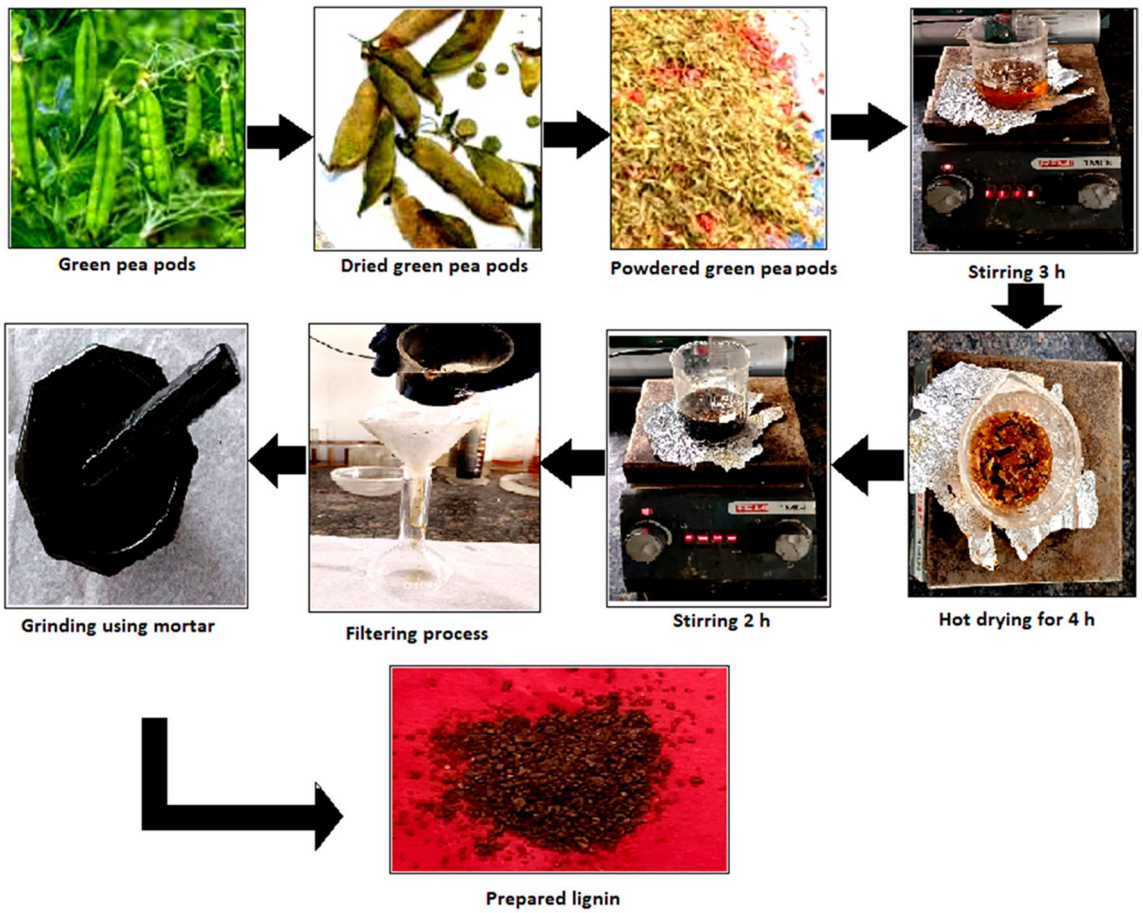

Fig. 1 Lignin preparation of green pea pods

3 Characterizations

The polyester composites made using hemp and lignin were further subjected to testing according to the ASTM standards specified in Table 3. All samples were tested 5 times to compute the average results. Figure 3 represents the composite sample made and ASTM test specimens prepared from the composite designation PHL3 (understanding purpose).

4 Results and discussions

4.1 Mechanical study

The values of mechanical properties for green pea pod lignin and industrial hemp fiber–reinforced polyester composites are represented in Table 4 along with a stress strain graph and load vs. displacement curve (Fig. 4). The pure polyester resin shows the lower mechanical strength as observed by values of composite designation P of about 43 MPa, 1.56 GPa, 68 MPa, 2.24 GPa, and 76 shore-D for tensile strength, tensile modulus, flexural strength, flexural modulus, and hardness correspondingly. These lower mechanical values are due to the pure polyester resin's higher brittle nature, which shows flat and brittle fracture in fractured surface (Fig. 5a) [20]. But addition of industrial hemp fiber by 40 vol.% further enhances the mechanical properties of composite designation PH. This increment is about 78 MPa, 2.81 GPa, 116 MPa, 3.91 GPa, 16.4 MPa, and 77 shore-D for tensile strength, tensile modulus, flexural strength, flexural modulus, interlaminar shear strength, and hardness respectively. The reason behind these increased mechanical values is due to the effective load sharing phenomenon of fibril structure of hemp fiber. Moreover, the silane surface treatment also improves the bonding between fiber and matrix and thus enhances the uniform load distribution throughout the composite as represented in Fig. 5b. The industrial hemp fiber shows the load bearing mechanism, which is uniformly distributed in the polyester resin and reduces the stress intensity factor, results in an improvement in the composite's mechanical characteristics [30].

