International Journal of Plastics Technology (December 2019) 23(2):229–238
https://doi.org/10.1007/s12588-019-09253-4

RESEARCH ARTICLE

Effect of gamma radiation on mechanical properties of pineapple leaf fiber (PALF)-reinforced low-density polyethylene (LDPE) composites

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Received: 3 December 2018 / Accepted: 2 December 2019 / Published online: 11 December 2019

Abstract

Pineapple leaf fiber (PALF) is one of the abundantly available agro-waste materials in Bangladesh. PALF-reinforced low-density polyethylene (LDPE)-based composites were fabricated by compression molding with randomly oriented fiber loading varying 10–60 wt%. In this study the influence of the fiber loading on the mechanical properties such as tensile, flexural and Izod impact was investigated. Water absorption tests of the composites were also carried out for determining water resistance properties of composites. Thermal properties of PALF were analyzed by thermogravimetry and derivative thermogravimetry. Scanning electronic microscopic studies were performed to understand the fiber–matrix adhesion and fiber breakage. To improve the compatibility between fiber and matrix, 50/50 PALF/LDPE composites were irradiated with gamma rays (Co-60) of doses where composites irradiated with 7.5 kGy dose showed the best results. Tensile properties of the composites were found to be improved significantly after gamma irradiation.

Keywords PALF · LDPE · Polymer composite · Tensile properties · Water absorbency · Gamma radiation

Introduction

Natural fiber-reinforced polymer composites have become a very popular material in the past four decades for biodegradability, high specific strength, lightweight, sustainability, low cost and high modulus. Natural fibers are obtained directly by cultivation of agricultural sources or from the wastages of seeds, fruits, straws, barks, leaves, etc. [1]. On the other hand, the non-degradable thermoplastics composites are not possible to degrade biologically, but these can be recycled easily rather than thermoset composites [2]. From the socio-economic prospective the combination of natural fibers and biodegradable polymers used to fabricate a green composites are easily decomposed by bacteria or enzyme, has a very good impact in the country's economy because of its environmental and biodegradable nature [3, 4]. At present natural fibers such as sisal, hemp, flax, jute, coir, rice straw, banana, wood, bamboo, etc., have drawn attention as a substitute of synthetic fibers as filler or reinforcement in polymer matrix to increase productivity and improve mechanical properties [5]. Outstanding heat and noise insulation characteristics can be obtained for cellular structures of plant fibers [6].

The importance has been imparted on using the agro-wastage for growing the effective deployment of natural resource such as pineapple leaf, banana and wheat straw, betel nut shell, etc. Among these pineapple (*Ananas comosus*) is harvested for its fruit throughout the world. Its leaves are the prime parts of the plant that were unused or sometimes festering by burning to be short of the knowledge of its financial impending. This has drawn an attention to the modern technologist for development of green and biodegradable

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products instead of synthetic materials [7]. The usual practices of decomposing and burning the leaves in situ did not add any value to the enhancement of the fertility of land and burning of these beneficial agricultural wastes but causes environmental pollution [8].

Several researchers have studied about pineapple leaf fiber (PALF) in different aspects of physical, mechanical and chemical characteristics from a variety of pineapple for logical and reasonable deployment for various applications [9, 10]. This has been studied that yield of 1.22 tons leaves per hectare, with the production of 40 leaves per pineapple plant, a mass of 0.065 kg per leaf [9]. Raw leaves hold approximately 85% water, 10% non-fibrous material and about 2.8% PALF by weight [11]. Different chemical compositions in PALF were found, such as, cellulose 67.12–82%, hemicellulose 9.45–18.80%, lignin 4.4–15.4%, pectin 1.2–3%, fat and wax 3.2–4.2% and ash 0.9–2.7% [12].

The researchers have accelerated their concentration for using the PALF as prospective reinforcement in structural, non-structural, micro- and nanocomposites due to its outstanding physical, chemical, mechanical characteristics that is sustainable for environment [13]. Hence, without any supplementary contribution of cost, waste product of pineapple cultivation, PALF which exhibit outstanding mechanical properties can be used for industrial purposes [14]. To fabricate needle-punched nonwovens for the purpose of technical textiles, PALF can be blended with polyester fibers for replacing jute fiber [15]. There are several effects of waste materials, residues or process biproducts of multiple types on prospective natural fiber-reinforced composites, and additional complete attentions are required for solving the challenges concerned with focusing not only on a particular problem but also both economically and ecologically reasonable [16].

This is said that inadequate research has been conducted on thermal and electrical properties, thermal conductivity, dynamic mechanical analysis and modeling of mechanical properties of PALF reinforced mostly in PP and unsaturated polyester matrix composites. Therefore, there are lot of opportunities to study the behavior of PALF with other resins to get its vast application in biocomposites and hybrid composites manufacturing [17].

Though the lignocellulosic bast fibers have a number of limitations like higher wet ability and inadequate interface between the polymer matrix and fiber may deteriorate the mechanical properties of composites. So for obtaining the most favorable fiber–matrix properties in thermosets, thermoplastics, rubber, cement, hybrids and biocomposites, now the physical or chemical modification of these fibers is the main target of research [18]. The natural fibers are generally hydrophilic in nature which deteriorates the compatibility with matrix in polymer composites and trends the lower mechanical properties. For reducing the hydrophilic nature of the fibers different treatments are imparted for improving the adhesion with polymer in composites [19]. Different types of chemical treatments have been analyzed including alkali, silane, acetylation, benzoylation, acrylation, maleated coupling agents, isocyanates, permanganate, etc., for attaining the desired properties [20]. The NaOH-treated composites showed higher modulus than silanized composites resulted from a development of flexible polysiloxane and tensile strength exhibiting minor growth with the addition of PALF in injection-molded polycarbonate reinforced with PALF composites [5]. PMPPIC [poly(methylene)-poly(phenyl) isocyanate] treatment of fiber exhibits maximum interfacial interactions between PALF and polyethylene matrix in composite, thereby enhancing the mechanical properties than NaOH, silane and peroxide treatment [21]. There is a significant effect on fiber size, loading %, orientation and mixing (melt and solution) techniques with mechanical properties of PALF-reinforced low-density polyethylene (LDPE) composites. It was suggested that 6-mm longitudinal orientation fibers were appropriate for PALF-reinforced LDPE composite and mechanical properties get better and elongation at break is reversed in increment of fiber loading [22]. The tensile modulus, tensile strength, flexural modulus and flexural stress of the composites were found to be increased with the increment of fiber volume fraction according to the rule of mixtures attributed to fiber-to-fiber interaction; voids and dispersion are generated in PALF–polypropylene (PP) composites [14].

