Mechanical properties of leaf sheath date palm fibre biomass waste reinforced polycaprolactone (PCL) biocomposites

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ABSTRACT

Date palm fibres are one of the most available natural fibres in North Africa and the Middle East. A significant amount of date palm fibres biomass is wasted annually and only limited amounts are used in low value products. In this study, tensile and low-velocity impact response of biodegradable lignocellulosic biomass reinforced polycaprolactone (PCL) biocomposites are reported. Two different types of laminates reinforced with date palm fibre obtained from agriculture waste were manufactured by an extrusion process. The influence of processing parameters, such as screw rotation speed on the tensile and low velocity impact damage characteristics have been investigated. The tensile strength increased for neat PCL from 19 MPa to 25 MPa with 28 wt.% reinforcement of date palm fibres. Similarly, the tensile modulus for neat PCL was increased from 140 MPa to 282 MPa upon reinforcement. The screw rotation speed showed a moderate effect on palm fibre morphologies, and slight effect on tensile properties of the biocomposites. Specimens with lower incident energy of 25 J achieved better impact resistance compared to that of 50 J. The impact damage of biocomposites analysed through electron microscopy on the fractured surface showed various modes of damage. The biocomposites developed in this work can be used as an economically and environmentally attractive alternative materials for lightweight applications in automotive and marine sectors.

Keywords: *Date Palm Fibres; Low-velocity impact, Biocomposites; Delamination.*

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1. Introduction

The total costs of production (energy/power) and maintenance of conventional (synthetic) fiber-reinforced polymer (FRP) composites such as glass and carbon FRP composites are relatively higher when compared with that of natural FRP composites such as date palm, hemp or flax biocomposites. In addition, the problems of unstable interfacial adhesion of the fiber and matrix often results in fiber-pull out, and matrix de-bonding as well as inter-ply delamination are more rampant with synthetic FRP composites than the natural counterparts. Importantly, date palm fiber/polycaprolactone biocomposites are completely biodegradable, renewable, sustainable and recyclable materials, unlike the synthetic FRP composites~~, hence~~. Hence, date palm/PCL have a very low level of toxicity which makes them environmentally friendly and relatively safe for human health during processing and life cycle. Moreover, their light weight leads to attractive specific properties such as high strength-to-weight ratios in comparison to their non-renewable, high energy-intensive reinforcing synthetic counterparts such as glass and carbon fibres. These positive attributes of natural fibre reinforcements are particularly attractive to the automotive original equipment manufacturers (OEMs) as they are facing the challenge of producing light parts at low cost. In this context, biocomposites reinforced with low density fibres such as date palm and biodegradable matrix such as polycaprolactone (PCL) can offer alternative solutions to the petroleum based polymers and non-renewable synthetic reinforcements (Faruk et al., 2012; Paul et al., 2015).

There are several research works reported in the past focusing on the development and applications of natural plant fibre reinforced thermoplastic and thermoset composites in automotive, marine, and construction industries (Dhakal et al., 2007; Mohanty et al., 2000). Due to their main constituents being cellulose, hemicellulose and lignin, plant fibres are also known as lignocellulosic fibres. Investigations on mechanical properties of these fibres suggest that the specific tensile stiffness of some commonly used natural fibres such as hemp, flax and sisal are comparable to those exhibited by synthetic reinforcements (Joshi et al., 2004; Summerscales et al., 2010). However, these reported works also point out that despite their attractive mechanical and environmental attributes, these plant fibre reinforcements suffer with non-uniform properties leading to variable mechanical performances, poor fibre-matrix compatibility, and concerns relating to long-term durability (Charlet et al., 2007). Moreover, a plant fibre bundle for example consists of several cells composed of cellulose, hemicellulose and lignin. The ratio of these constituents vary from one fibre to the other. This structural complexity and dimensional inhomogeneity often contribute to varied and distinct properties of plant fibres which influence the final properties of the composites (Stamboulis et al., 2001).

In the last several years, significant interest has emerged in the development of composite materials from waste precursors. This new approach will not only tackle waste disposal problems, but also provide an adequate route for resource utilisation, hence supporting the sustainable development agenda by balancing social, environmental and economic considerations. The utilisation of waste date palm fibres in composite reinforcements can be a step forward in contributing resource maximisation. Currently, the bulk of date palm fibres are used in low value products. Therefore, the use of agricultural residues such as date palm fibres through sensible and innovative ways of utilisation is of potential interest to researchers and industry (Bledzki and Gassan, 1999; Nasser et al., 2016).

Date palm fibres are derived from the date palm tree. The date palm tree (*Phoenix dactylifera L.*), a member of the palm tree family (*Arecaceae*), is one of the most cultivated palms in North Africa and the Middle East, including in countries such as Tunisia, Algeria, United Arab Emirates, Saudi Arabia, Egypt, Iraq and Iran. After date fruit harvesting, date palm rachis waste is accumulated on agricultural land every year in these countries (Chao and Krueger, 2007). The major constituent of date palm fibre is cellulose (46%), hemicelluloses (18%), lignin (20%) and ash (10.54%). Date palm trees produce a large quantity of agriculture waste. For example, each tree produces 20 kg of dry leaves annually. This waste is burned in the farms, causing serious environmental pollution as well as death of important soil microorganisms (Alawar et al., 2009).

The part of the date palm tree which is often used as fibres is the sheath. The sheath is the part of the tree which surrounds the trunk of the plant attached to its lateral edges near the top of the trunk as shown in Fig. 1. Sheath is also known under the name of leaf and is often torn lose when pruning the leaves. Seeking to use them as useful material resources instead would bring economic growth. If these agricultural residues are utilised in building materials (Alsaeed et al., 2013) or for example as composite reinforcements, a tremendous value-added by-product can be realised. The residue generated from the palm tree is currently used in a variety of applications such as particle board, low and medium density fibre board, pulp and paper. But these wastes have not been fully-utilised as an economic alternative (Abdelaziz et al., 2016; Nasser et al., 2016).

Despite several benefits of date palm fibres outlined, to the authors' best knowledge, there are limited reported studying biocomposites developed from waste date palm fibre residue and investigating their low velocity impact behaviour. The main objective of this study is to evaluate the suitability of date palm fibre as alternative reinforcements in composite materials. The reinforcing effects of date palm fibres obtained from palm leaf sheath on the resulting extruded and injected PCL biocomposites are investigated by categorising the important parameters influencing on the low velocity impact and tensile properties. In addition, the influence of screw rotation speed on palm fibre defibrillation (Alawar et al., 2009) and flow conditions along the twin screw extruder (TSE) are analysed in order to calculate the specific mechanical energy (SME) provided to the fibres. Furthermore, the influence of extruder screw rotation speed and palm fibre reinforcements on the tensile and impact properties including load bearing capability, energy absorption, impact damage characteristics from the falling weight impact are analysed and discussed.