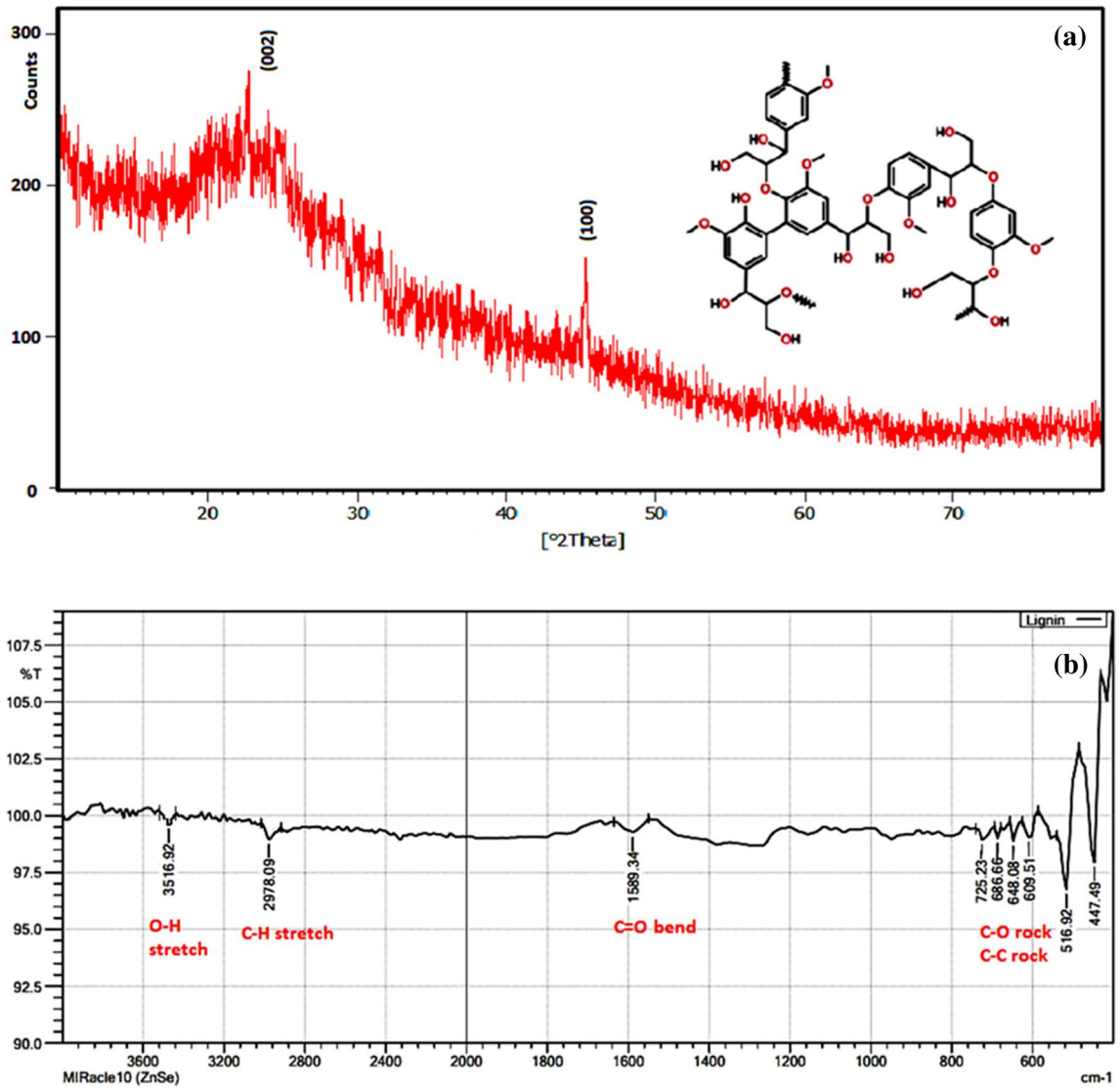

Fig. 2 Plots of **a** XRD and **b** FTIR spectra of synthesized lignin

Table 2 Various material combinations used

Composite designation	Resin (vol.%)	Fiber (vol.%)	Lignin (vol.%)
P	100	–	–
PH	60	40	–
PHL1	59.5	40	0.5
PHL2	59	40	1.0
PHL3	58	40	2.0
PHL4	56	40	4.0