The high-modulus PALF has superior load transfers to the ductile matrix of LDPE than the brittle matrix of PP, and the tensile strength of the composites increased with increase in long, unidirectional (0–25%) fiber content for better dispersion and improved interfacial bonding [23].

Stress relaxation of PALF-reinforced polyethylene composites decreased with strain level due to the addition of fiber content because of better reinforcing effect in tension at higher temperature. Longitudinally oriented reinforced fiber composites have higher relaxation rate than transversely oriented reinforced fiber composites. It is also found that isocyanate, silane, alkali and peroxide treatment of fiber has a significant influence on the relaxation behavior [24]. The melt viscosity of short PALF-reinforced LDPE composite increased with fiber loading due to an amplified impediment to the flow, and reverse phenomenon was shown due to rise of temperature, but in case of peroxide-treated composites viscosity is augmented due to the cross-linking of composite at higher temperature [25]. The viscosity of short PALF–LDPE composites improved in lowered degradation temperature [26].

There are various suitable techniques to enhance the mechanical properties of composites such as low-pressure plasma treatment improving the better adhesion between LDPE matrix and natural fibers reinforcement which acts as a barrier against moisture and the water absorption without affecting the thermal properties [27]. For reducing the hydrophilic character of natural fibers by improving the better surface cross-linking with polymer matrix in composite materials gamma (ionizing) and UV (non-ionizing) irradiation can be imparted [28]. Gamma irradiation is recognized to impose energy in solid cellulose by Compton scattering and the quick localization of energy among molecules that fascinated macro-cellulosic radicals. This is conscientious for varying the physical, chemical and biological characteristics of cellulosic fibers [29]. The sterilization process of aging after gamma irradiation on physical, mechanical and thermal properties accelerated cross-linking in composite as a short-term effect [30]. There is also a significant impact of gamma irradiation on dielectric properties of composites by producing active site up to a certain dose. But in case of higher irradiation doses, mechanical properties reduce particularly; only bond scission of the polymer matrix occurred [31].

The main purpose of this work was to study the effect of gamma radiation on mechanical and physical properties of PALF-reinforced LDPE composite made with different weight percentages of PALF (10–60 wt%). The optimum percentage of PALF-reinforced LDPE composite and most favorable gamma dose was established for the application of sport equipments, clothing accessories, domestic components, playing boats and structural substances with better strength, lightweight, durability, serviceability and cost-effectiveness.

Experimental details

Materials

The raw materials applied to fabricate the composite samples are low-density polyethylene (LDPE) pellets as matrix materials and pineapple leaf fiber (PALF) as reinforcement. Pineapple leaf fiber (*Ananas comosus*) was obtained from Madhupur Thana under Tangail district, Bangladesh, and commercially available LDPE was collected from Atomic Energy Research Establishment, Savar, Dhaka. The physical and mechanical properties of PALF and LDPE are given in Table 1.

Table 1 Physical and mechanical properties of PALF and LDPE

Properties	PALF	LDPE
Density (g/cm^3)	1.526	0.918
Linear density (tex)	2.5	–
Fiber tenacity (g/tex)	100	–
Tensile strength (MPa)	1572	8.6
Elongation at break (%)	2.77	110.0
Young's modulus (MPa)	6260.0	130.0
Moisture regain (%)	12.0	–

Determination of tensile strength

Single fibers were manually separated from the fiber bundles of PALF samples. These single fibers were tested for measuring tensile properties according to ASTM D3822. Tensile tests of fibers were carried out by Titan SN 1410 series (James Heal) universal testing machine in standard atmospheric conditions. A load cell of 200 N was applied, and a gauge length of 25 mm along with cross-head speed of 10 mm/min was maintained for PALF fibers during the application of tensile loading.

Determination of fiber diameter

Single fibers were manually separated from the fiber bundles of PALF samples. Single fibers were tested for determining diameter (μm) using microscope.

Thermogravimetric analysis (TGA)

To study the thermal stability and decomposition pattern of PALF, thermogravimetry (TG) and derivative thermogravimetry (DTG) were carried out with Netzsch STA 449 F3 (Germany). PALF was scanned from 20 to 600 °C at a heating rate of 10 °C/min in nitrogen atmosphere, and the corresponding percentage weight loss was recorded.

Composite fabrication process

Fabrication of LDPE sheets

Prior to fabricate PALF/LDPE composites, trash analyzer machine was used to prepare uniform lap of PALF for even distribution of PALF throughout the composite samples. The LDPE sheet of 1 mm thickness was fabricated by melting and compressing pre-weighed LDPE pellets by the CARVER heat press machine (Carver, INC, USA Model 3925) at 115 °C and a pressure of 5 ton for 5 min using a mold dimension of $300 \times 300 \times 1$ mm^3. Fabricated LDPE sheets were then cooled at room temperature (25 °C) for 15 min.

Fabrication of composite laminates

Composites having 3 mm thick were prepared by sandwiching 2 layers of PALF between 3 pre-weighted LDPE sheets. The sandwiched LDPE sheets were then placed between two steel molds with randomly oriented PALF sheet and heated at 150 °C for 5 min to soften the polymer sheets prior to press 5 bar pressure for 3 min, and finally, it was allowed to cool by passing water from inlet pipe for both upper and lower plates for 10 min. After that the composite sheet was removed from the mold plate to undergo the natural cooling process for 30 min at room temperature. PALF/LDPE composite laminates with different fiber weight proportions, such as, 10, 20, 30, 40, 50 and 60 wt.% were prepared and subsequently, the composite samples of the required dimensions were cut for determining different physical and mechanical properties of composite samples.