2. Materials and methods

2.1 *Materials*

Date palm fibres (*Phoenix dactylifera L.*) were obtained from a farm in Al-Ahsa, located in the Eastern Province of Saudi Arabia, as decametric bundles (Fig 1, a-b). Prior to Twin Screw Extrusion (TSE), the palm bundles were chopped into a master batch with an average length of approximately 1 cm (Fig 1, c, average length Lw equal to 10400 µm) with a plant shredder equipped with a 2 mm sieve (Retsch, Haan Germany). The chopped fibre bundles were then stored at 20°C C and 50% relative humidity in a climatic chamber prior TSE. The SEM images of date palm fibre are depicted in Fig. 2.

The box plot give the upper Quartil (Q1), the quartil 3 (Q3), the median length (Lmed) and the mean Length (Lw) with values incrusted in the graphic.

Fig. 1.

The thermoplastic matrix used was polycaprolactone (PCL) of low melting temperature (60 °C). PCL (Capa© 6800) was provided by Perstorp, United Kingdom, having a molecular weight of 80,000 g/mol and a melt flow index (MFI) of 3 g/10 min (160 °C, 2.16 kg).

The longitudinal morphology of the date palm fibre examined by SEM is shown in Fig. 2. The tensile strength and stiffness of the composites is presented in the form of an Ashby's materials selection chart in Fig. 3 (Shah, 2014), comparing the performance with other natural bast fibre composites. The comparative physical and mechanical properties of date palm fibre with other commonly used bast fibre are presented in Table 1 (Dhakal et al., 2007; Mohanty et al., 2000; Pickering et al., 2016).

Table 1

Fig. 2.

Fig. 3.

2.2 *Composite manufacturing*

The compounds were prepared using chopped palm fibre (Fig 1, c) mixed with a PCL matrix at a concentration of 20 wt.% with a laboratory-scale twin-screw co-rotating extruder TSE ZSE 27 MAXX (Leistritz, Germany). Its main characteristics are as follows: centerline distance 22.7 mm, screw diameter 28.3 mm, length/diameter ratio 36. In addition to screw conveying elements, it comprises a left-handed element in zone 3 to ensure the melting of the polymer matrix and two mixing blocks in zones 6 and 8, to disperse the fibres. The first one is constituted of a block of kneading discs, staggered at 90°, and the second one of a block of kneading discs, but staggered at -60°. The matrix is introduced in zone 1, melted in the left-handed element (zone 3) and the fibres are then added in zone 4. During all experiments, the barrel temperature was kept constant at 120 °C, the feed rate retained was 3.5 kg/h, and screw speed (100 and 400 rpm) was varied.

In order to estimate values of parameters that cannot be measured experimentally during the compounding process, we have used the flow simulation software Ludovic© dedicated to twin screw extrusion (Vergnes et al., 1998). Specifically, Ludovic© was used to calculate the specific mechanical energy (SME) transmitted to the composite all along the extruder.

The SME is calculated from equation (1):

$$EMS = \frac{1}{Q}\int_0^x \eta(x)\dot{\gamma}^2(x)V(x)dx \qquad (1)$$

where, Q is the mass flow rate, η the viscosity, $\dot{\gamma}$ the shear rate and V the design volume considered. Fig. 4 represents the change in SME along the screws for two different screw speeds.

Fig. 4.

After extrusion, the composite strands were cooled down at room temperature and the compounds were granulated (approx. 8 mm in length).

Standard dumbbell specimens were injected using a bench scale DSM Xplore (Geleen, The Netherlands) according to the procedure of -Haag et al. (2017). Ten specimens were tested for each condition.

To analyse the morphometry of the compounded samples, the PCL dissolution was done as described by Beaugrand and Berzin (2013) (Fig 1, d-e). Then, the morphometric description was done according to the method of Di Giuseppe et al. (2016) using a 2D high-resolution image scanning.

Laminates of 200x200 mm length, 5 mm thick were manufactured by press moulding as described in Ismail et al. (2016). The press is a two columns automatic laboratory hydraulic press (Carver, Wabash, IN) equipped with heating platens.

2.3 Tensile testing

Tensile testing was carried out on a universal testing machine (Testwell, Saint Ouen, France) equipped with a mechanical extensometer. The tensile testing was carried out according to the ISO 291:2008 standard. The loading rate used was 1 mm/min.

2.4 Low velocity impact test

Zwick/Roell HIT230F instrumented falling weight drop impactor was used for instrumented falling weight impact testing. The composite specimens were cut from the Palm/PCL composite laminates using a band saw to a square dimension of 60 x 60 mm with 5.7 mm thickness at two energy levels: 25J (with an impact velocity 1.47 m/s) and 50J (with an impact velocity 2.08 m/s) at room temperature. The diameter of the hemispherical steel tup was 19.8 mm. Impact parameters such as peak force, absorbed energy, deformation were continuously recorded for every specimen at each impact event performed using a load cell and a strain–gauge striker fitted on the system. A catcher mechanism was activated to avoid the multiple damage on the specimens. A schematic of drop weight impact mass, hemispherical impact tup and clamping systems are shown in Fig. 5. Similar impact test parameters were used to impact hemp/PCL composites in order to compare the impact damage behaviour of palm/PCL biocomposites.

Fig. 5.

2.5 Fractured surface characterisation by SEM

Impact failure surfaces of different biocomposites were pre-coated with a thin gold film and observed in a Phillips XL30CP scanning electron microscope (SEM) at 15 kV acceleration voltages.

3. **Results and discussion**

3.1. Tensile properties (strength and modulus)

The tensile properties of different reinforcement configurations are summarised in Table 2. The tensile results show that there is a clear influence of date palm reinforcement on the tensile strength, modulus and strain at break. There was improvement in tensile strength for example from 19 MPa for neat PCL to 24 MPa for 20wt.% Palm/PCL. Moreover, there is a significant improvement in tensile modulus from 140 MPa for neat PCL to 284 MPa for 20 wt.% Palm/PCL biocomposites. This increase in strength and modulus is attributed to the fibre reinforcement effects as well as employed extruder parameters. The elongation at break is significantly higher for neat PCL compared to palm fibre/PCL biocomposites and this is expected as the PCL is a ductile matrix and the strain at break is matrix dominated property in this case. The tensile strength properties obtained in this study are in close agreement with the reported work by Mahdavi et al. (2010) where they have presented tensile strength of date palm fibre reinforced polyethylene composites. In comparison, the results obtained (24 MPa) in this work were found to be higher than their reported results using rachis 20 wt.% from date palm as reinforcement in polyethylene matrix. In our case, the use of a PCL matrix, having more interfacial compatibility with plant components, is a significant advantage

Furthermore, the effect of the screw rotation speed (100 and 400 rpm) was tested during compounding. There is a slight variation in terms of measured tensile Young's modulus and tensile strength (Table 2). The rotation speed also seems to affect the palm fibre morphologies (Fig. 1) with Lw of 985 and 765 when extruded at 100 and 400 rpm, respectively. Because some extrusion parameters, including screw speed, are known to impact lignocellulosic fibre morphologies, one could have expected pronounced differences in composite tensile properties between those two. Indeed, the feed rate, (Beaugrand and Berzin, 2013; Berzin et al., 2014), the recycling (Bourmaud et al., 2016), could impact on the fibre morphology which in turn impacts mechanical properties (Beaugrand and Berzin, 2013) or processing alteration (Ismail et al., 2016). Because screw rotation speed is known to modulate the specific mechanical energy (SME), the commercial software Ludovic© was used to calculate SME transmitted to the composite all along the extruder. This commercialised software is based on a one-dimensional (1D) approach. It allows the calculation of the main thermomechanical parameters of the process, from the hopper to the die exit, including solid conveying, melting and melt conveying. It has been shown that the fibre fragmentation depended on the SME provided to the fibres (Beaugrand and Berzin, 2013; Berzin et al., 2014, 2017). As an example, Fig. 4 shows the evolution along the screw profile of the global SME that we can compare to experimental values calculated from the measured torque. It is observed that the SME increases in the left handed element, in the blocks of kneading discs and in the filled section prior to the die. Marked differences between 100 rpm and 400 rpm are then obtained.

