Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-023-05183-9

ORIGINAL ARTICLE

Development and mechanical characterization of PLA composites reinforced with jute and nettle bio fibers

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Received: 27 September 2023 / Revised: 22 November 2023 / Accepted: 25 November 2023

Abstract

Awareness of sustainable utilization of materials boosted the consumption of natural resources to develop non-toxic and biodegradable composite materials for different synergistic applications. In the present study, composite materials were developed by the biopolymer (polylactic acid) as a matrix and bio-fibers (jute and nettle) as reinforcement. The goal of the present study is to utilize the natural resources in the field of material science and evaluate the physical properties (density and surface roughness) and mechanical properties (tensile, flexural, and impact strength) of all developed bio composites. Experimental results showed that the incorporation of fiber reinforcement with polylactic acid (PLA) enhanced the results of mechanical properties of all developed composites as compared to neat PLA composite. Hybridization of fiber reinforcement with polylactic acid (PLA) also achieved substantial changes in each property as compared to single-fiber reinforced composite material. Nettle/PLA composite achieved a higher density of 1.378 and minimum surface roughness of 0.918 as compared to another developed composite. Tensile strength and Young's modulus were the highest of hybrid jute/nettle/PLA composites at 2.426 MPa and 69.68 MPa. Hybrid jute/nettle/PLA had the highest flexural strength and flexural modulus of 157.33 MPa and 16219.4 GPa. Impact strength was achieved by jute/PLA composite at 17.6 kg/cm^2 as compared to all other developed composites. Thus, it was found that hybridization of jute and nettle fiber provided the better mechanical performance of composite materials.

Keywords Jute fiber · Nettle fiber · Polylactic acid · Bio composite · Hybridization

1 Introduction

Environmental pollution such as hazardous gases, chemical pollution, non-decomposable materials, polybags, and other objects are big issues of living things. These are directly hazardous to the environment and human life. Some motivated researchers investigated and followed the simplest path of the replaceable source, which is reducing these toxic pollutions. Biodegradable fibers and biodegradable polymer matrix are the prominent and replaceable sources of the plastic matrix [1–3]. Biodegradable fibers' impurities and drawbacks are reduced by some chemical treatments. Properties and decompositions of the fibers are not affected by chemical treatments. Although it enhances properties [3]. Biodegradable fibers are extracted by nature carriers which are extruded from plants, birds, and grasses such as jute, nettles, dhak, cotton, hemp, sisal, areca, abaca, bamboo, etc. These biodegradable fibers are utilized for the reinforcement of manufactured composites [4–6], due to their strengths such as better formability, nature of biodegradability, abundance, lower price rate, and availability in huge amounts. These biodegradable fibers have capacities to achieve plastic fibers' strengths. Environmental concerns have led to the interest in using green composites which are filled with biodegradable fibers [7]. These biodegradable fibers are also able to grant composites certain benefits such as low density,

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simple fabrication processes, little health hazards, and a high degree of flexibility [6–8]. Polymers play a significant role and provide the structure to the composite material. Various bio polymers are extracted from natural resources and have good compatibility with natural fibers to develop biodegradable composite materials. Bio polymers are exhaustively used in every industry to make the different components and have a good potential to serve as a matrix material for composites [7–11]. PLA used in present research consists of aliphatic polyester and lactic acid. It was acknowledged by many polymer scientists and industries since 1845. PLA can be synthesized by the polymerization of lactic acid (LA) or the ring-opening polymerization (ROP) of lactide. The nontoxic and biodegradable nature of PLA focused the attention of researchers for development of polymeric materials [12–15].

Composite materials contain two or more than two stages that are not fully soluble in each other and form a single material recognized as composite. Composites can be categorized in two forms either based on matrix or based on reinforcement. Composites are the material utilized in numerous areas having more conspicuous physical parameters and mechanical features. Developed composites are used for specific industries. Composite materials have a lot of numerous advantages compared to other traditional materials and provide better performance on tensile strength, flexural strength, impact strength, fatigue, and stiffness characteristics [9]. Biodegradable composites are prominent applications of structural and nonstructural portions in numerous areas such as aerospace parts, automotive components, building, and construction. In automobiles, headliners, door panels, dashboards, seats, and various interior parts of the vehicle have been developed by bio composites [10].

Various authors carried out their study on the physical and mechanical performance of developed composites. Authors investigated the impact of different forms of reinforcement, their size, and volume fraction, aging behavior of bio fibers with biodegradable polymer. In addition, various manufacturing paths, such as compression molding, hand-lay techniques, and vacuum bagging were also explored in various studies. Manral et al. [11] fabricate kenaf fiber/polylactic-acid (PLA) based composites with different orientations such as (bidirectional, unidirectional, and randomly oriented). The author concluded that unidirectional fiber reinforced PLA composites obtained maximum tensile strength as compared to bidirectional fibers and randomly oriented fibers reinforced PLA composites. Bidirectional fiber fabricated PLA composites obtained maximum flexural strength and randomly oriented reinforced PLA composites succeeded higher impact strength. Chaudhary et al. [16] developed jute/hemp/flax/epoxy-based polymer composites. The authors concluded that hybrids composite achieves higher mechanical properties. Jute/hemp/flax/epoxy-based hybrid composites observed higher tensile strength, modulus of elasticity and impact strength. Jute/hemp/epoxy-based composites achieved higher flexural strength.

No other research was found that shows the effect of the hybridization of jute and nettle fiber mat on the physical and mechanical properties of bio composites. The present study will give a roadmap to new studies regarding the influence of the hybridization of bio fibers on unexplored factors in the direction of density, surface roughness, and mechanical properties of composite materials. The significance of the present study incorporates the various structural applications where bio composites are being used. In this research work, jute and nettle fiber serve as reinforcement and polylactic acid (PLA) as a biodegradable matrix. The fractured interfaces between fiber and matrix were examined by scan electron microscopy (SEM) after mechanical testing.

2 Materials and methods

2.1 Fibers and matrix

Jute and nettle fibers were supplied by compacts buying services in Faridabad (India). Bi-directional woven mats were used in the fabrication of composites. The GSM of jute fiber mat was 250 GSM and nettle fiber mat was 150 GSM. Each fiber mat has 0.75 mm thickness, and each developed composite has 4.5 mm thickness. The tensile strength of jute fiber is 223 MPa and nettle fiber is 159 MPa. Fiber mats of nettle and jute are shown in Fig. 1. In this present study, poly lactic acid (PLA) was used as matrix material.