Mechanical testing of composite samples

A universal testing machine (Model: H50KS-0404, HOUNSFIELD Series S, UK) was used for measuring the tensile test and 3-point bending test of the composite samples based on ASTM D 638 and ASTM D790, respectively. Izod impact test of un-notched specimens was measured for the composite samples according to ASTM D256. For removing moisture from fiber and composite samples, drying oven was used. A Co-60 (25Kci) gamma ray source (Model Gamma beam 650 No. 1lR) was used to irradiate the composite samples. It was capsule type, housed in cavity and raised by remote-controlled electromechanical system. This gamma beam was loaded with source GBS-98 which comprises of 36 double-encapsulated capsules. This unit had twelve tubes, each containing three active capsules intersperse with to springs. The irradiation was done in Bangladesh Atomic Energy Research Establishment, Savar, Dhaka. Five specimens were tested for each type of test, and data presented are the average of the five tests for each case.

The water absorbency of composite samples was measures based on ASTM D570-81 standard. The interaction of LDPE and PALF was examined by scanning electron microscopy (SEM). The SEM images of fractured surfaces of LDPE/PALF composite sample are shown in Fig. 9. Scanning electron microscopy (JSM-6490LA, JEOL) tests were done at 20 kV power from the Centre for Advanced Research in Sciences (CARS) Laboratory, University of Dhaka (DU), Bangladesh.

Results and discussion

Thermal analysis

The thermal stability of PALF was evaluated by thermogravimetric analysis (TGA) and derivative thermogravimetric analysis (DTGA). The thermogravimetric analysis (TGA) and the derivative thermogravimetric analysis (DTGA) curves of PALF are presented in Fig. 1. Throughout the PALFs thermal stability study, typically two stages of degradation were observed. The preliminary degradation peak

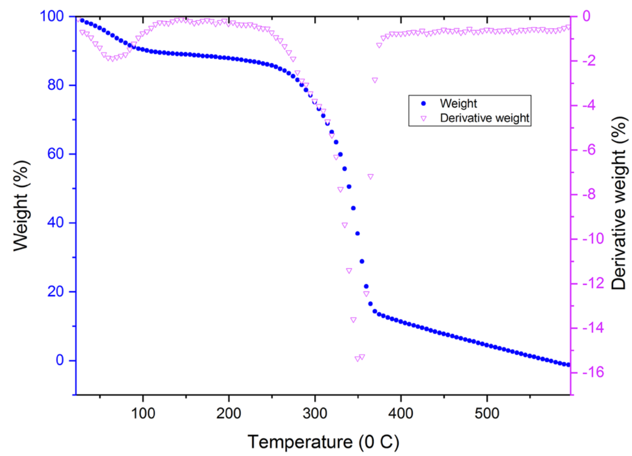

Fig. 1 TGA and DTGA curves of PALF

was perceived at a temperature of 64.0 °C (with weight loss of 10.9%); this may be because of the vaporization of moisture existing in the PALFs. The additional major degradation progress in the temperature ranges between 260 and 330 °C. The peak at a temperature close to 330 °C with a mass loss of 25% can be related to thermal depolymerization of hemicelluloses. The other prominent peak at 370 °C exposed a weight loss of 46% owing to degradation of cellulose. Similar results for the degradation of cellulose are also observed for other natural fibers like flax (250 °C), hemp (220 °C) and jute fibers (300 °C) [32].

Tensile properties of composite samples

The tensile properties of the composites are given in Table 2. A comparison of the tensile properties (tensile strength and tensile modulus) is shown in Fig. 2. Five samples of each composite were tested, and average values were recorded. The error bar shows the standard deviation of values from mean. The fiber loading of PALF varied from 10 to 60 wt.%. It is observed that tensile strength and tensile modulus of the composites increase with the increase in fiber weight fraction. The maximum values of tensile strength and tensile modulus are attained at 50/50 PALF/LDPE composite. Addition of 50 wt.% fiber increased the tensile strength and tensile modulus by 68.98% and 106.40%, respectively, comparing with the corresponding values of 10/90 PALF/LDPE composites. The tensile strength and tensile modulus of the PALF/LDPE composites slightly decrease with the addition of 60% fiber weight fraction. The further increase in fiber weight fraction (at 60 wt%) lowers tensile strength by 24.44%. This is because at higher fiber weight fraction, the fibers act as flows and the fibers were not properly aligned with matrix. In addition lower interfacial shear strength has speculated at higher fiber weight fraction. It is observed

Table 2 Tensile and flexural properties of PALF/LDPE composites

Composite sample ID	Tensile strength (MPa)	Tensile modulus (MPa)	Extension at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)
10/90 PALF/LDPE	16.83 ± 0.40	403.58 ± 1.90	83.72 ± 1.01	53.47 ± 0.70	889.73 ± 3.92
20/80 PALF/LDPE	18.65 ± 0.17	474.21 ± 4.34	78.94 ± 0.14	56.80 ± 1.07	1257.08 ± 13.46
30/70 PALF/LDPE	19.26 ± 0.18	572.97 ± 0.36	75.19 ± 0.56	62.74 ± 0.99	2193.55 ± 46.64
40/60 PALF/LDPE	20.96 ± 0.23	659.06 ± 4.67	73.07 ± 0.57	67.55 ± 1.04	3608.24 ± 89.81
50/50 PALF/LDPE	28.44 ± 0.26	832.99 ± 6.50	66.53 ± 0.87	78.42 ± 0.75	5765.02 ± 126.74
60/40 PALF/LDPE	21.49 ± 0.32	684.21 ± 3.83	75.63 ± 0.84	73.18 ± 0.46	4626.95 ± 101.44