Furthermore, it is noted that the addition of green pea pod lignin by 0.5, 1.0, 2.0, and 4.0 vol.% in this fiber-reinforced polymer matrix composites shows the improved mechanical properties for composite designation PHL1, PHL2, PHL3, and PHL4. When compared to all of the above composite designation, the highest mechanical values were observed for composite designation PHL3 which contains about 2.0 vol.% of lignin. This maximum increment in mechanical properties of this composite noted up to the 128 MPa, 4.24 GPa, 161 MPa, 5.92 GPa, and 21.8 MPa for tensile strength, tensile modulus, flexural strength, flexural modulus, interlaminar shear strength, and hardness correspondingly. It is because the uniform distribution of lignin improves the cross-linking density of the polyester matrix and enhances the bonding interface of matrix reinforcements as demonstrated in Fig. 5c. The lignin has long-chain hydrocarbon derivatives in it which gives higher toughening and bonding strength when added with the matrix material [31]. However, further increase in lignin content shows the slightly decreased vales for mechanical properties of composite

Table 3 ASTM standards for various tests and their specification

Test conducted	ASTM standard	Machines utilized
Tensile	D-3039	INSTRON 4855, UK Traverse speed of 1.1 mm/min
Flexural	D-790-17	
ILSS	D-2344	
Izod impact	D256–10	Metro Precision Testing Machine Tools, India, Pvt. Ltd Maximum striking load of 25 J was utilized for testing
Hardness	D 2240	Shore durometer (bluesteel, India)
Wear properties	G 99–17	Novus Tribo Solutions, India, Pvt. Ltd. Applied load of 20N, sliding speed of 800 rpm and track run of 1000 m were elected
Fatigue behavior	D-3479	MTS Landmark 370 load frame, United States. Applied load of 50% of UTS, stress ratio of 1 and frequency of 5 Hz
Contact angle	D-7334	HOLMERC, HO-IAD-CAM-01
Flammability	D 635 (UL-94 horizontal and vertical test)	Metro Precision Testing Machine Tools, India, Pvt. Ltd
SEM	–	HITACHI, S-1500, JAPAN

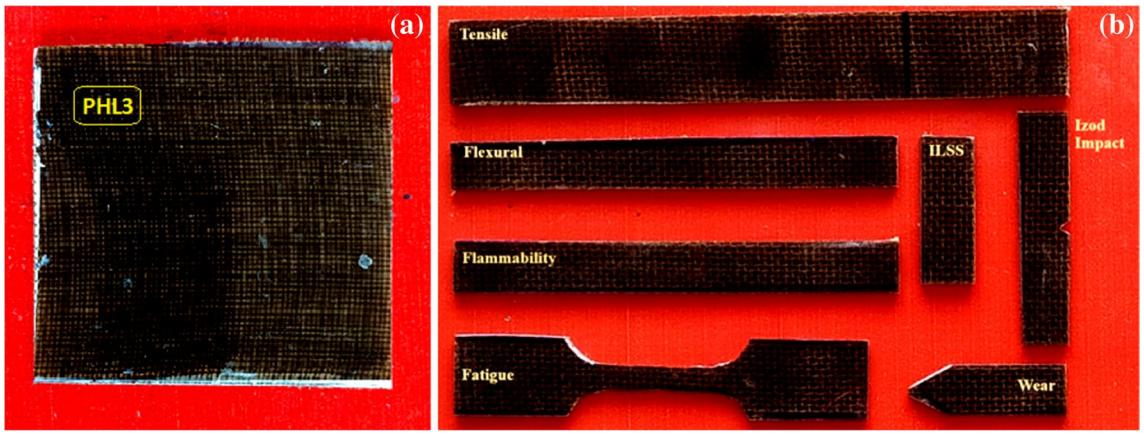

Fig. 3 Photographic view of **a** PHL3 composite prepared and **b** test specimens prepared for different tests as per the ASTM standards