However, there is no pronounced difference in tensile properties between samples made at 100 and 400 rpm. A close look at the length population distribution (Fig. 1 box plots) sheds a new light. Indeed, the overall length distribution is first quite disperse, and additionally the trend is not so different, despite the distinct Lw. This illustrates that only one average or median value is generally not enough to describe lignocellulosic fibre morphology (Di Giuseppe et al., 2016; Hamdi et al., 2015)

Table 2

The materials selection chart in Fig. 3 enables comparison of the tensile strength and stiffness of the injection moulded date palm fibre composites with other bast fibre composites. We find that the date palm fibre composites have comparable strength to other injection moulded bast fibre composites and neat resins, however the stiffness is much lower. This is explained by the substantially lower stiffness of date palm fibres in comparison to bast fibres like flax, jute and hemp (Table 1). Anecdotal observations from tensile properties of compression moulded, unidirectional date palm fibre composites reveal substantially lower strength and stiffness in comparison to compression moulded, unidirectional bast fibre composites. Rather the former have similar performance to compression moulded, non-woven (2D random fibre orientation) bast fibre composites.

3.2. Low velocity impact characteristics

3.2.1 Force-displacement analysis

To evaluate impact damage characteristics, criteria such as maximum force, energy absorbed, force displacement and visual observation were used. Force versus displacement traces obtained from the low velocity impact testing for palm fibre/PCL specimens impacted at two different energy levels are depicted in Fig. 6 (a). Contact force is generally defined as reaction force exerted by the specimen to the impactor. As shown in Fig. 6 (a), the maximum contact force has slightly increased with the increase in incident energy level. From these curves, it can be seen that the increase in energy level from 25 to 50 J has not caused a major difference in peak load. The maximum load reached for 25 J impacted specimen is approximately 2425 N, with a displacement of approximately 8 mm at peak force.

The peak force for specimens impacted at energy level of 50 J has been recorded at approximately 2535 N and unlike 25 J energy level, the curve for this specimens has reached zero which is an indication of samples fully perforated.

Fig. 6 (a-c).

3.2.2 Force-time comparisons

The contact force-time traces corresponding to impact event for each specimen subjected to incident energy of 25 and 50 J are illustrated in Fig. 6 (b). The time taken to complete the impact event is different for each specimen. It is evident that at the lower energy level, the palm fibre/PCL biocomposite shows more impact resistance, thereby taking longer time to complete the impact event compared to higher energy impacted samples.

3.2.3 Energy-time comparisons

The impact strength of composites is defined by its ability to withstand fracture or the amount of energy required to initiate damage. Absorbed energy versus time plots for different specimens are shown in Fig. 6 (c). It is evident from the figure that the absorbed impact energy for both samples are almost identical. However, the visual inspection of impacted samples at 50 J incident energy level shows a big difference than that of incident energy of 25 J. On the samples being impacted at the incident energy of 50 J, the material was fully penetrated. This is due to the high incident energy allowing the impactor to penetrate.

Fig. 7 (a) –(c) show the impact parameters (peak load and absorbed energy) of hemp/PLC biocomposites used to compare the results obtained for palm/PCL biocomposite specimens. It is evidenced from the Figure 7 (a) that hemp/PCL specimens have lower peak load and displacement compared to palm/PCL specimens. Similarly, the hemp/PCL specimens absorbed low impact energy (lower dissipated energy) as depicted in Fig. 7 (c) compared to palm/PCL specimens. This results are evidences that the palm/PCL biocomposites can be promising sustainable materials when improved impact performance is critical.

Fig. 7

3.3 ***Impact damage characterisation***

The visual inspection of palm/PCL impacted at 25 J (Fig. 8) clearly shows that the specimens have not been fully penetrated but there is a clear indication of radial cracking and perforation.

Fig. 8.

For samples impacted at higher energy level (50 J), there is evidence of matrix cracking around the impacted hole, as energy was not distributed throughout the specimen and it was penetrated through (Fig. 9). The higher velocity of impact event allowed the impactor to puncture the samples. The damage area and size for this sample was larger than the samples impacted at 25 J incident impact energy.

Fig. 9.

The rear faces of all specimens show similar damage propagation. However, larger penetration hole and fibre shear out are visible for specimen impacted at higher energy level (Fig. 9). The extent of damage is larger for samples with 50 J incident energy level.

3.4 Fractured surface of impacted samples

Representative SEM images of impact fractured surfaces of these two samples are shown in Figs. 10 and 11. From SEM images of the impact at incident energy level of 25 J specimens (Fig. 10), it is observed that matrix bending and fibre delamination are apparent. The SEM images suggest that there was poor fibre matrix interface leading to better energy dissipation which has resulted in better impact resistance behaviour but lower tensile strength and modulus. For higher incident energy level, the fractured surfaces reveal that the fibres are exposed, unravelled and also pulled out. The PCL is a ductile matrix while the SEM images (Fig. 11, b) show no residue of matrix on the pulled out fibre which is an indication of poor fibre-matrix adhesion. This behaviour normally leads to better toughness properties and lower tensile strength and modulus. It can be observed from SEM images that there are some gaps between matrix and fibre which is an indication of insufficient consolidation of fibres during the manufacturing and caused by incompatibility between fibre and the matrix.

Fig. 10.

Fig. 11.

4. Conclusions

Using date palm fibres from waste as reinforcements in PCL based biocomposites was found to be effective approach for obtaining an acceptable tensile and impact resistance behaviour. It was evident from the experimental results that samples with higher extrusion screw speed have average fibre length shorter than those extruded with lower screw speed (400 vs 100 rpm) but the specimen composites do not withstand more than a slightly higher tensile stress than that of 100 rpm, arguably due to a very disperse fibre morphology population. However, the tensile test results showed that date palm fibre reinforced PCL biocomposite laminates have acceptable tensile strength and modulus with respect to currently available literature data.

With regards to low velocity impact resistance behaviour, both samples showed similar behaviour apart from 25 J incident energy level showing resistance to penetration in comparison to 50 J of incident energy.

Investigating the suitability of date palm fibres biomass waste as reinforcement in light weight composite materials shows a tremendous opportunity of utilising this material to develop ~~a~~ low cost composites. Hence, it can contribute to reduce the overall environmental damage, better way of utilisation of resources and reduction of total cost for the manufacturing of composites, which is a clear benefit in many applications. Furthermore, the findings of this study has a great potential of benefitting composite manufacturing industries, research institutes and academia, as they work or study/research to improve the properties of natural fiber-reinforced biocomposite materials.