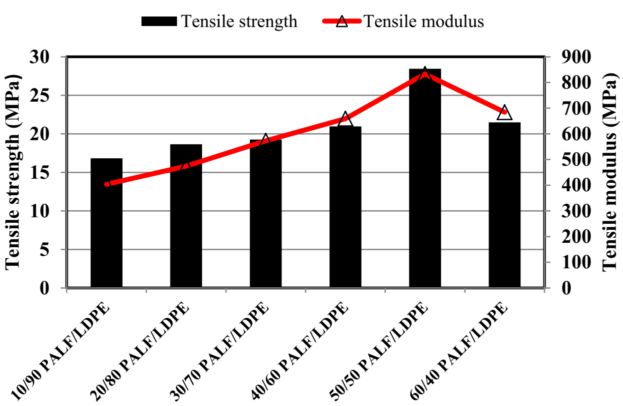

Fig. 2 Tensile properties of the PALF/LDPE composites

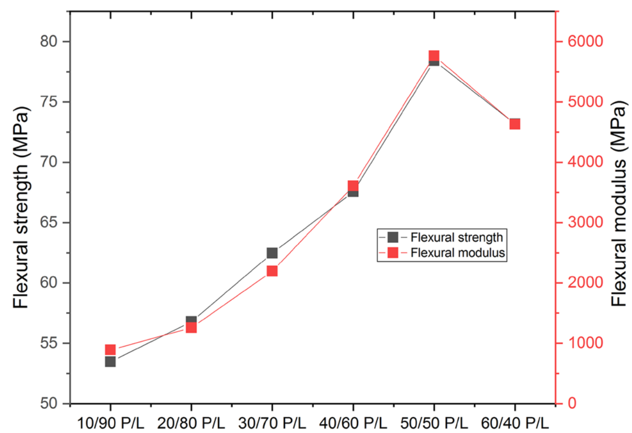

Fig. 3 Flexural strength and flexural modulus of the PALF/LDPE composites

that the composites having 50% fiber weight fraction is the stiffest and shows the highest tensile strength.

At intermediary point of fiber loading (50%), the population of the fibers is just right for highest orientation and the fibers actively contribute in stress reassign. High levels of PALF content showed that the augmented population of fibers leads to agglomeration and stress transfer gets barren and the consequential composite property is again found to decrease [33–35].

The extension at break % of pure LDPE is quite high (see Table 1). As expected the extension at break % of the composites decreases with the increase in fiber weight fraction till 50% fiber weight fraction and then further increases the extension at break % with the addition of PALF as observed in Table 2. Luo and Netravali reported that void could affect tensile strength of the composites [6]. It was observed that during the composite fabrication composites having higher fiber weight fraction demonstrated higher void content.

Flexural properties of composite samples

A comparison of the flexural properties (flexural strength and flexural modulus) of the composites is given in Table 2. Five samples of each composite were tested, and average values were recorded. It is revealed that flexural strength and flexural modulus of the composites increase with the increase in fiber weight fraction. The maximum values of flexural strength and flexural modulus are obtained at 50/50 PALF/LDPE composite. Addition of 50% fiber increased the flexural strength and flexural modulus by 46.70% and 547.95%, respectively, comparing with the corresponding values of 10/90 PALF/LDPE composites. However, further increase in fiber weight fraction to 60% lowers the flexural modulus by 19.74%. The flexural modulus of the composites is significantly higher than that of the corresponding tensile modulus (Table 2). The decrease in flexural modulus at higher fiber weight fraction may be due to the increase in fiber–fiber interactions, and the fibers were not perfectly aligned with matrix, void and dispersion problems [14].

Figure 3 shows flexural strength and flexural modulus versus fiber weight fractions of PALF/LDPE composites. The flexural strength of the composites containing 50% fiber weight fraction was found to be higher than that of 10/90 PALF/LDPE composites by 47.60%. But the results seemed to be very high compared to the results of George, Bhagawan and Thomas [22]. The flexural properties showed decreasing trend for the composites with fiber weight fraction above 50%. The reasons why flexural properties are lower for the fiber weight fraction above 50% are possibly due to the fiber–fiber interaction, void and dispersion problem.

Izod impact strength of composite samples

Impact strength is defined as the ability of a material to absorb energy. The impact strength of composites is directly related to its overall toughness. The composite toughness is affected by interlaminar and interfacial strength parameters. Figure 4 shows the variation of Izod impact strength of PALF/LDPE composites with PALF fiber loading. The impact strength of PALF/LDPE composites with 10 wt% of PALF fiber is 8.37 kJ/m^2. With the increase in PALF fiber loading from 10 to 50 wt%, the impact strength increases significantly by about 299%, However, with the further increase in PALF fiber loading (i.e., 60 wt%), there is a drastic drop (about 19.30%) in impact strength. The fibers play a vital role in impact strength of composites as they interact with the crack formation in the matrix material and act as a stress-transferring medium [36].

Water absorption % of composite samples

Figure 5 shows the water absorption % of the composites versus time of exposure (in day). The data given are the average values of six samples for each type of composite. It is observed that the composites having higher fiber wt. (%) have better water absorption capacity. The water uptake percentage of 60 wt.% PALF-reinforced LDPE composites attained highest (20.90%) in 8th day. In 8th day water uptake (%) of 60/40 PALF/LDPE composites has increased by about 26.32% as compared with that of 10/90 PALF/LDPE composites. However, the water absorption % of 10/90 PALF/LDPE composites was found to be lower than all other PALF/LDPE composites with different fiber wt% in all stages of water exposures. As PALF is lignocellulosic and hydrophilic in nature, composites having higher fiber contents show higher water absorbency. The water molecule can only penetrate the amorphous region and get linked with the available hydroxyl (-OH) groups which is one of the important functional groups in fiber that causes the formation of a large amount of hydrogen bonds and induces their swelling [37].