Table 4 Mechanical properties for various composite designations

Composite designation	Tensile strength (MPa)	δ_{ts}	Tensile modulus (GPa)	δ_{tm}	Flexural strength (MPa)	δ_{fs}	Flexural modulus (GPa)	δ_{fm}	ILSS (MPa)	δ_{L}	Hardness (shore-D)	δ_{H}
P	43	1.3	1.56	1.2	68	1.4	2.24	1.6	–	–	76	1.2
PH	78	1.4	2.81	1.2	116	1.1	3.91	1.1	16.4	1.3	77	1.5
PHL1	92	1.2	3.47	1.3	131	1.7	4.26	1.6	18.2	1.8	79	1.2
PHL2	115	1.8	3.96	1.7	149	1.4	4.85	1.5	20.6	1.2	80	1.2
PHL3	128	1.5	4.24	1.7	161	1.8	5.92	1.7	21.8	2.0	81	1.1
PHL4	109	2.0	4.10	1.8	144	1.5	5.51	1.6	19.6	1.1	82	1.3

designation PHL4. It occurs due to the higher lignin vol.%, which increases high cross-linking structures, which creates the inter-penetrating polymer network (IPN) and makes composite brittle in nature as Fig. 5d shows.

4.2 Wear properties

Figure 6 shows the wear properties for various composite designations. The composite designation P shows lower