2.2 Processing

Compressive molding is a versatile technique for reinforced composites. A compressive molding technique was used to fabricate biodegradable composites. The closed mold of mild steel was used to manufacture laminated bio fiber polymer composites. The weight percentage ratio of biodegradable fibers used to manufacture each type of composite was 30% by weight ratio. During the hybridization of composites, the total weight fraction of different biodegradable fiber reinforcements was 30% by weight and the remaining 70% was a polylactic acid polymer. For example, in the case of jute/polylactic acid (PLA), the composition of material natural fiber 30% and biodegradable polymer 70%. The case of the hybridized composites ratio of natural fibers and the biodegradable polymer is 30% and 70%, respectively. PLA pellets were converted into PLA films of 1 mm thickness by compression molding machine at a temperature of 170 °C. Initially, 0.4 MPa of pressure was applied and increased up to 3 MPa. Then, films were permitted to cool. For each type of composite fiber reinforcement and polymer films were

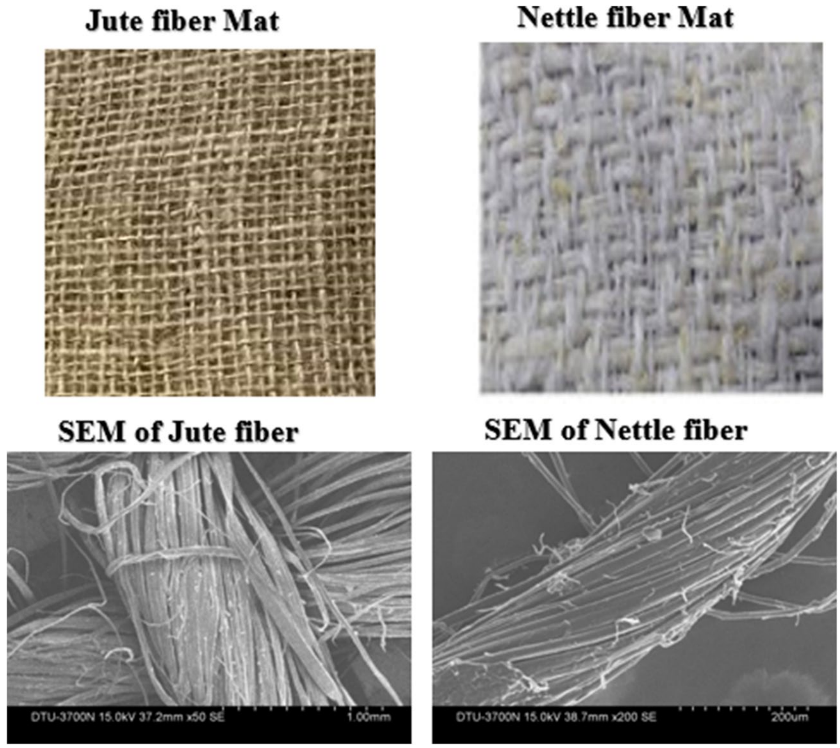


Fig. 1 Jute and nettle fiber mat with SEM images of both fibers

fixed alternatively in a metallic mold. Teflon sheet was cut according to mold and fix at upward and downward of the mold surface to avoid the sticking behavior of the PLA. Then, the whole assembly was heated at 180 °C at a high pressure of 3 MPa for 10 min. After some time, reduces the pressure and pulls out the composite laminate from the molds. Composite samples were stored in a desiccator until further use to avoid moisture absorption.

Jute/PLA, nettle/PLA, and hybrid composites laminates (jute/nettle/PLA) are shown in Fig. 2.

2.3 Density measurement

The Archimedes principle was used to measure the actual density of the developed specimens. Density measurement was performed to identify the flaws present inside the developed composite material. Flaws present inside the specimens indicate the voids developed during the fabrication of the specimen. Difference between experimental and theoretical density used to calculate the void content of a developed composite material. Void content was analyzed in accordance with ASTM D2734 standards. The dimensions of the sample were 25 mm × 25 mm (length × breadth).

2.4 Surface roughness

Surface roughness was measured by the Mitutoyo SJ-201 portable surface roughness testing device. Surface roughness analysis of the specimen helps in identifying the several uneven surface attributes exhibited on the specimen.

3 Mechanical characterization

3.1 Hardness

A Shore D harness tester was used to evaluate the hardness of the developed specimens. A hardness tester having flat and parallel top and bottom faces is placed on a horizontal platform located below the indenting tip. The platform can be raised by rotating a screwed wheel. This upward movement of the platform causes the test specimen to come in contact first with the pressure foot and later with the indenting tip under the specified contact load. The indenting tip was made of hardened steel of 1.1 to 1.4 mm diameter with a conical point of 30° and 0.1 mm radius tip. The net force applied by the indenter on the specimen was 44.64 N.

3.2 Tensile testing

ASTM D3039 was used to prepare specimens for tensile tests. Tensile test of all the developed composites was performed on Instron3369 with a crosshead speed of 10 mm/min. In a tensile test, the specimen was gripped in the upper and lower cross heads. The tester applies the tensile load of the specimen exerted on the stationary grip of the specimen was measured by a load cell of the machine and was