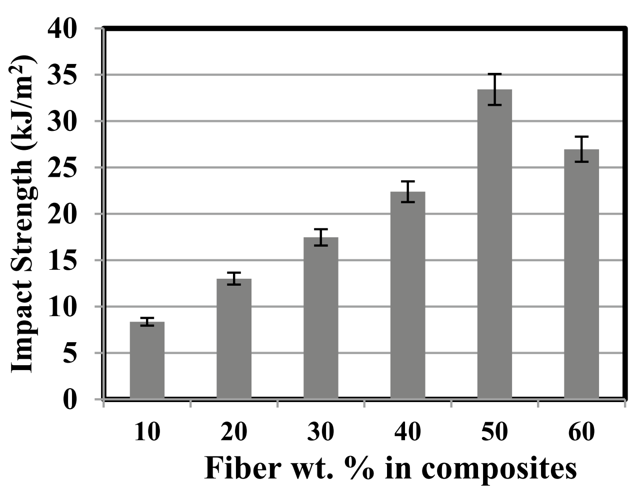

Fig. 4 Effect of fiber loading on impact strength

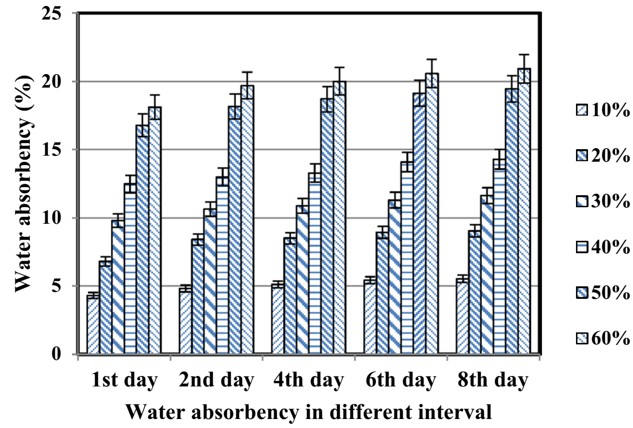

Fig. 5 Effect of fiber loading on water absorbency

It was observed that water absorbency (%) increases linearly with the increase in PALF fiber content in composites. The amount of water absorbed by the composites increased with the increase in the quantity of the pineapple fibers in the composites. This was in conformity with results of similar works [38].

Effect of gamma radiation on properties of composite samples

It was observed that mechanical and physical properties of PALF/LDPE composites increased with gamma radiation up to a certain dose and then decreased due to the two opposing phenomena, namely photo-cross-linking and photo-degradation that took place simultaneously under gamma radiation. At lower doses, free radicals are stabilized by a combination reaction; as a result, photo-cross-linking occurs. The higher the number of active sites generated on the polymeric substrate, the greater the grafting efficiency. But at higher radiation, the main chain may be broken down and polymer may degrade into fragments; as a result, mechanical and physical properties will diminish after certain gamma doses. An intense radiation consequence in a loss of tensile strength and a abridged degree of polymerization was observed [39]. From this investigation, it was clear that gamma radiation has a strong role on the enhancement of the mechanical properties of the composites. Throughout degradation, there will be a loss in strength due to primary bond fracture in the cellulose constituents and, as a result, associated changes taking places in the middle lamella, which diminish the ultimate cell [40].

Tensile properties of composite samples

The tensile properties of the composites (both radiated and non-radiated) are given in Table 3. It is clearly observed that both tensile strength and tensile modulus increased significantly with increasing fiber wt% for gamma radiation doses of 2.5–7.5 kGy, which saturated at 50 wt% of fiber loading. Further increasing of gamma radiation (at 10 kGy), both tensile strength and tensile modulus decreased slightly by about 7.6% and 3.4%, respectively. Fiber loading of PALF fiber by 50 wt% increases the tensile strength and tensile modulus of radiated composites by about 35.34% and 16%, respectively, as compared with corresponding non-radiated composites. It is observed that the maximum tensile properties are obtained at the gamma radiation of 7.5 kGy [31, 40].

It was observed that the lowest elongation at break of 50/50 PALF/LDPE composites was 36.17% with gamma radiation of 7.50 kGy and then the elongation at break increased to 44.44% at 10.00 kGy radiation due to the two facts, such as photo-cross-linking and photo-degradation that took place simultaneously under gamma radiation. The lowest elongation at break percentage was 33.20% lower than the corresponding elongation at break of non-radiated composites.

Flexural properties of composite samples

The effect of PALF fiber loading on the flexural properties of the composites (both radiated and non-radiated) is given in Table 3. The flexural strength and flexural modulus of non-radiated composites at 50 wt% PALF fiber loading are found to be 78.42 MPa and 5765.02 MPa, respectively. It is observed that with the increase in gamma radiation doses from 2.5 to 7.5 kGy, the flexural strength and flexural modulus increase steadily, i.e., from 84.0–98.94 MPa to 6041.14–7313.93 MPa, respectively. By adding gamma radiation of dose 7.5 kGy, the flexural strength and flexural modulus increase by about 26.17% and 26.87%, respectively, as compared to the corresponding non-radiated composites. With the further addition of gamma radiation at 10 kGy, both flexural strength and flexural modulus decrease by about 11.13% and 13.77%, respectively. It is also observed that the maximum flexural properties are obtained at the gamma radiation of 7.5 kGy. However, similar trend was observed for both tensile and flexural properties of composites.

In three-point bending test, various mechanisms such as tension, compression, shearing, etc., occur simultaneously. In consequence of the increased PALF fiber weight fraction, the flexural strength enhances owing to the increased resistance to shearing. In a three-point bending test, failure occurs because of bending failure and shear failure.

Izod impact strength of composite samples

Figure 6 shows the variation of Izod impact strength of 50/50 PALF/LDPE composites with different levels of gamma radiation. From Fig. 6 it is observed that the impact strength of non-radiated 50/50 PALF/LDPE composites is 33.42 kJ/m^2. With increasing gamma radiation from 2.5 to 7.5 kGy, impact strength of composites increases significantly by about 36.12%. However, with the further increase in gamma radiation (i.e., 10 kGy), there is a slight drop

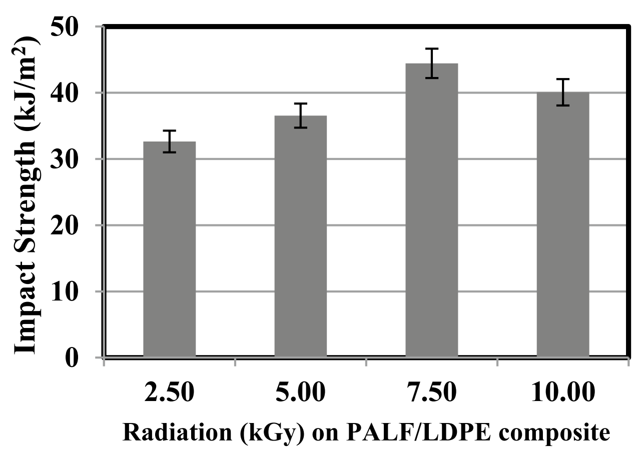

Fig. 6 Impact strength (kJ/m^2) of radiated 50/50 PALF/LDPE composites

Table 3 Tensile and flexural properties of non-radiated and radiated 50/50 PALF/LDPE composites