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Figure captions:

Fig. 1. Schematic representation of sequence and processing steps of Date Palm Tree grown in Kingdom of Saudi Arabia and fibre extracted from leaf sheath a) Date Palm Tree grown in Kingdom of Saudi Arabia and b) fibre (fibrillum) extracted from leaf sheath. c) palm fibers lot chopped prior to twin screw extrusion; d) palm fibres from c) extruded at 100 rpm after extraction of the PCL matrix, e) palm fibres from c) extruded at 400 rpm after extraction of the PCL matrix. The scale bar = 1 cm. Lower part: box plots corresponding to the three images.

Fig. 2. SEM images of date palm fibre used in this study showing pores morphology: (a) longitudinal section at lower magnification x 150; (b) at higher magnification x 500

Fig. 3. Ashby chart presenting strength versus modulus of our date palm composites (red) in an Ashby chart, comparing with other bast fibre composites. Adapted from (Shah, 2014). Acronyms are: IM injection moulded, CM compression moulded, RTM resin transfer moulded, UD unidirectional, TP thermoplastic, TS thermoset

Fig. 4. Evolution of SME at 3.5 kg/h (○ : 100 rpm ; ● : 400 rpm) along the screw profile and comparison with experimental SME measured at the die exit (restrictive zones are in grey)

Fig. 5. Schematic of low velocity impact test set up

Fig. 6. (a) Force versus displacement, (b) Load versus time and (c) Work versus time traces of palm/PCL biocomposites.

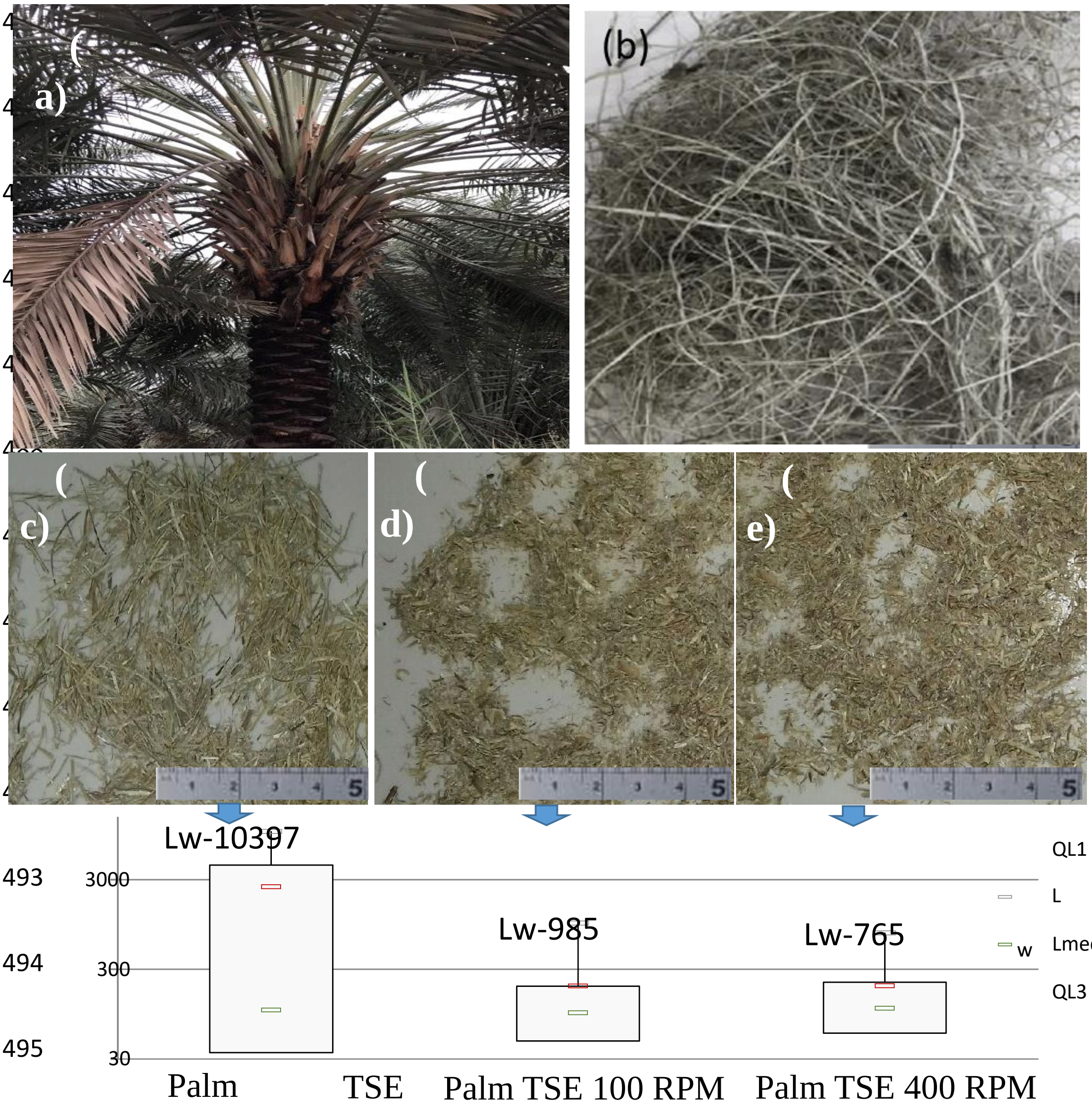
Fig. 7. (a) Force versus displacement, (b) Load versus time and (c) Work versus time traces of hemp PCL for comparison purpose.

Fig. 8. Damage pattern of Palm/PCL specimens impacted at 25 Joules (a) front face damage and (b) rear face damage.

Fig. 9. Damage pattern of Palm/PCL specimens impacted at 50 Joules (a) front face damage and (b) rear face damage

Fig. 10. SEM images of Palm/PCL after impact test at 25J, 1: delamination and debonding, 2: matrix bending, 3: fibres breakage, 4: fibre pull out, 5: pull out fibre side

Fig. 11. SEM images of Palm/PCL after impact test at 50J, 1: delamination, 2: matrix breaking, 3: fibres breakage


(a)
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Lw-765
3000
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QL3
w
Palm TSE
Palm TSE 100 RPM
Palm TSE 400 RPM

Fig. 1. Schematic representation of sequence and processing steps of Date Palm Tree grown in Kingdom of Saudi Arabia and fibre extracted from leaf sheath a) Date Palm Tree grown in Kingdom of Saudi Arabia and b) fibre (fibrillum) extracted from leaf sheath. c) palm fibers lot chopped prior to twin screw extrusion; d) palm fibres from c) extruded at 100 rpm after extraction of the PCL matrix, e) palm fibres from c) extruded at 400 rpm after extraction of the PCL matrix. The scale bar = 1 cm. Lower part: box plots corresponding to the three images.