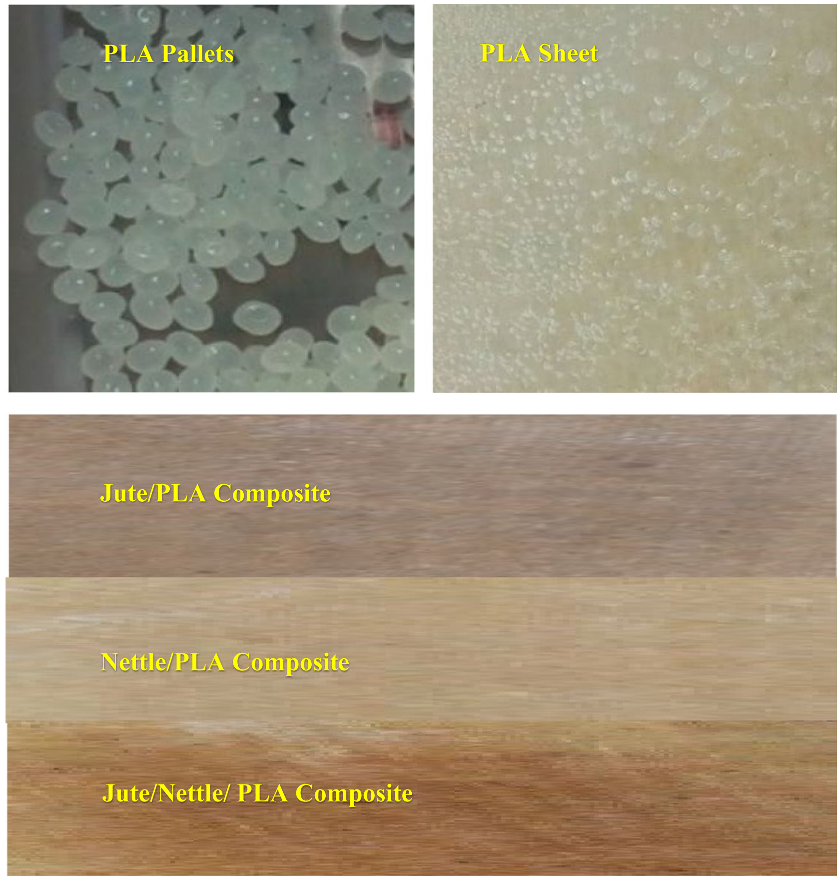


Fig. 2 Developed bio composites. Jute/PLA, nettle/PLA, and hybrid composites laminates (jute/nettle/PLA), respectively

displayed on a digital indicator. The indicator has a peak force retention memory, which can be recalled displaying the maximum load exerted on the test specimen before its failure.

3.3 Flexural testing

ASTM D790 was used to prepare specimens for flexural tests. Flexural tests of all the developed composites were performed on Instron3369 with a crosshead speed of 2.5 mm/min. Flexural testing is a versatile, common, and fundamental measurements of mechanical testing, which is prob the resistance to stiffness and flexing of a material.

3.4 Impact test

The Izod impact strength test is widely used in mechanical testing and plays a very important role in investigating the effects of material when applied a sudden force. It is prob the impact resistance and toughness behavior of materials. A material's toughness behavior is a very important factor in its capability to absorb energy at the time of plastic deformation. Izod impact experiments on impact tester were performed to calculate the impact energy of the developed composites. As per standard test procedure for testing, specimens are prepared as per ASTM D256.

3.5 Scanning electrode microscopy (SEM)

SEM was used to examine the microstructure of the specimen after mechanical test. EVO 18 special edition 20 KN (medium vacuum) scanning electron microscope (SEM) apparatus was used with a high magnification of × 30,000.

4 Result and discussions

4.1 Density

The equation used for the calculation of theoretical density is shown in Eq. 1.

$$\frac{1}{\rho_{ct}} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} + \frac{W_n}{\rho_n} \quad (1)$$

ρ_{ct} density of nanocomposite

ρ_f density of fiber.

ρ_m density of matrix material.

ρ_n density of nanofiller material.

W_f weight fraction of fiber in nanocomposite.

W_m weight fraction of matrix in nanocomposite.

W_n weight fraction of nanofiller in nanocomposite.

The equation used to find the void content is shown in Eq. 2.

$$Void\ content = \frac{Theoretical\ Density - Experimental\ Density}{Theoretical\ Density} \times 100\% \quad (2)$$

Equations 1 and 2 were used to calculate the theoretical density and the void content for developed bio composites. Table 1 represents the values of experimental and theoretical density with void content for all developed bio composites. In all developed composite materials, experimental density varies from 1.269 to 1.378 gm/cm^3 and theoretical density varies from 1.312 to 1.461 gm/cm^3. Void content for all developed composites was less than 6%. A low percentage of void content defends the suitability of the processing method and optimizes the percentage of matrix and reinforcement. Void content appears due to interstitial sides between the fiber and matrix phase and due to the air entrapment inside the developed structure. Jute/nettle/PLA hybrid bio composite achieved a lower value of void content 2.37% as compared to jute/PLA 4.41% and nettle/PLA 6.68%. A higher value of hybrid jute/nettle/PLA composite is due to the different surface properties of jute and nettle fiber. The higher roughness of jute fiber and high smoothness of nettle provide good compatibility with low void content which provides good interfacial adhesion between fiber and matrix. Good interfacial adhesion improves the overall stability of the developed composite material.

Table 1 Experimental and theoretical density with void content of developed bio composites

Composite	Experimental density (g/cm^3)	Theoretical density (g/cm^3)	Void content (%)
Jute/PLA	1.3	1.36	4.41
Nettle/PLA	1.378	1.461	5.68
Jute/nettle/PLA	1.269	1.312	3.27

4.2 Surface roughness

Surface roughness represents the unevenness of the external surface of developed composite material. Analysis of surface roughness is useful in evaluating the smoothness of the surface of the specimen which leads to determination of the wear rate of the specimen during the application of developed composite. Rough surfaces of specimen lead to increased wear rate when compared to specimen with smoother surface. Surface roughness of developed bio composites is shown in Fig. 3. Jute/PLA bio composite obtained maximum surface roughness of 1.052. Nettle/jute/PLA hybrid composite has almost similar surface roughness of jute/PLA composites which is 1.044. Nettle/PLA composites obtained the smallest value of roughness which is 0.918. Surface roughness depends upon the thread of natural fibers and woven mats [1, 7]. Smooth surface property of netter offers the lower value of surface roughness to the Nettle/PLA composite.

4.3 Hardness

The hardness property of the composites obtained was calculated and it is an essential property to know where these composites find their application where there is a chance that they undergo plastic deformation by indentations and scratching. The values are shown in Table 2. This type of deformation is faced by the composite material in automobile dashboards, luggage cabins, and various structural and

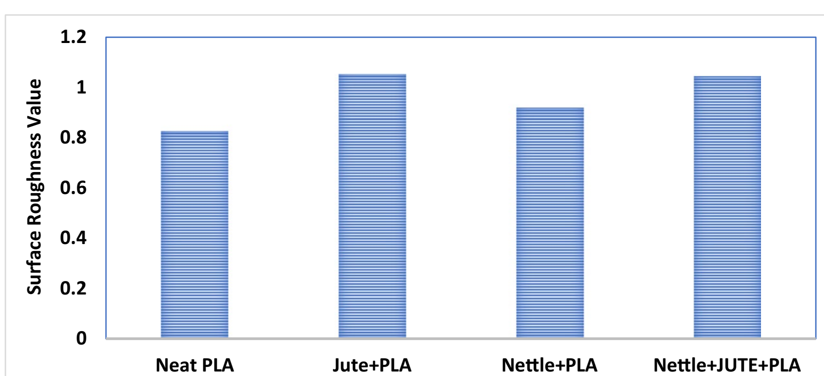


Fig. 3 Surface roughness of developed bio composites

Table 2 Hardness values of the composite samples

Polymer composite	Shore D hardness
Neat PLA	84
Jute/nettle/PLA	97
Jute/PLA	90
Nettle/PLA	94