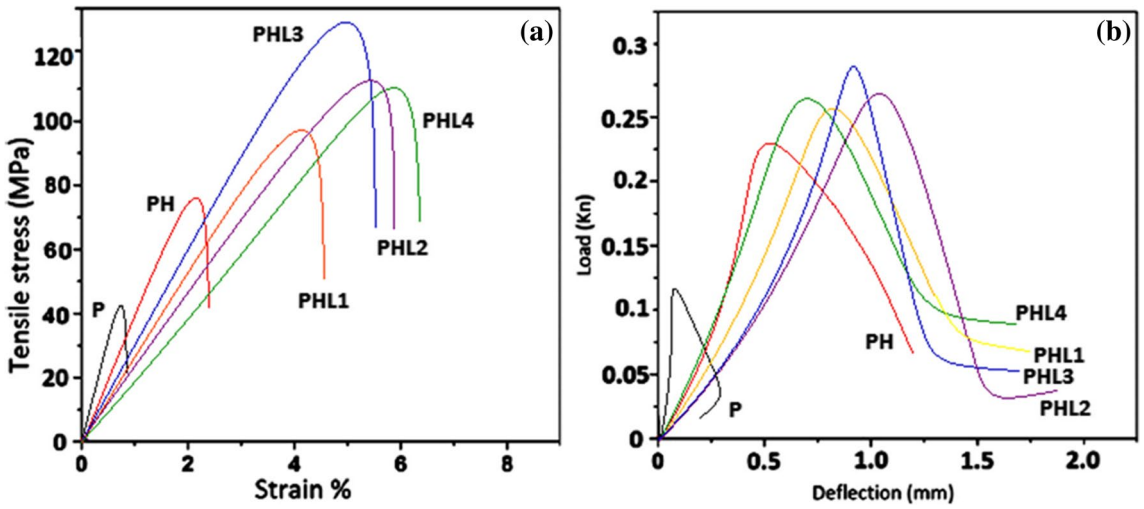

Fig. 4 **a** Stress vs strain and **b** load vs displacement

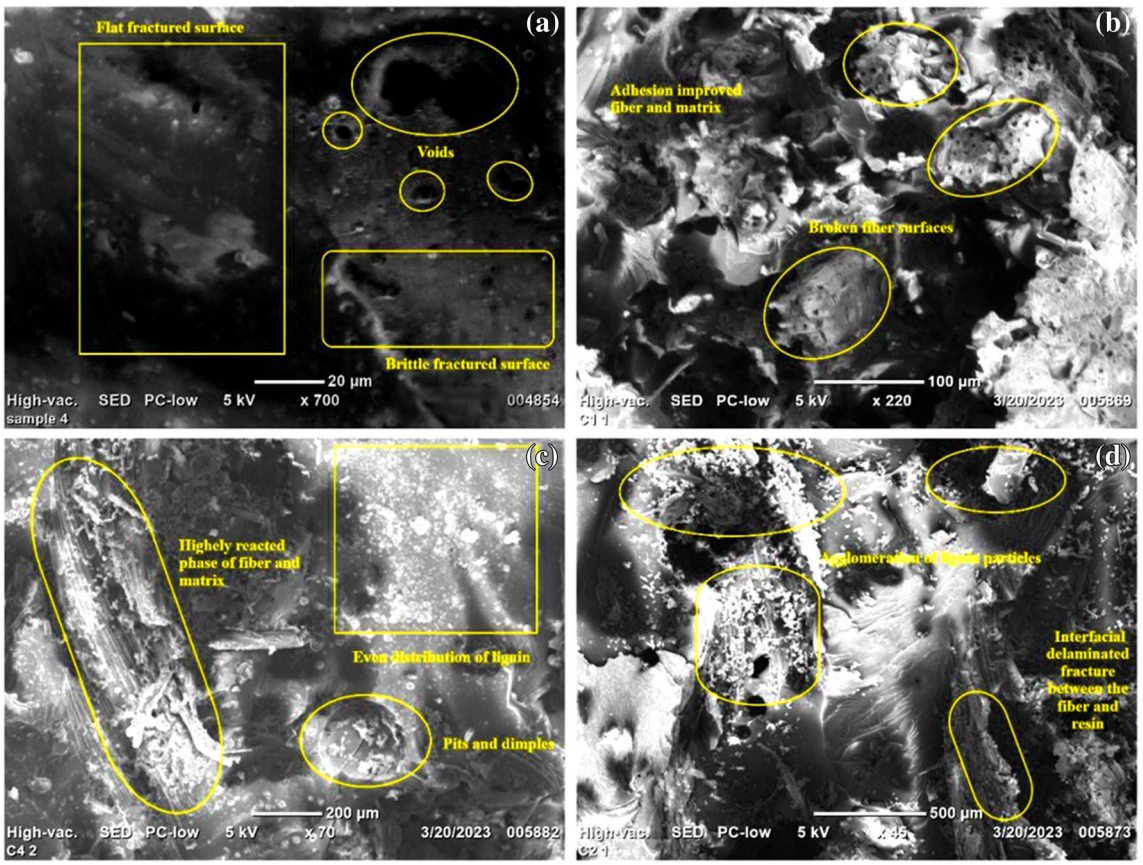

Fig. 5 **a**–**d** SEM fractograph of tensile tested samples

wear resistance value of 0.224 mm^3/Nm in specific wear rate and 0.61 of coefficient of friction (COF). The reason behind the lower wear resistance is inducing of two body abrasions when the composite comes in contact with abrasion disk [32]. But further addition of industrial hemp fiber by 40 vol.% shows the decreased in sp. wear rate values up to the 0.186 and COF values about 0.54 for composite designation PH. Because of the silane-treated fiber, more effective

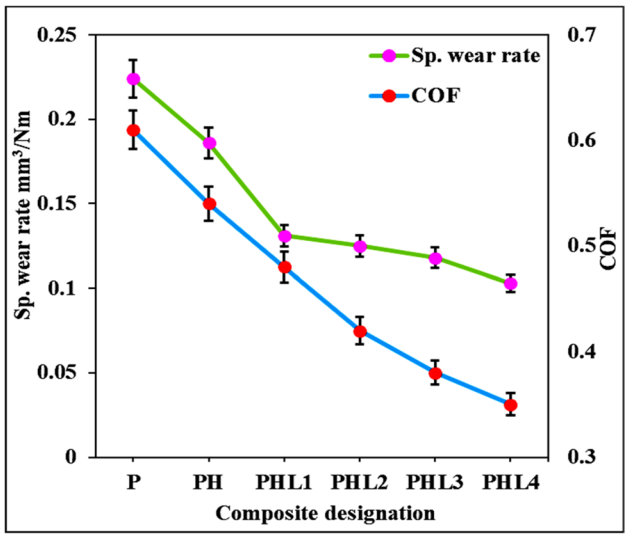

Fig. 6 Wear properties for various composite designations

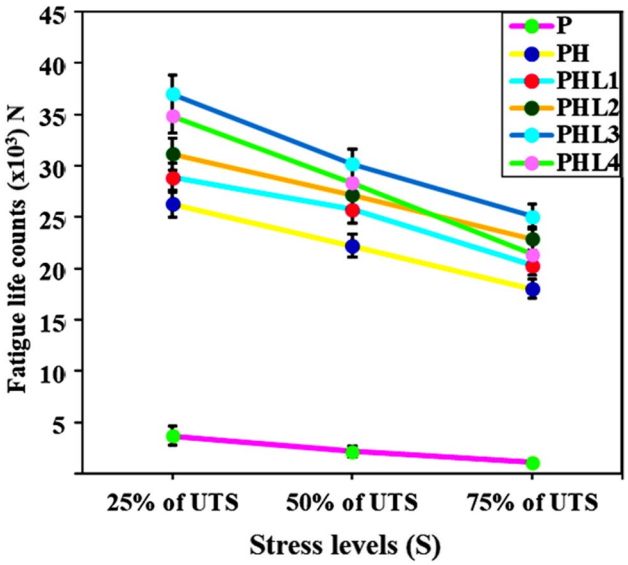

Fig. 7 Fatigue behavior of various composite designations tested

adherence between the fiber and matrix is observed which further enhanced the wear resistance. Sliding motion causes shear force to be produced when the composite material comes into contact with the abrasion disk. Due to a strong interfacial contact with the matrix, silane surface-modified fiber offers improved resistance to the exterior shear force and reduced the two body abrasion phenomenon. An extremely high rate of stability is retained against the abrasion, adhesion, and erosion wear loss phenomenon as a result to the efficient transfer of the applied stress to the matrix.