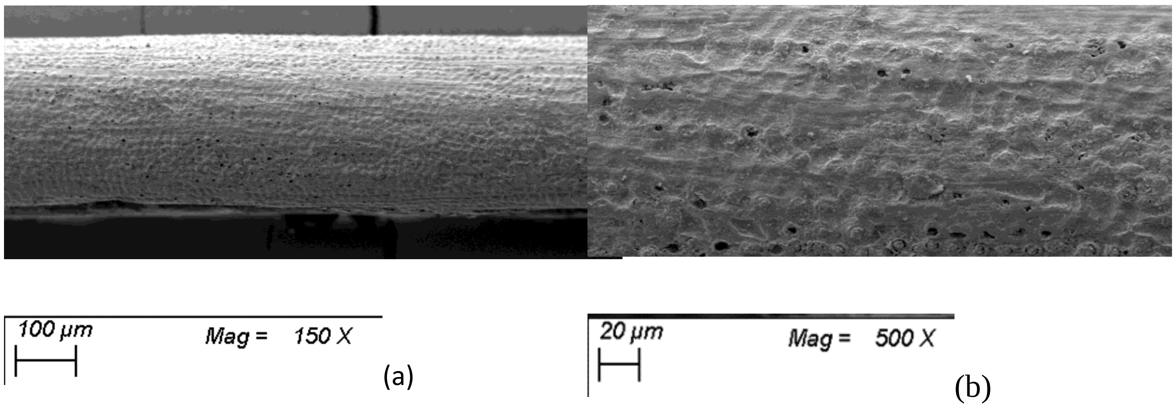

Fig. 2. SEM images of date palm fibre used in this study showing pores morphology: (a) longitudinal section at lower magnification x 150; (b) at higher magnification x 500.

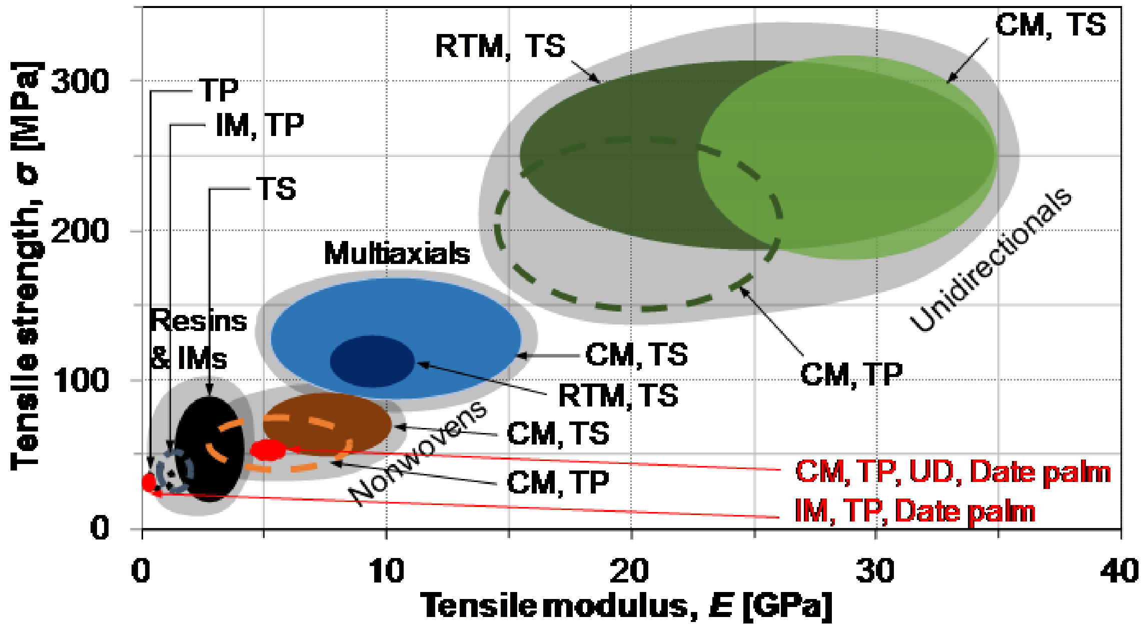

Fig. 3. Ashby's chart presenting strength versus modulus of our date palm composites (red) in an Ashby chart, comparing with other bast fibre composites.The strength versus modulus in as Ashby's chart (adapted from REF: Shah, 2014). Acronyms are: IM injection moulded, CM compression moulded, RTM resin transfer moulded, UD unidirectional, TP thermoplastic, TS thermoset.

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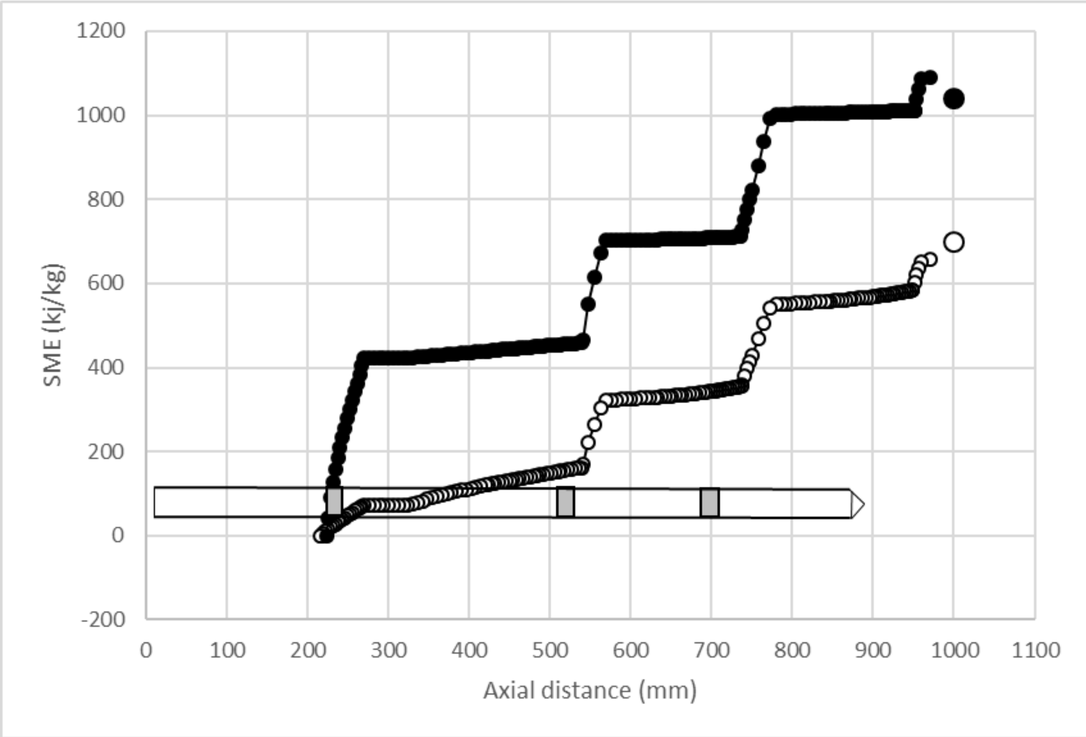


Fig. 4. Evolution of SME at 3.5 kg/h (○ : 100 rpm ; ● : 400 rpm) along the screw profile and comparison with experimental SME measured at the die exit (restrictive zones are in grey).