non-structural components. From the results, the incorporation of natural fibers with PLA matrix enhanced the value of hardness. Neat PLA shows a hardness of 84 Shore D. Hybridization of jute and nettle fiber with PLA achieved the maximum hardness of 97 Shore D. Jute/PLA and nettle/PLA composites achieved the hardness of 90 and 94 Shore D. Different properties of jute and nettle fiber provides the stiffness to the developed composite against scratching and indentation. Similar results were found by Chaudhary et al. [16] for hybridization of jute, hemp, and flax fiber. The authors concluded that hardness depends on percentage of fiber loading, interfacial adhesion between fiber and matrix. Interfacial adhesion will be enhanced due to different surface properties of fibers like rough surface of jute fiber shows good wettability with polymer and smooth surface of nettle fiber have low void contents. Combination of jute and nettle fibers achieved better interfacial adhesion between fiber and matrix which increased the overall strength of the developed hybrid composite [16–18].

4.4 Tensile test

The experimental results of tensile testing were obtained from a universal testing machine. Such as tensile strength, tensile modulus, and elongation at break for natural fibers (jute and nettle) reinforced polylactic acid matrix composites and their hybrid composites. Experimental results of tensile tests of developed bio composites are represented in Fig. 4. The tensile strength of developed composites depends upon interfacial adhesion between matrix and reinforcement woven mat of different types of natural fibers. In the case of developed bio composites, the tensile strength of fiber reinforced composites obtained a high tensile strength value as compared to tensile strengths of pure PLA matrix. Jute/nettle/PLA composite obtained the highest tensile strength of 2.4261 MPa as compared to the remaining composites. Nettle/PLA and jute/PLA composites represented a tensile strength of 2.2928 MPa and 1.5045 MPa, respectively. Jute/PLA composites achieved a minimum tensile strength of 1.5045 MPa. From the results, reinforcement of bio fibers with PLA resin enhances the values of tensile strength and also hybridization of different bio fibers with PLA matrix achieving the highest value of tensile strength as compared to other developed composites. The higher tensile strength of Nettle/jute/PLA hybrid composite is due to the different surface property of jute and nettle fiber. The higher value of roughness of jute fiber with high smoothness of nettle fiber optimizes the wettability of both the fibers with PLA matrix with good interfacial adhesion. Strong interfacial adhesion with lower void content gives the overall strength of developed composite. Similar results were obtained by Chaudhary et al. [16] for jute/hemp/flax/epoxy hybrid composites. The authors concluded that the hybridization of different fiber mats enhanced the tensile strength of the developed hybrid composite. Similar results of hybridization of fiber mat were performed by Duan et al. [17]. Hybridization of sisal/coir reinforced PLA composite shows maximum tensile strength of the developed composite.

Young's modulus of all bio-fiber reinforced PLA composites was greater as compared to pure PLA resin as shown in Fig. 5. Experimental results of Young's modulus represented that the Jute/nettle/PLA hybrid composite achieved the maximum Young's modulus of 69.9868 MPa. Nettle/PLA and jute/PLA composites achieved tensile modulus of 55.9038 MPa and 42.8154 MPa, respectively. Whereas jute/PLA composite and pure PLA showed minimum Young's modulus of 42.8154 MPa and 36.3931 MPa. A higher

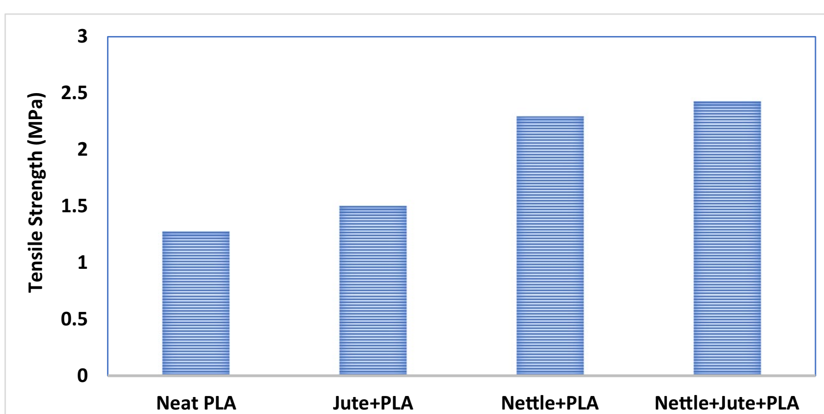


Fig. 4 Tensile strength of developed bio composites

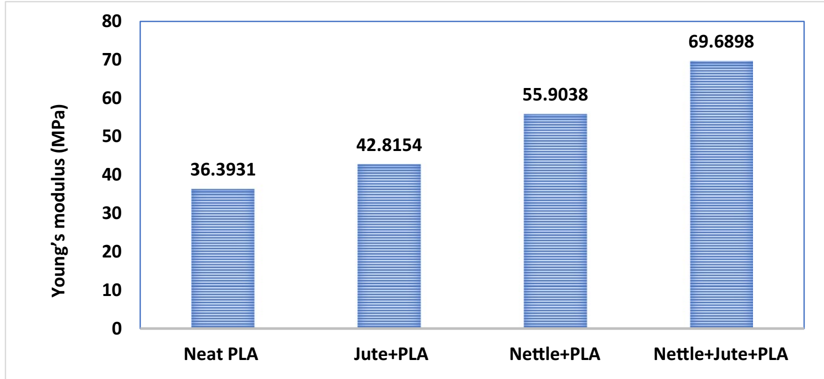


Fig. 5 Young's modulus of composites of developed bio composites

modulus value of hybrid composites represents higher stiffness of material comparatively to other developed composites. Young's modulus of the developed composites and their hybrid depends on the type and proportion of reinforced fibers and its interaction with the PLA matrix [16, 17]. The surface condition of jute and nettle fiber is different hence the level of adhesion will be different which in turn affects the properties. The rigidity of the developed composites and hybrid composites was increased by the combination of jute and nettle fiber mats to PLA resin. Young's modulus of composite laminates is mainly influenced by fiber properties like wettability, fibril angles of fiber, orientation of fiber mat with its geometry, etc. Similar results were found by various authors in their research. Authors concluded that properties of bio fiber such as mat structure, the ratio of fiber length to diameter, and its orientation in the laminate effects Young's modulus of developed bio polymer composites [18, 19].