However, inclusion of green pea pod lignin by 0.5, 1.0, 2.0, and 4.0 improves the wear resistances for composite designations. Further, a maximum decrement in wear rate is observed for composite designation PHL4 was about 0.103 and 0.35 in sp. wear rate and COF correspondingly. It is due to the higher carbon content of lignin which makes composites harder and stiffer. Similarly, due to the surface treatment process, the NH_2 functional group on lignin surface reacts with matrix and reduces the two-body and three-body abrasion. This improves higher wear resistance in composites [33].

4.3 Fatigue behavior

The fatigue life counts for various composite designations are shown in Fig. 7. The composite designation P gives the lowest fatigue life counts as 3681, 2174, and 1079 for 25%, 50%, and 75% of UTS. While a repetitive load is applied, the cured pure polyester resin molecules stretched out minimal extent and accumulate residual stress. These newly acquired stresses further evolved into microcracks that spread quickly and results in plastic deformation of composites [34]. However, the incorporation of the industrial hemp fiber of 40 vol.% further increased the fatigue life counts for composite designation PH. This improvement in fatigue life counts is about 26,252, 22,197, and 18,003 for 25%, 50%, and 75% of UTS. The addition of fiber has the ability to sustain and distributes it evenly, which suppresses the micro-crack formation in composites. Also improved bonding mechanism is observed because of the NH_2 functional group present on the fiber surface due to the silane treatment as shown in Fig. 8a and b. Furthermore, addition of green pea pod lignin by 0.5, 1.0, 2.0, and 4.0 vol.% gives the increased numbers of fatigue life counts for composite designation PHL1, PHL2, PHL3, and PHL4 correspondingly.

But from all of the composite designations, the maximum fatigue life counts were observed for composite designation PHL3 about 36,972, 30,147, and 25,034 for 25%, 50%, and 75% of UTS. It is due to the addition of lignin, which improves energy storage during stretching by improved cross linking density and IPN structures toughen the matrix as represented in Fig. 8c. On the other hand, lignin possesses larger carbon networks, which are able to stretch and hinders the microcrack formation [35]. Nevertheless, composite designation PHL4 shows marginal reduction in fatigue life counts by addition of 4.0 vol.% of lignin. The large molecular chains entangling and highly disordered structure makes composite brittle in nature as observed in Fig. 8d.

4.4 Contact angle measurement

Figure 9 illustrates the contact angle values for various composite designations. Figure 9a shows the contact angle value for composite designation P which represents the higher