Composite sample ID	Tensile strength (MPa)	Tensile modulus (MPa)	Extension at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)
Non-radiated	28.44 ± 0.26	832.99 ± 6.50	66.53 ± 0.87	78.42 ± 0.75	5765.02 ± 126.74
2.50 kGy	28.97 ± 0.50	866.85 ± 2.16	50.66 ± 0.61	84.00 ± 0.62	6041.14 ± 41.51
5.00 kGy	32.05 ± 0.63	910.95 ± 1.96	47.63 ± 0.98	92.08 ± 0.62	6622.07 ± 57.48
7.50 kGy	38.49 ± 0.81	966.22 ± 1.64	36.17 ± 0.53	98.94 ± 0.18	7313.93 ± 33.24
10.00 kGy	35.58 ± 0.90	933.08 ± 0.52	44.44 ± 0.50	87.93 ± 0.68	6306.37 ± 62.05

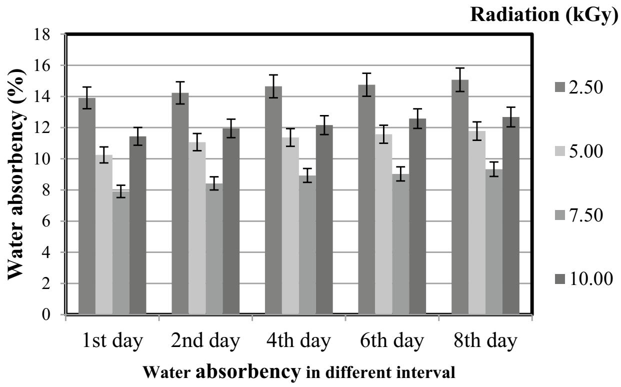

Fig. 7 Water absorbency % of radiated 50/50 PALF/LDPE composites

(about 9.81%) in impact strength (Fig. 6). This may be due to the opposing phenomena, namely photodegradation that takes place simultaneously under gamma radiation [31, 40].

Water absorption % of composite samples

Figure 7 shows the variation of water absorbency of radiated 50/50 PALF/LDPE composites with different levels of gamma radiation. The reduction of water absorbency of radiated composites was 54% than non-radiated 50/50 PALF/LDPE composite in 8th day at 7.5 kGy radiation. The maximum value of absorbency was 15.07% at 2.50 kGy radiation in 8th day which gradually decreases with increasing the radiation dose to 9.33% at 7.5 kGy radiation. After application of more dose than 7.5 kGy radiation, i.e., 10.00 kGy radiation, the absorbency further increased to 12.68% which indicates the more dose decreases the cross-linking and increases the amorphous regions in composite. The reduction in water absorbency after gamma radiation with the presence of PALF is attributed to improve interfacial adhesion that reduces water accumulation in interfacial spaces and prevents water molecules penetration in composites. The decrease in water absorption by post-irradiated composites attributed to the fact that gamma irradiation reduced the –OH group as well as increased crystalline regions in PALF and LDPE, through cross-linking which in turn decreases amorphous regions.

Scanning electron microscopy (SEM)

Scanning electron microscope has been used to reveal the interfacial region, cross section, fiber distribution, interfacial adhesion and fiber pullout from matrix. SEM images of composite samples before tensile strength test and the fractured composite samples of 50/50 PALF/LDPE composite are shown in Figs. 8 and 9, respectively. The results show good interfacial bond between the fibers and the matrix as well as superior reinforcement allocation in the matrix [41]. The crystallinity of the LDPE matrix can influence the bonding between the fiber and the matrix. Figure 8a, b shows the fiber–matrix interfaces in 50/50 PALF/LDPE composite. Some voids are observed in fiber–matrix adhesion area.

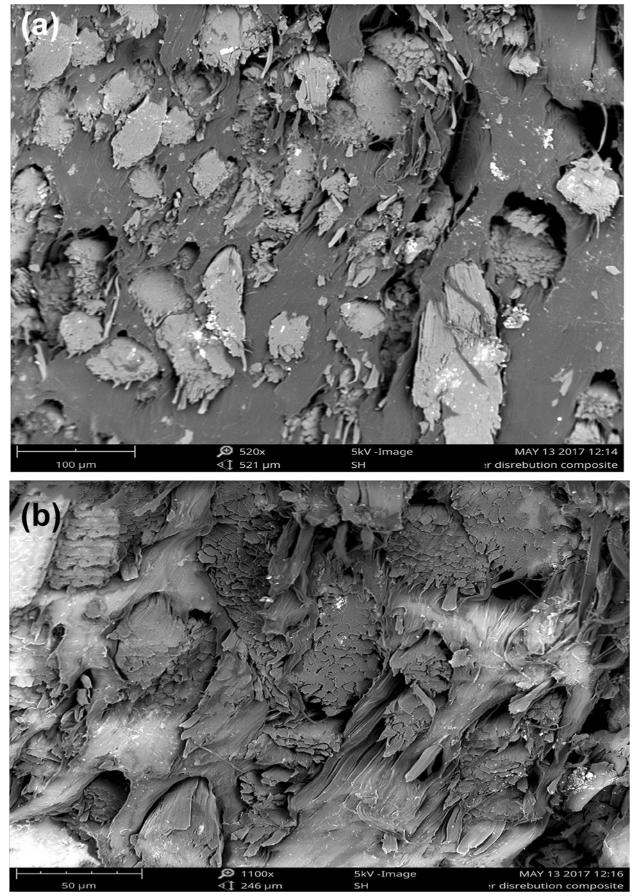

Fig. 8 Fiber–matrix interfaces before tensile test **a** 100 µm and **b** 50 µm

The high branching of LDPE improved the strength and strain values of the composites. The presence of interfacial interaction between fiber and polymer indicated stronger mechanical properties. Figure 9 shows the fracture surface of the composite in which Fig. 9a indicates that most of the reinforced fibers have broken rather than pulling out from matrix. Figure 9b shows some scattered fiber in the matrix, and most of them were clumped collectively.