During tensile testing, the elongation of any material before the break is an important property that shows evidence of elastic and plastic behavior of a material. Figure 6 shows the percentage elongation of the developed composites and hybrid composites along with pure PLA. Nettle/PLA composite obtained a maximum percentage elongation of 4.101% at break. While jute/PLA and jute/nettle/PLA composites achieved 3.514% and 3.4813% elongation at break, respectively. The incorporation of jute and nettle fibers enhanced the value of percentage elongation as compared to pure PLA resin. This means that the ductility of the developed composites and hybrid composites was enriched by adding the reinforced fibers which helps for achieving a value of percentage elongation as compared to brittle behavior of PLA resin. This improvement leads to the usage of developed bio fibers in different application areas in various fields such as automobile, naval sectors, and aerospace. Similar results were found by Pappu et al. [20] for PLA reinforced sisal and hemp hybrid composites. The authors concluded that the incorporation of bio fiber gives ductility to the developed composites which enhanced the percentage elongation of the developed composite specimen.

The fractured samples obtained after tensile testing were used for SEM analysis. The images generated from SEM are shown in Fig. 7. From the figure, it is visible that the main reason for the failure of the composite is due to fiber debonding, fiber breakage, and matrix breakage. Similar findings have also been found in earlier studies [21, 22]. It is also visible in the SEM images that the matrix breakage and voids due to fiber debonding. Fibers are broken in very short strands which shows good wettability in case of the hybrid

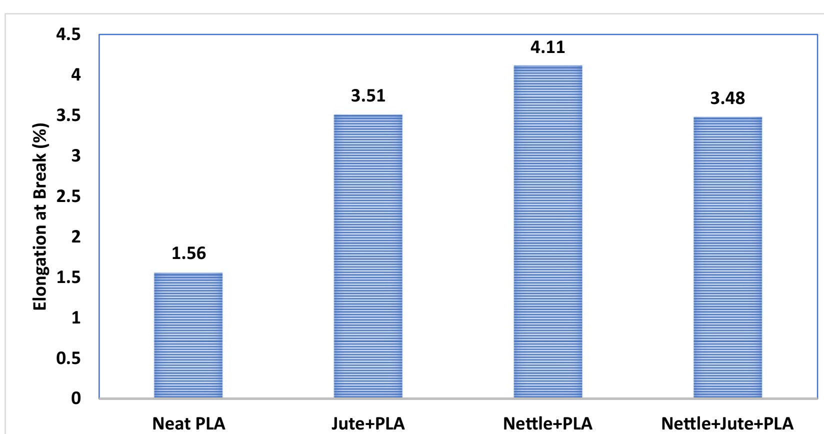


Fig. 6 Elongation at break (%) of developed bio composites

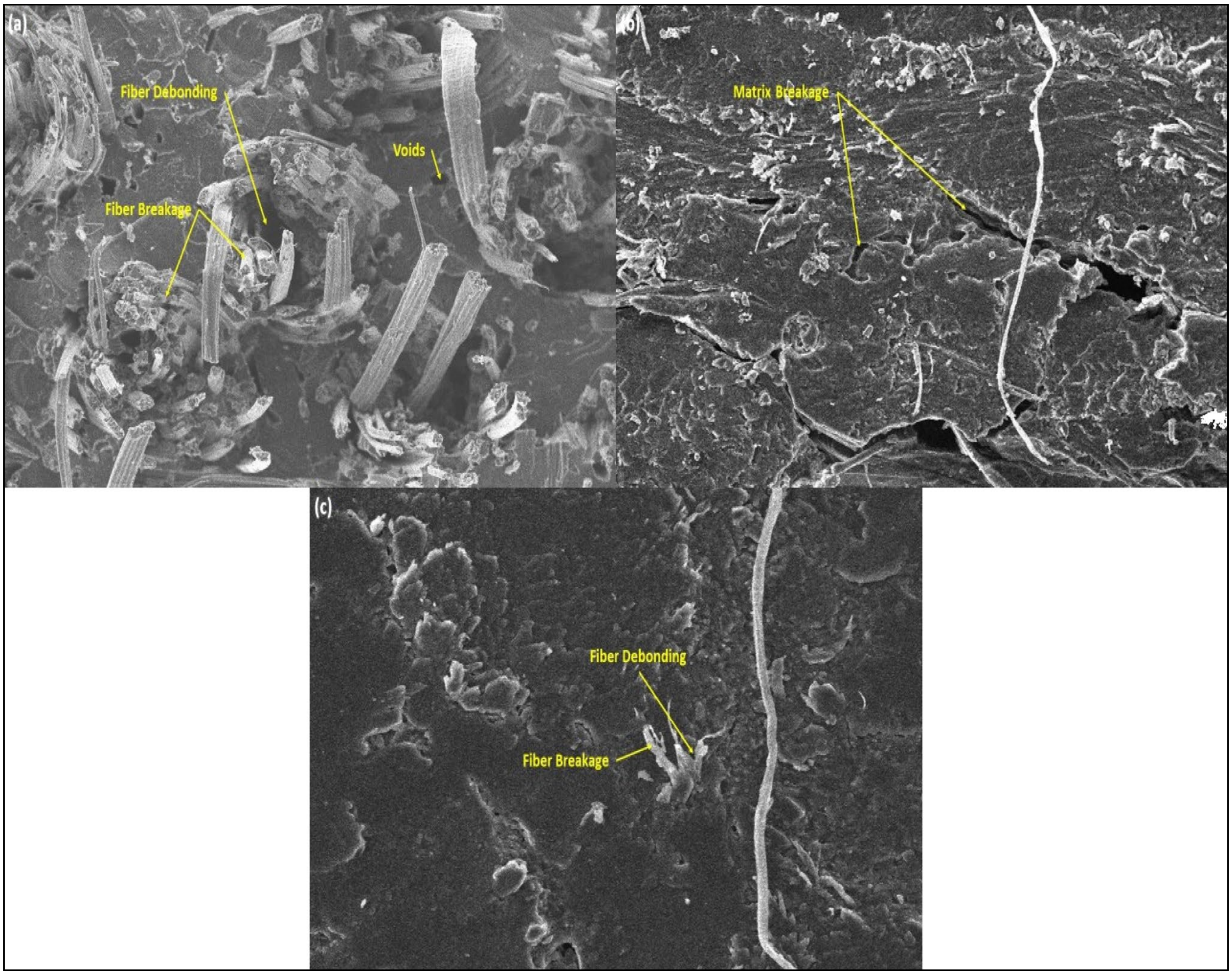


Fig. 7 SEM micrographs of fractured specimens after tensile testing. **a** Jute/PLA, **b** nettle/PLA, and **c** jute/nettle/PLA

reinforcement [23, 24]. Ejaz et al. [25] studied the properties of jute/flax reinforced PLA composite. It was found that the addition of fiber reinforcement led to improvement in the tensile properties of the composite. The authors conducted a SEM analysis of the fractured specimens and found that the major cause of failure was fiber breakage and fiber pullout.