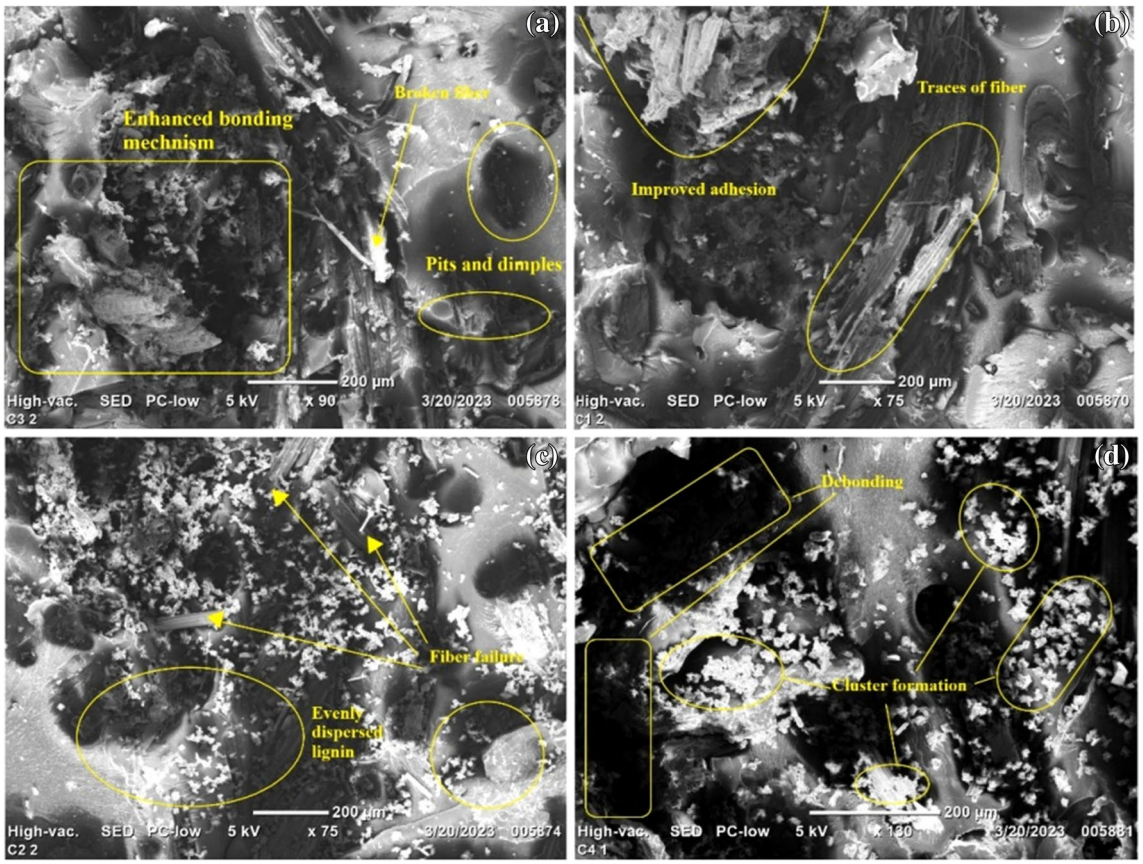

Fig. 8 **a–d** SEM fractography of fatigue tested samples

contact angle of about 103° due to the pure polyester resin as main constituent and its hydrophobic nature. However, the inclusion of industrial hemp fiber by 40 vol.% gives the contact angle of about 87° for composite designation PH (Fig. 9b). The decreased in contact angle is due to the hydrophilic nature of natural fibers which attract water molecules within the composite via more surface energy [36]. But further incorporation of lignin by 0.5, 1.0, 2.0, and 4.0 vol.% gives the increased contact angle for composite designation PHL1, PHL2, PHL3, and PHL4 correspondingly (Fig. 9c, d, e, f). This is because of hydrophobic nature of lignin, which repels the water molecules to enter inside. When compared to all of the composite designations, the higher contact angle is observed for composite designation PHL4 which is about 107°. These higher contact angle values are due to the lignin's long hydroxyl chain which shows strong hydrophobicity and decreases the surface energy of the composite material [37].

4.5 Flammability

The outcomes of UL-94 tests for the pure epoxy and green pea pod lignin with industrial hemp fiber–reinforced polyester composites are shown in Table 5. The vertical flame UL-94 test clearly showed that pure polyester resin composites had enhanced combustion, because their combustion times were longer than 10 s but under 50 s, they were given a V-2 grade. But none of the samples observed any indications of dripping; since thermosetting polyester is the matrix, it never melted off and flowed. Thus, no dripping is found [38]. Because the structure of the molecules of polyester resin is affected, resulting in an additional layer of char on the external face of composites that protects the surface from flames, the resulting composites were classified as V-0 and V-1 independent of the amount of cellulose component [39]. The other composite which has combustion rate significantly less than that of pure resin, as measured by the horizontal approach to the UL-94 HB test, was the composites' designation made up of 40% industrial hemp fiber and 5 vol.% lignin particles, as shown in Table 5. This study shows that as the lignin loading is raised up to 5.0 vol.% with 40 vol.% of industrial hemp fiber, the resistances to burning improve. The composite designation PHL3 has the shortest recorded propagation rate, which is about 11.90 mm/min. It is because the lignin in green pea pods resists