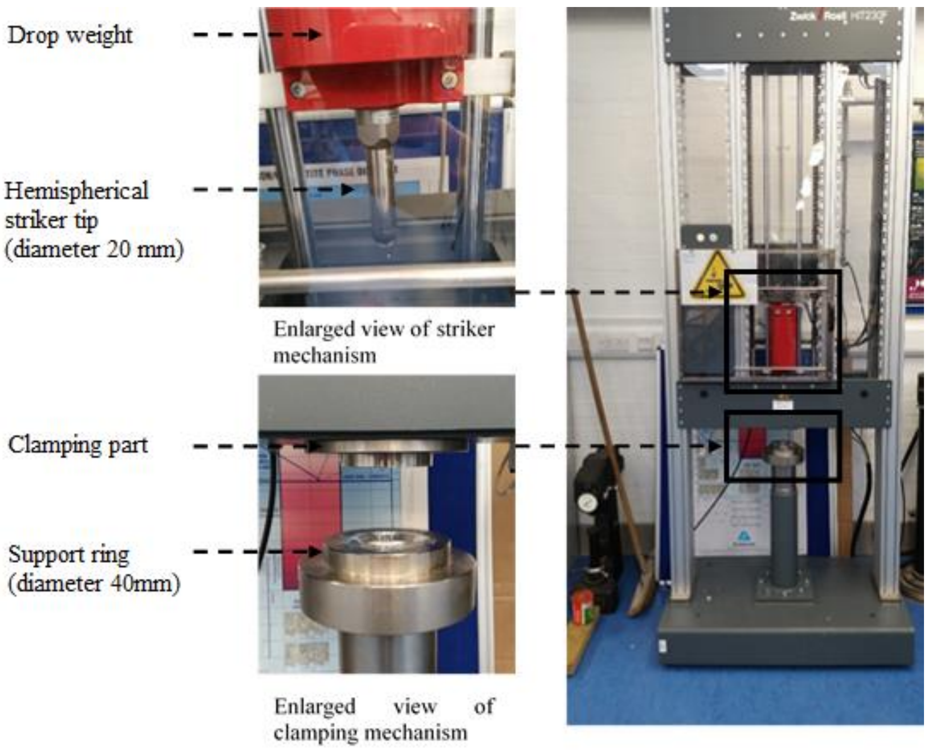
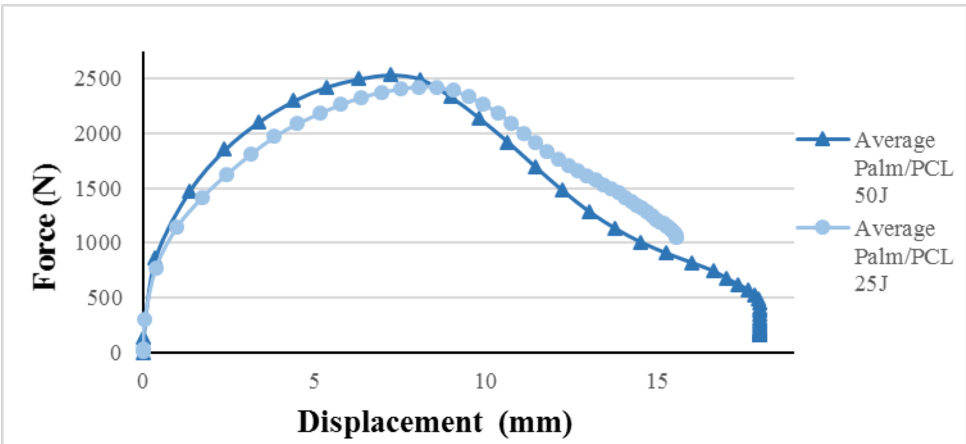
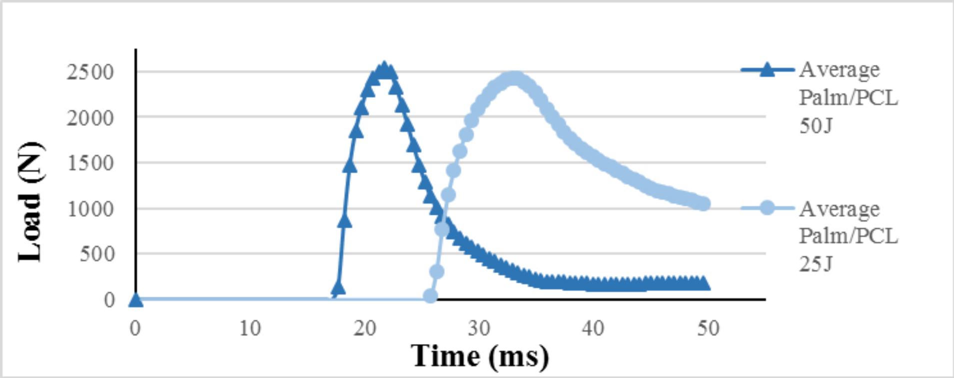


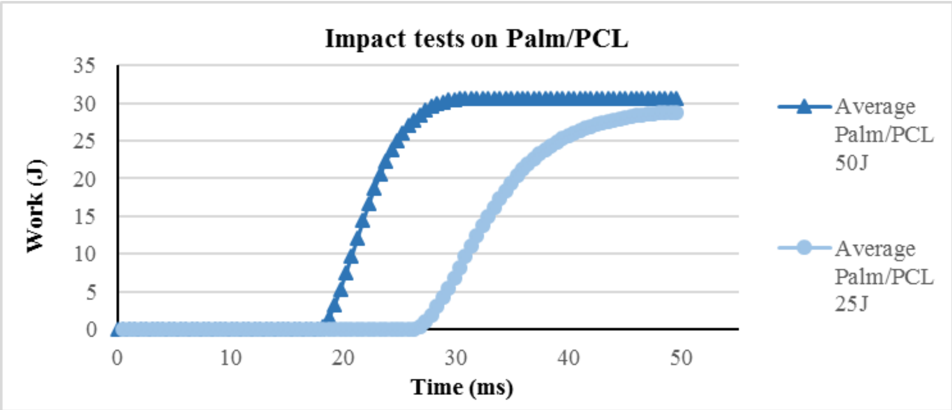
Fig. 5. Schematic of low velocity impact test set up.