4.5 Flexural test

The flexural test was performed using a three-point bending test to check the bending strength of developed composite materials. The flexural properties of fabricated composites were enhanced eventually. The experimental outcomes of flexural strength and flexural modulus are shown in Figs. 8 and 9. Flexural strength and flexural modulus of the fabricated composite laminates have achieved impartial improvement depending upon the type of natural fiber mat reinforced to PLA resin. Pure PLA resin was noted for a flexural strength of 67.7384 MPa and a flexural modulus of 3319.4304 MPa. While the jute/nettle/PLA hybrid composite obtained the maximum flexural strength of 157.3334 MPa with a flexural modulus of 16,219.4087 MPa. Nettle/PLA and jute/PLA composites showed flexural strength of 138.4615 MPa and 79.6923 MPa, respectively. The smallest value of flexural modulus showed nettle/PLA of 3688.2506 MPa lesser than jute/PLA of 8557.8504 MPa. The surface properties of bio fibers affected the flexural properties of fabricated composites. Maximum flexural properties are obtained due to the higher roughness and interaction of fiber with matrix materials in hybrid composites. Hybridization of jute fiber having a rough surface and nettle fiber having a smooth surface, achieved good elastic behavior with optimized ductility with strength. The optimized property of elasticity helps to optimize the flexural strength and modulus during the three-point bending [26–30]. Similar results were also explained by various previous authors.

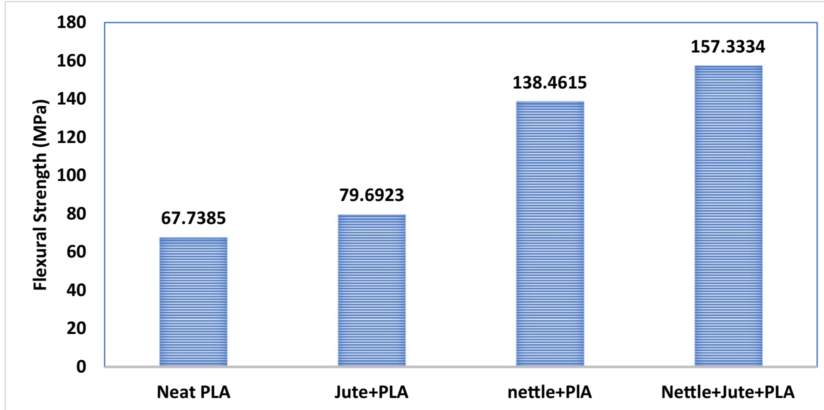


Fig. 8 Flexural strength results of developed bio composites

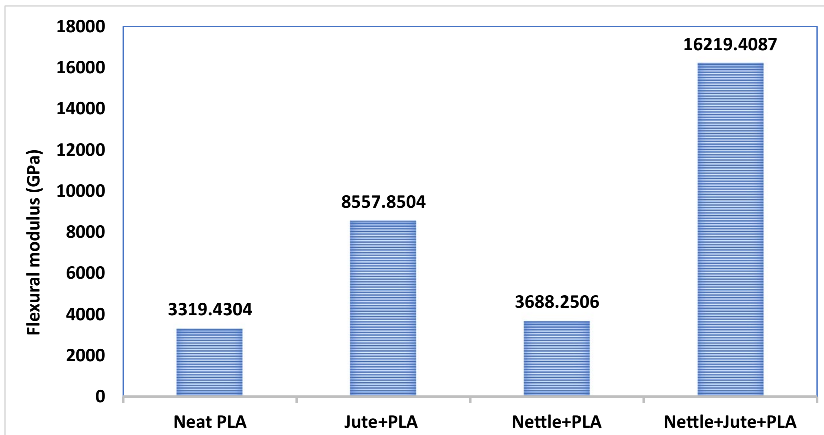


Fig. 9 Flexural modulus of developed bio composites

Wang and He [31] investigated how nanosilicon dioxide, titanium dioxide, and aluminum oxide impact the flexural characteristics of a composite made from corn straw and polyvinyl chloride. The study revealed that incorporating nanofillers into the composite enhanced its flexural properties by improving the interfacial bonding, evident in the absence of significant fiber breakage and micro-cracks observed in the SEM examination of the fractured composite. In a separate study, Hallad et al. [32] explored the influence of graphene oxide nanofillers on the flexural properties of a hemp/epoxy composite. The findings indicated that adding nanofillers improved the flexural properties, but increasing the amount of nanofillers led to agglomeration, adversely affecting the composite's flexural characteristics.

The fractured samples obtained after flexural testing were used for SEM analysis. The images generated from SEM are shown in Fig. 10. From the figure, it is visible that the main reason for the failure of the composite is due to fiber debonding, fiber breakage, and matrix breakage. Similar findings have also been found in earlier studies [21, 22, 28]. In flexural testing, fiber pull out is more visible in the case of the jute reinforced composite which is visible in the SEM images but in nettle composite, the fibers are broken very short which proves that the bonding between the fiber and the matrix is stronger in nettle reinforced composite [29, 30]. But when hybrid reinforcement is used the strength of the reinforcement further increases which increases the flexural strength of the composite like the increase in the tensile strength of the composite. Singh et al. [33] studied the influence of volume fraction and curing temperature on the mechanical properties of jute/PLA composite. The authors found that maximum strength was found at 30% fiber reinforcement fraction and 160 °C curing temperature. Sem analysis showed that the major causes of failure were fiber pullout and matrix breakage.