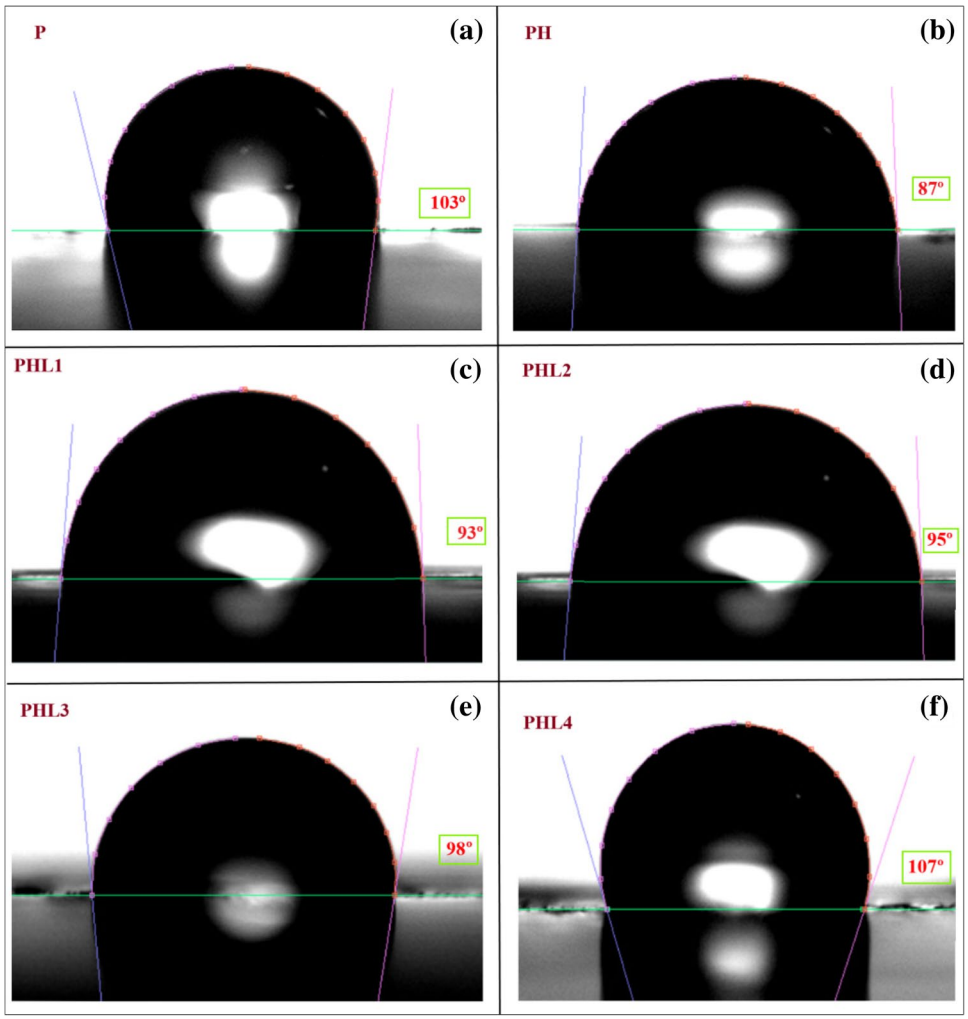

Fig. 9 **a–f** Contact angle images for various composite designation

Table 5 Flammability outcomes for various composite combinations

Composite designation	Propagation speed (mm/min)	UL 94 rating (Horizontal)	Falling drops	Cotton lightens	UL-94 rating (Vertical)
P	10.69	HB	No	No	V-0
PH	22.17	HB	No	No	V-2
PHL1	18.38	HB	No	No	V-2
PHL2	16.55	HB	No	No	V-1
PHL3	13.72	HB	No	No	V-1
PHL4	11.90	HB	No	No	V-1

heating and has a silane surface layer on it which acts as heat barrier [40]. Moreover, since the cross-linking density is increased in the composite via lignin addition, more energy is needed to burn the molecules and break their structure. Figure 10 shows the flammability tested various composite designated samples.

5 Conclusions

The effect of adding green pea pod lignin and industrial hemp fiber into the polyester resin was investigated in this study to develop lightweight composite materials for

Fig. 10 Flammability test performed on various composite designations

making unmanned aerial vehicles for defense applications. The detailed outcomes from this analysis show that the lignin derived from green pea pod is a noteworthy extraction and reinforcement for lightweight composite fabrication:

a. The inclusion of 2.0 vol.% of lignin addition for the composite designation PHL3 resulted in maximum increase in mechanical properties noted up to 128 MPa, 4.24 GPa, 161 MPa, 5.92 GPa, and 21.8 MPa for tensile strength, tensile modulus, flexural strength, and modulus, respectively. But increase in lignin vol.% up to 4.0 vol.% gives adverse effects on wear resistance.
b. However, the addition of lignin of 2 vol.% improved the fatigue life counts of about 36,972, 30,147, and 25,034 for 25%, 50%, and 75% of UTS.
c. On the other hand, incorporation of lignin up to 4.0 vol.% highest contact angle of 107° is observed (hydrophobic region) with a lowest flame propagation speed of 11.90 mm/min.
d. Thus, the lightweight composite using lignin from the waste material could alter and improve the useful properties of bare polyester resin and prevent the excessive usage of synthetic reinforcements on composite technology.
e. Such lightweight highly toughened and water-resistant composites could be used in unmanned aerial vehicle, morphing wing and drone applications.

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Mostefa Bourchak, Khalid A Juhany—conceptualization and testing support.

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Declarations

Ethical approval NA.

Competing interests The authors declare no competing interests.

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