(a)

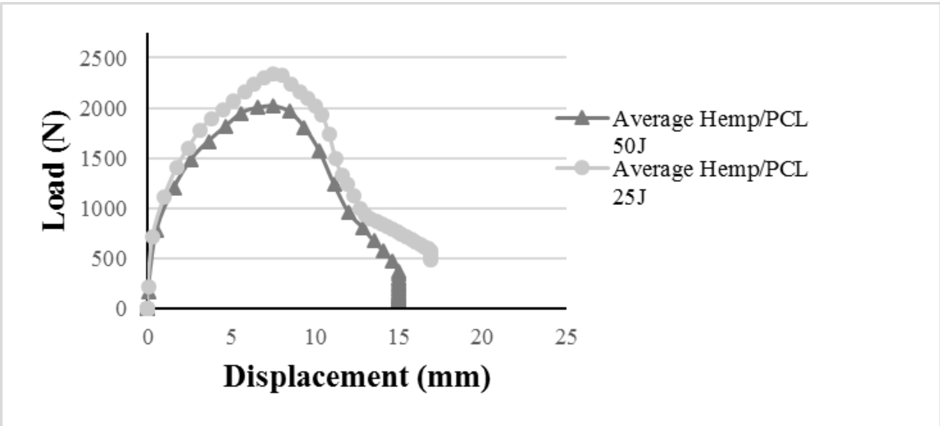


(b)

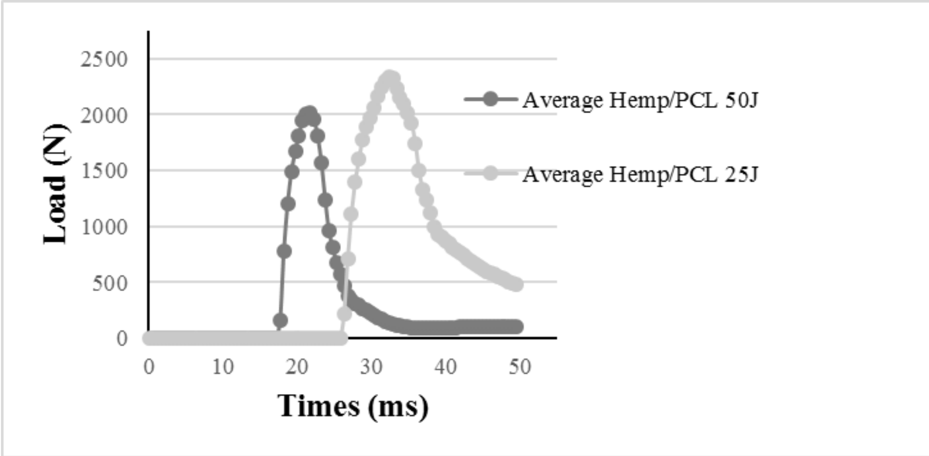


(c)

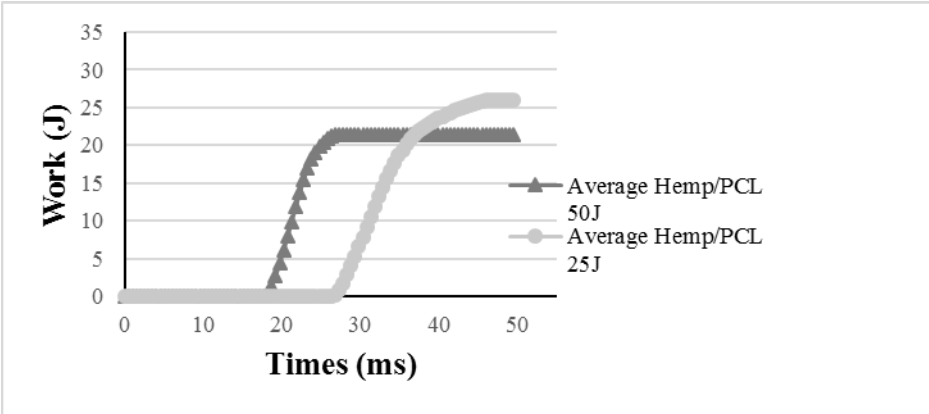
Fig. 6. (a) Force versus displacement, (b) Load versus time and (c) Work versus time traces of palm/PCL biocomposites.



(a)



(b)



(c)

Fig. 7. (a) Force versus displacement, (b) Load versus time and (c) Work versus time traces of hemp PCL for comparison purpose.

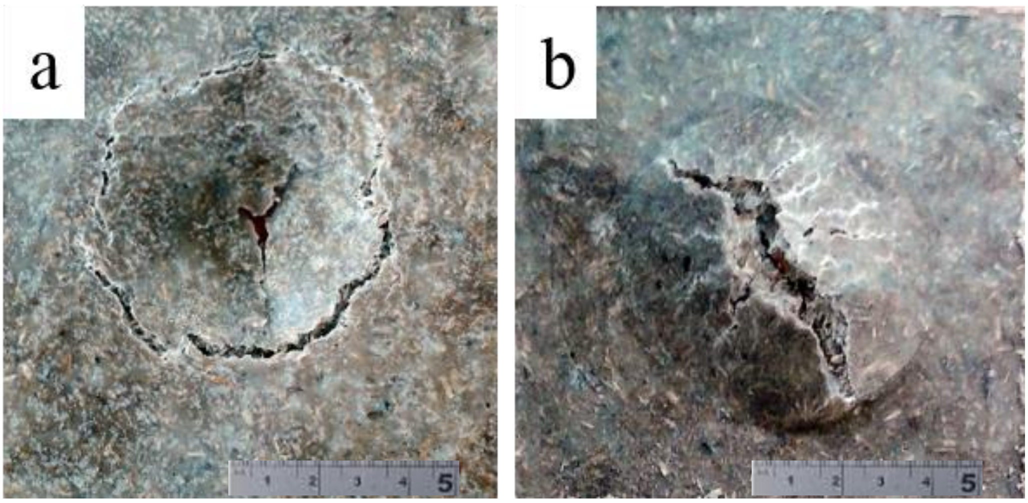


Fig. 8. Damage pattern of Palm/PCL specimens impacted at 25 Joules (a) front face damage and (b) rear face damage.

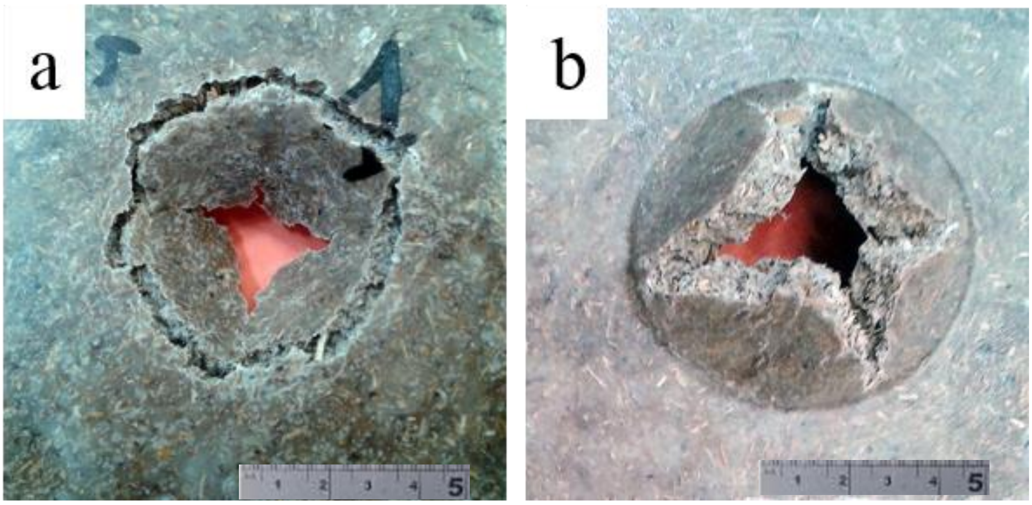


Fig. 9. Damage pattern of Palm/PCL specimens impacted at 50 Joules (a) front face damage and (b) rear face damage.