Conclusions

The effects of pineapple leaf fiber (PALF) loading on the properties of PALF/LDPE composite had been studied. The tensile strength has increased gradually till 40 wt% of PALF, and maximum tensile strength (28.44 MPa) reached at 50 wt% fiber loading. The increase in fiber-to-fiber

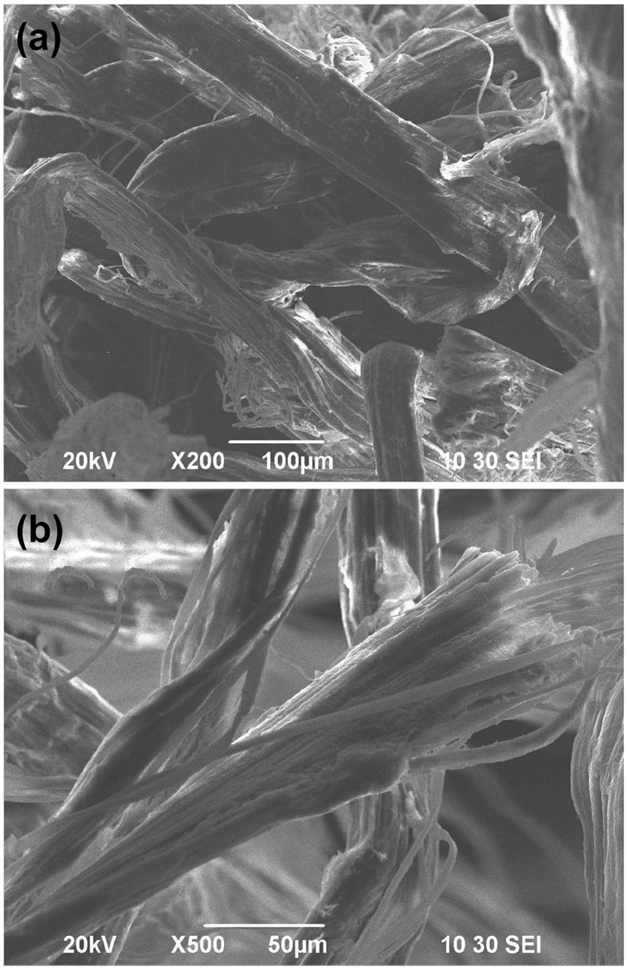

Fig. 9 Fibers in fractured point of composite **a** 100 µm, ×200 and **b** 50 µm, ×500

interaction and better dispersion in matrix had contributed to this phenomenon. The tensile strength has decreased at 60 wt% of PALF because of the excess fibers acted as flaws those stay non-bonded in LDPE matrix which initialized crazing and created stress concentration. In case of flexural strength and impact strength, the same trends were also found for 50 wt% fiber loading in composite and maximum flexural strength, flexural modulus and impact strength were found to be 78.42 MPa, 5.77 GPa and 33.42 kJ/m^2, respectively. The water absorbency has increased gradually with increasing fiber loading because of the increased cellulose content of PALF. It had also observed that the water absorbency rate was decreased gradually with increasing the number of days. It was observed from SEM images that the structure of the fabricated composite was compatible with PALF though some voids were found in the adhesion area. Furthermore, the 50/50 PALF/LDPE composite was radiated with different doses of gamma radiation. The improved tensile properties were found after application of gamma radiation at certain dose because of better intercross-linking between the neighboring cellulose molecules and matrix. The tensile strength, flexural strength and impact strength of composites were optimum at 7.5 kGy radiation and then started to decrease at 10 kGy radiation due to the two opposing phenomena, namely photo-cross-linking and photodegradation that took place simultaneously under gamma radiation. The study has demonstrated that the optimum performance obtained in PALF/LDPE composite is at 50 wt.% fiber loading and fiber–matrix interaction is compatibly well adhered at 7.5 kGy gamma radiation.

References

1. Bassyouni M, Waheed Ul Hasan S (2015) The use of rice straw and husk fibers as reinforcements in composites. In: Faruk O, Sain M (eds) Biofiber reinforcement in composite materials. Woodhead Publishing, Cambridge, pp 385–422
2. Sain M, Panthapulakkal S (2004) Green fibre thermoplastic composites. In: Baillie C (ed) Green composites: polymer composites and the environment. Woodhead Publishing, Cambridge, pp 181–206
3. O'Donnell A, Dweib MA, Wool RP (2004) Natural fiber composites with plant oilbased resin. Compos Sci Technol 64(9):1135–1145
4. Dweib MA, Hu B, O'Donnell A, Shenton HW, Wool RP (2004) All natural composite sandwich beams for structural applications. Compos Struct 63(2):147–157
5. Threepopnatkul P, Kaerkitcha N, Athipongarporn N (2009) Effect of surface treatment on performance of pineapple leaf fiber–polycarbonate composites. Compos Part B 40:628–632
6. Luo S, Netravali N (1999) Mechanical and thermal properties of environment-friendly "green" composites made from pineapple leaf fibres and poly (hydroxybutyrate-co-valerate) resin. Polym Compos 20(3):367–378
7. Yusof Y, Yahya SA, Adam A (2015) Novel technology for sustainable pineapple leaf fibers productions. Procedia CIRP 26:756–760
8. Ahmed OH, Husni MH, Anuar AR, Hanafi MM (2004) Towards sustainable use of potassium in pineapple waste. Sci World J 4:1007–1013
9. Neto SAR, Araujo MAM, Souza FVD, Mattoso LHC, Marconcini JM (2013) Characterization and comparative evaluation of thermal, structural, chemical, mechanical and morphological properties of six pineapple leaf fiber varieties for use in composites. Ind Crops Prod 43:529–537
10. Mohamed AR, Sapuan SM, Shahjahan M, Khalina A (2009) Characterization of pineapple leaf fibers from selected Malaysian cultivars. J Food Agric Environ 7(1):235–240
11. Kengkhetkit N, Amornsakchai T (2014) A new approach to "Greening" plastic composites using pineapple leaf waste for performance and cost effectiveness. Mater Des 55:292–299
12. Sapuan SM, Mohamed AR, Siregar JP, Ishak MR (2011) Pineapple leaf fibers and PALF–reinforced polymer composites. In: Kalia S, Kaith B, Kaur I (eds) Cellulose fibers: bio- and nano-polymer composites, vol 1. Springer, Berlin, pp 325–343
13. Leão AL, Cherian BM, Narine S, Souza SF, Sain M, Thomas S (2015) The use of pineapple leaf fibers (PALFs) as reinforcements in composites. Biofiber Reinf Compos Mater 1:211–235
14. Arib RMN, Sapuan SM, Ahmad MMHM, Paridah MT, Zaman HMDK (2006) Mechanical properties of pineapple leaf fibre reinforced polypropylene composites. Mater Des 27(5):391–396