4.6 Impact strength

The results of the impact strength of the fabricated composites were noted by the Izod impact test in which unnotched specimens were tested, and the results are shown in Fig. 11. Results indicate that the combination of fiber in PLA enhanced the impact strength of fabricated composites. Incorporation of jute and nettle fiber reinforcement with PLA matrix achieved higher values of impact strength as compared to neat PLA. Neat PLA shows an impact strength

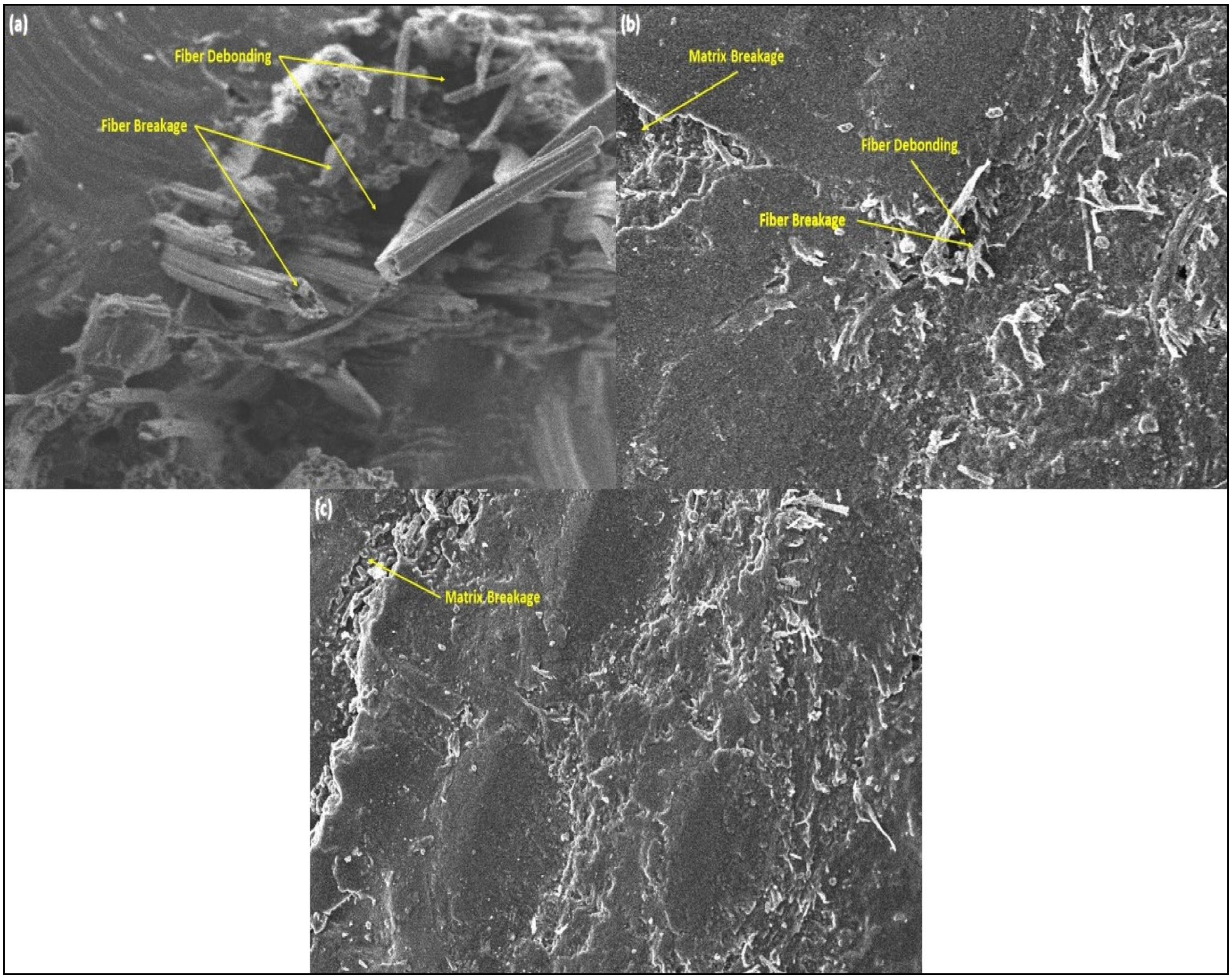
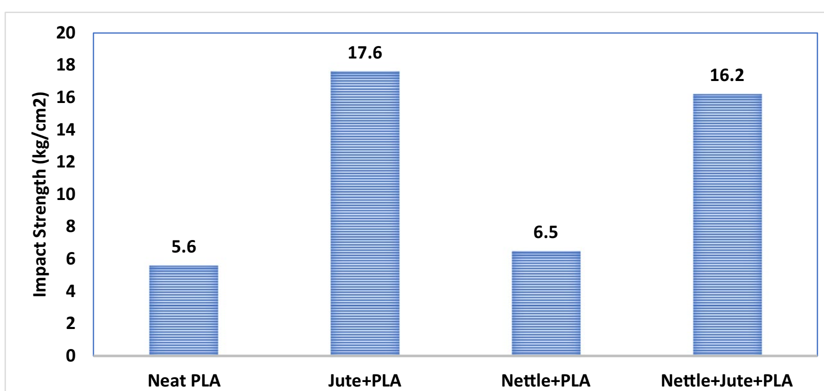


Fig. 10 SEM micrographs of fractured specimens flexural testing. **a** Jute/PLA, **b** nettle/PLA, and **c** jute/nettle/PLA

Fig. 11 Impact strength of developed bio composites



of 5.525 kg/cm^2. Jute/PLA composite obtained the maximum impact strength of 17.6 kg/cm^2. While nettle/PLA and nettle/jute/PLA composites have obtained lesser impact strengths compared to jute/PLA composites with impact strength of 6.5 kg/cm^2 and 16.2 kg/cm^2, respectively. The discrepancy in impact strength of several composites fabricated in this study is recognized due to the different levels of bonding between the numerous natural fiber mats and PLA

matrix. The dependency of impact strength of composites largely depends upon the crack propagation in the material during the fracture as well as interfacial adhesion bonding between matrix and reinforcement. The weaker interfacial shear strength of natural fibers and matrix reduced the impact strength of the developed composites. A similar study was conducted by Felix et al. [34] for jute, hemp reinforced PLA composite, and its hybrids. Authors concluded that jute and hemp fibers provide better interfacial strength with good strength to the developed composites which enhanced the impact behavior of developed composites.

The fractured samples obtained after impact testing were used for SEM analysis. The images generated from SEM are shown in Fig. 12. From the figure, it is visible that the main reason for the failure of the composite is due to fiber debonding, fiber breakage, and matrix breakage. Similar findings have also been found in earlier studies [11, 16, 18]. Unlike the tensile and flexural testing nettle reinforced composite had lower impact strength than jute composite due to interaction between the fiber and matrix which provides good strength in other conditions but at the sudden application of force is weak. In the case of hybrid composite, the strength has decreased in comparison to the strength of jute reinforced composite. Kanakannavar et al. [35] studied the tribological behavior of 3D braided yarn woven nettle reinforced PLA composite. The authors found that the specific wear rate was reduced by about 95% at 35 wt.% of nettle reinforcement. SEM analysis showed fiber fracture, fiber peeling, debonding, and micro-cracks as the major failure mechanisms.