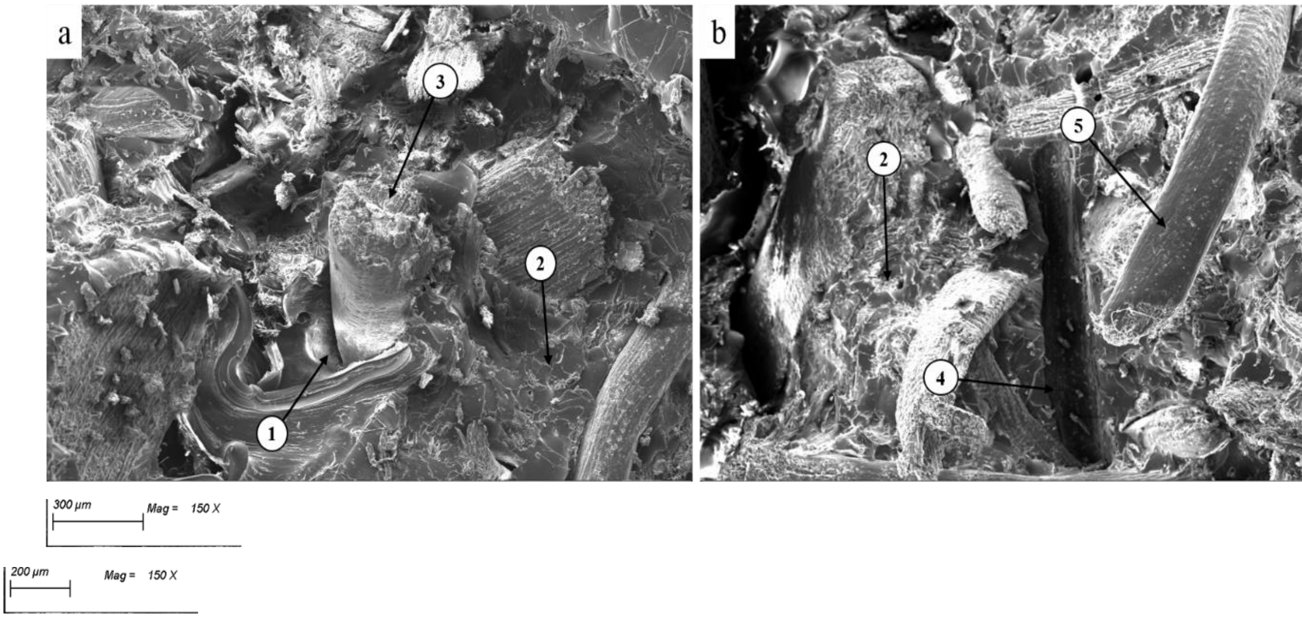


Fig. 10. SEM images of Palm/PCL after impact test at 25J, 1: delamination and debonding, 2: matrix bending, 3: fibres breakage, 4: fibre pull out, 5: pull out fibre side.

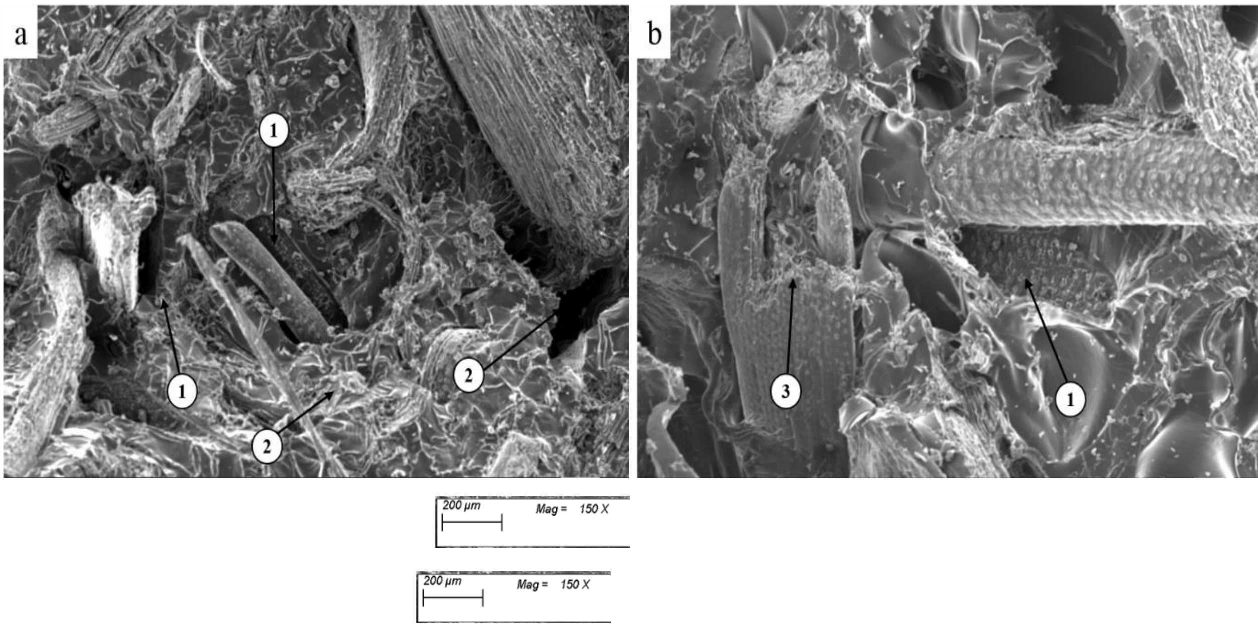


Fig. 11. SEM pictures of Palm/PCL after impact test at 50J, 1: delamination, 2: matrix breaking, 3: fibres breakage.

Table captions:

Table 1: Comparative physical and mechanical properties of date palm fibre (bundles) with commonly used bast fibres (Dhakal et al., 2007; Mohanty et al., 2000; Pickering et al., 2016).

Fibre types	Density (g/cm^3)	Tensile strength at break (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Date palm	0.92	170-275	5-12	5-10
Hemp	1.14	550-1110	58-70	1.6
Flax	1.50	345-1100	27.6	2.7-3.2
Jute	1.3-1.45	393-773	13-26.5	1.16-1.5

Table 2: Effects of palm fibre reinforcement on tensile properties of different palm/PCL biocomposites.

Specimen types	Tensile strength at break (MPa)	Tensile modulus (MPa)	Tensile strain (%)
PCL neat	19.00 (±1.70)	140.00 (±24.0)	418.00 (±60.0)
PCL Palm 20 wt.% 100 RPM	24.00 (±2.90)	284.00 (±15.20)	21.00 (±4.0)
PCL Palm 20 wt.% 400 RPM	25.00 (±0.70)	279.50 (±14.50)	24.00 (±3.0)

Highlights:

- The focus of the study was valorisation of waste agriculture biomass leaf sheath date palm fibre through the development of composite laminates.
- Fully biodegradable date palm/PCL based biocomposites developed and their damage mechanisms under LVI investigated.
- Important mechanical properties were investigated and compared against hemp PCL biocomposites.
- The developed biocomposites have high potential to be utilized for lightweight engineering applications.