15. Hayavadana J, Jacob M, Sampath G (2003) Diversified product of pine apple leaf fibres. Man Made Text India 46:301–305
16. Väisänen T, Das O, Tomppo L (2017) A review on new bio-based constituents for natural fiber–polymer composites. J Clean Prod 149:582–596
17. Asim M, Abdan K, Jawaid M, Nasir M, Dashtizadeh Z, Ishak MR, Hoque ME (2015) A review on pineapple leaves fibre and its composites. Int J Polym Sci 2015:1–16
18. Mishra S, Mohanty AK, Drzal LT, Misra M, Hinrichsen G (2004) A review on pineapple leaf fibers, sisal fibers and their biocomposites. Macromol Mater Eng 289(11):955–974
19. Kabir MM, Wang H, Lau KT, Cardona F (2012) Chemical treatments on plant-based natural fibre reinforced polymer composites: an overview. Compos Part B 43(7):2883–2892
20. Li X, Tabil LG, Panigrahi S (2007) Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J Polym Environ 15(1):25–33
21. George J, Bhagawan SS, Thomas S (1997) Improved interactions in chemically modified pineapple leaf fiber reinforced polyethylene composites. Compos Interfaces 5(3):201–223
22. George J, Bhagawan SS, Thomas S (1998) Effects of environment on the properties of low-density polyethylene composites reinforced with pineapple-leaf fibre. Compos Sci Technol 58(9):1471–1485
23. Chollakup R, Tantatherdtam R, Ujjin S, Sriroth K (2011) Pineapple leaf fiber reinforced thermoplastic composites: effects of fiber length and fiber content on their characteristics. J Appl Polym Sci 119:1952–1960
24. George J, Sreekala MS, Thomas S (1998) Stress relaxation behavior of short pineapple fibre reinforced polyethylene composites. J Reinf Plast Compos 17(7):651–672
25. George J, Janardhan R, Anand JS, Bhagawan SS, Thomas S (1996) Melt rheological behaviour of short pineapple fibre reinforced low density polyethylene composites. Polymer 37(24):5421–5431
26. George J, Joseph K, Bhagawan SS, Thomas S (1993) Influence of short pineapple fiber on the viscoelastic properties of low-density polyethylene. Mater Lett 18(3):163–170
27. Enciso B, Abenojar J, Paz E, Martínez MA (2018) Influence of low pressure plasma treatment on the durability of thermoplastic composites LDPE-flax/coconut under thermal and humidity conditions. Fibers Polym 19(6):1327–1334
28. Khan MA, Hassan MM (2004) Surface modification of natural fibers by photo-grafting and photo-curing. Polym Surf Modif Relev Adhes 3:263–283
29. Valdez-Gonzalez A, Cervantes-Uea JM, Oleyob R, Franco HPJ (1999) Effect of fiber-surface treatment on the fiber-matrix bond strength of natural fiber reinforced composites. Compos Part B 30(3):309–320
30. Alothman OY, Almajhdi FN, Fouad H (2013) Effect of gamma radiation and accelerated aging on the mechanical and thermal behavior of HDPE/HA nano-composites for bone tissue regeneration. BioMed Eng Online 12(95):1–15
31. Haydaruzzaman KhanRA, Khan MA, Khan AH, Hossain MA (2009) Effect of gamma radiation on the performance of jute fabrics-reinforced polypropylene composites. Radic Phys Chem 78(11):986–993
32. Wanjale SD, Jog JP (2011) Polyolefin-based natural fiber composites. In: Cellulose fibers: bio-and nano-polymer composites, 2011th edn. Springer, Berlin, pp 377–398
33. Mohanty AK, Khan MA, Hinrichsen G (2000) Surface modification of jute and influence on performance of biodegradable jute-fabric/biopol composites. Compos Sci Technol 60:1115–1124
34. Li X, Tabil LG, Panigrahi S, Crerar WJ (2006) The influence of fiber content on properties of injection molded flax fiber-HDPE biocomposites. In: 2006 ASAE annual meeting 2006, p 1. American Society of Agricultural and Biological Engineers
35. Girisha C, Sanjeevamurthy RangasrinivasGunti (2012) Tensile properties of natural fiber-reinforced epoxy–hybrid composites. Int J Mod Eng Res 2(2):471–474
36. Mishra S, Mohanty AK, Drzal LT, Misra M, Parija S, Nayak SK, Tripathy SS (2003) Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. Compos Sci Technol 63(10):1377–1385
37. Khan MA, Khan RA, Haydaruzzaman HossainA, Khan AH (2008) Effect of gamma radiation on the physico-mechanical and electrical properties jute fiber reinforced polypropylene composites. J Reinf Plast Compos 28(31):1651–1660
38. Danladi A, Tunde AS (2013) Effect of fiber length on the physical and mechanical properties of sisal/polyethylene composites. Pak J Sci Ind Res Ser A Phys Sci 56(1):42–46
39. Marcovich NF, Ostrovsky AN, Aranguren MI (2000) In: Proceedings from the 3rd international symposium on natural polymers and composites-ISNaPol, Sao Pedro, pp 14–17
40. Khan MA, Shehrzade S, Hasan MM (2003) Effect of pretreatment with gamma-radiation on physical and mechanical properties of 1,6,hexanedioldiacrylate (HDDA) jute yarn by UV radiation. Polym Plast Technol Eng 42(5):795–810
41. Li RKY, Liang JZ, Tjong SC (1998) Morphology and dynamic mechanical properties of glass beads filled low density polyethylene composites. J Mater Process Technol 79:59–65