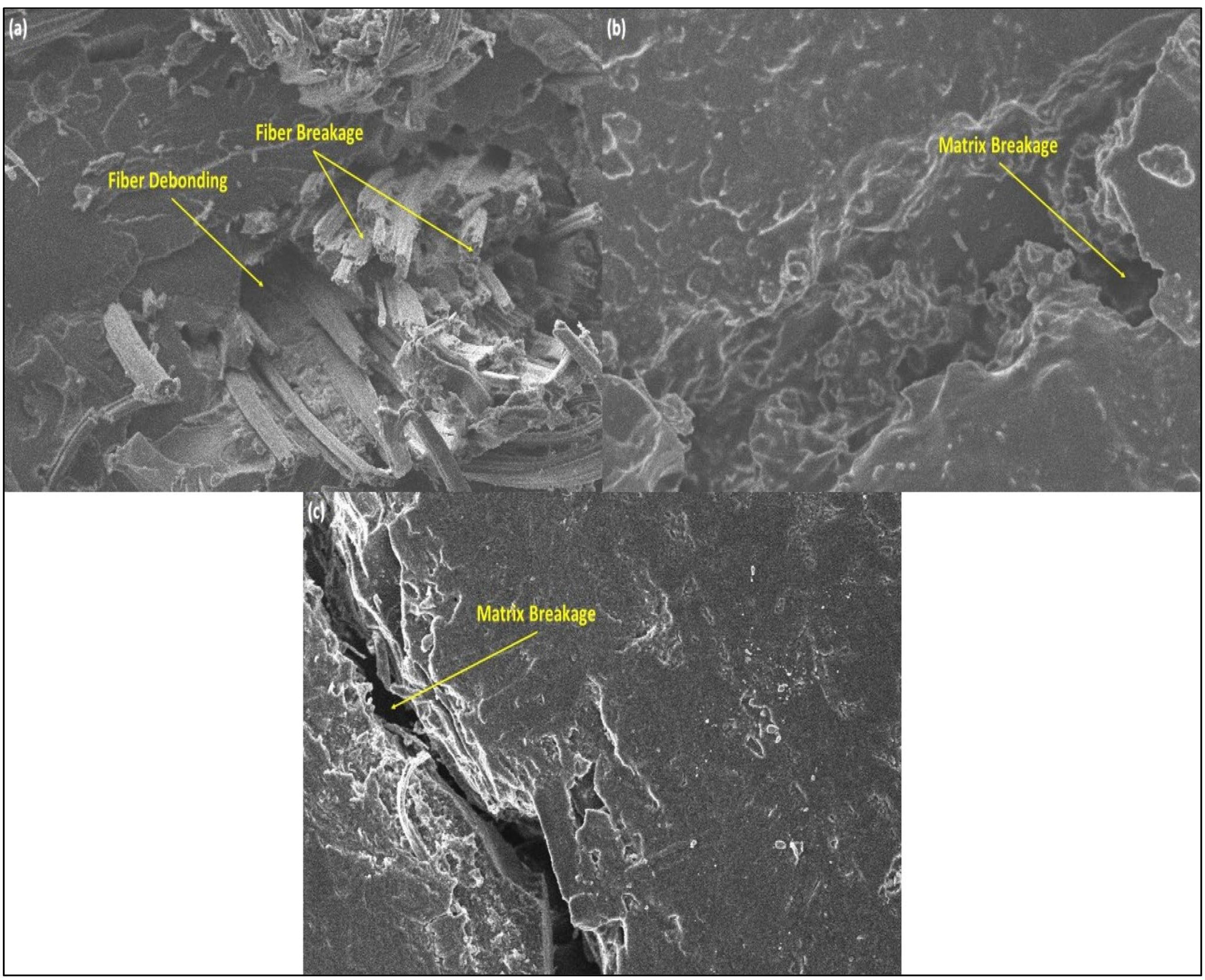


Fig. 12 SEM micrographs of fractured specimens after impact testing. **a** Jute/PLA, **b** nettle/PLA, and **c** jute/nettle/PLA

5 Conclusion

In the present study, polymer composites were fabricated using PLA as matrix and jute and mettle fiber as reinforcement. The composites formed were used for various mechanical characterization and their properties were studied. From the research conducted above on the various composite, the following conclusion can be drawn:

- The theoretical density of the composite which was calculated and the experimental density of the composite which was measured are close to each other with nettle/PLA composite showing a maximum void content of 5.68% which shows that the fabrication technique is feasible and conducted without much error.
- The surface roughness test showed that the jute/PLA composite has the highest surface roughness among the composite samples at 1.052 which is due to the rough surface of the jute fiber which leads to the rougher surface of the jute composite.
- The hardness test of the composite showed that the composite with hybrid reinforcement of nettle/jute showed the best hardness of 97 as compared to other composite samples. This is due to the fact that the combination of these fibers leads to better synergy between the fiber reinforcement and the matrix which leads to better strength.
- The tensile testing of the composites shows that the hybrid composite has the highest tensile strength and Young's modulus at 2.4261 MPa and 69.9868 MPa, respectively. All the composites had better tensile properties than pure PLA.
- Flexural testing of the composites showed that the hybrid composite had the highest flexural strength and flexural modulus of 157.3334 MPa and 16,219.4087 MPa, respectively. All the composite samples were found to have higher flexural properties than pure PLA.
- The impact testing of the composites shows that jute/PLA has the highest impact of 17.6 kg/cm^2. All the composites had better impact strength than pure PLA.
- The SEM analysis on the fractured surface of the specimen after tensile, flexural, and impact testing shows the presence of fiber breakage and fiber debonding which are the major causes of failure. In the case of flax reinforced nanocomposite fiber debonding was more prominent due to the surface characteristic of flax fiber which was very smooth as opposed to jute fiber which was rough around the surface.

From the result obtained through testing, it is clearly visible that the addition of fiber reinforcement has improved the properties of the composite and the improvement in the properties is more visible for hybrid reinforcement. In future research, more studies can be conducted on preparing nanocomposite by adding nanofillers into the composite to further study the variation in its properties depending on the type or quantity of nanofiller added.

Author contribution SR and SM: writing—original manuscript; VC, SPD, and PG: ideas, conceptualization, supervision; and PPD: writing—reviewing and editing.

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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