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RESEARCH ARTICLE

Flexural Strength and Load–Deflection Behaviour of Hybrid Thermoset Composites of Wood and Canola Biopolymers

Ikra Iftekhar Shuvo[1] · **Md. Saiful Hoque**[1] · **Md. Shadhin**[2] · **Lovely K. M. Khandakar**[2]

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Abstract

The study aims to incorporate cellulosic canola (*Brassica napus* L.) biopolymers with wood biomass to increase flexural strength more than wood fraction alone. A facile fabrication process—at ambient temperature—is employed for ease of producing two different sets of bio-composites utilizing unsaturated polyester resin: pristine composite structures of 100% wood and hybrid composite structures of a canola-wood blend. The curing process is accompanied by methyl ethyl ketone peroxide (MEKP). Besides the lightweight feature, the hybrid composite structures exhibit maximum flexural strength up to 59.6 and 89.58 MPa at 2.5 and 5% fibre polymer fraction, outperforming the pristine wood composites (49.25 MPa). Also, the bending behaviours of the composite structures are illustrated by the load–deflection curves and the associated SEM micrographs display their fractured and debonded surface at the cross-section. The novel canola fibre benefits from its inherent hollow architecture, facilitating an excellent strength to weight ratio for the thermoset composites. Interestingly, canola displays a fibre diameter and density of 79.80 (±41.31) μm and 1.34 (±0.0014) g/cc, contributing effectively towards the flexure performance and high packing density. The breaking tenacity (13.31 ± 4.59 g-force/tex) and tensile strength (174.93 ± 60.29) of canola fibres are comparable to other bast fibres. The synergy among fibre diameters, density and breaking tenacity creates a good interphase to successfully transfer the external compressive load from the resin matrix to the fibres. Further, the two-parameter Weibull distribution model is applied for predicting the failure and reliability probability of composite specimens against a wide range of compressive loads. Finally, prioritized SWOT factors have been summarized associated with the prospects and key challenges of canola biopolymers—an attempt to strategize the planning and decision-making process for a potential business environment. The introduction of canola into the plastic industries would ultimately promote the application of sustainable biopolymers in diverse grounds including the interior panels for aerospace, automotive, and furniture industries.

Keywords Flexural strength · Load–deflection · Fibre · Composite · Weibull distribution

Introduction

Engineered fibre reinforced composites (FRCs) have found diverse applications in modern days. Due to superior strength to weight ratio, fatigue resistance, and elevated chemical stability, the FRCs are used in railway, wind energy, and automotive industries [1–3]. Also, there are numerous application areas, where the FRCs are irreplaceable due to their excellent low-density features; examples include aerospace, sports or shipping industries [4–7].

Natural FRCs are fast getting momentum for the growing environmental awareness. Different natural FRCs exhibit good impact resistance and are suitable for non-conductive applications in electrical industries. Different natural fibres, for example, coir, oil palm, sisal, bamboo, banana, rice husk, jute or kenaf have shown satisfactory interfacial adhesion with synthetic polymer matrices for producing FRCs [8–14]. As a result, natural FRCs have shown good prospect for light and heavy industries as alternatives to steel, glass fibre, timber, concrete and so on [15]. Canola is a new generation hollow textile fibre, which is extracted from waste streams of canola plants [16–20]. The current work demonstrated the prospect of natural canola fibre polymers as FRCs.

✉ Ikra Iftekhar Shuvo
ikraecomm@gmail.com

[1] University of Alberta, Edmonton, Canada

[2] University of Manitoba, Winnipeg, Canada

Hybridization could improve the mechanical properties of composite structures, including toughness or flexure performance [21–23]. Studies have reported the improvement of overall mechanical performance from hybridisation of natural FRCs using coir, kenaf, bamboo, rice straws, glass fibres, etc. [24–27]. Interesting efforts have been made to partially or completely replace wood contents in wood-based products like plyboards or particle boards using flax shiv, wheat straw, oil palm trunks, and so on [28–30]. Even, in many cases, hybrid composites reinforced with natural fibre and wood biomass were marked to meet the minimum criteria of particleboards or exhibiting superior mechanical performances using varying proportions of the wood-jute, wood-peanut hull, wood-sunflower stalk, and wood-kiwi pruning [31–34]. Nevertheless, the design concepts of hybrid composite structures have remained demanding due to the effect of hybridization on flexural failure mechanism. The current study took a similar approach to hybridizing canola FRCs and characterizing their flexure performances.

To the best of our knowledge, there have been only one study on textile canola FRCs and its behavior in a hybrid composite configuration [35]. However, despite being a low-density fibre, no research work has been conducted to investigate the strain-to-failure quotient characteristics of canola FRCs. Hence, the current study aims to explore both the flexural strength and load–deflection behaviours of hybrid canola-wood composite laminates. The effect of hybrid ratio on the flexural performance of hybrid canola-wood composites is investigated as well. Next, a comparative study has been conducted to analyze the performance between hybrid and pristine wood (100% wood particles) composites. During the experimental work, different mechanical and physical properties of canola fibre reinforcements are analyzed: fibre diameter, density, breaking tenacity, and tensile strength. Finally, a two-parameter Weibull mathematical model is applied for a predictive analytical study to calculate the probability of failure or reliability percentage of the composite structures. Prioritized SWOT factors have been systematically generated from the current research perspective to benefit the textile composite and natural fibre industries for decision-making and building strategies.

Materials

Canola plants were employed for solvent-retting in a H_2O-bath. After the solvent-retting, fibres were extracted manually from the plant stems. Industrial-grade soft wood particles were blended with the canola biomass for composite fabrication with the mixture of polymer matrices and curing agent. Unsaturated polyester (UPE) and methyl ethyl ketone peroxide (MEKP) was used as the polymer matrix system and curing agent, respectively to impregnate the woody and nonwoody biomass fractions. The UPE has a density of 1.12 g/cc, modulus of elasticity of 1.91 GPa, and flexural strength of 61.26 MPa [36]. Pressley Fiber Bundle Strength Tester (Model F215, SDL Atlas Instruments, USA), FibreShape (Innovative Sintering Technologies Ltd, Switzerland), gas pycnometer (Quantachrome Ultrapyc 1200e, Quantachrome Instruments, USA), and a Tension Frame (Model 2017, UM, Canada) were used for analyzing mechanical strength, diameter, density, and flexural performance.

Methods

Preparatory Processes

Solvent-Retting for Fibre Production

Canola plant stems were immersed in a H_2O solvent bath. Solvent-retting was conducted in the retting bath. As retting time was gradually progressing towards the maturity, fibre ends started protruding out of the stem specimens. Manual fibre extraction was executed for collecting the solvent-retted fibres for subsequent processing.

Nonwoven Mat and Composite Preparation

Nonwoven mat was prepared by using the solvent-retted canola bast fibres. The fibres were randomly laid-up, compressed, and shaped to mat form-factor. By depositing woody fraction with the nonwoody canola biomass fraction and impregnating with UPE resin solution, composite specimens were developed (Fig. 1). With the aid of MEKP curing agent, room temperature curing process was applied to cure the impregnated specimens to produce the composite specimens for further characterization process. Control (pristine) wood composites were made of 100% wood particles. Similarly, a blend of canola and wood particles were employed for fabricating hybrid composite specimens at two different polymer fractions as shown in Table 1 to investigate the influence of incorporating canola fibres into the composites.

Characterization

Mechanical Properties of Canola Fibre Reinforcements

According to ASTM D1445-12 [37], strength index and breaking tenacity of the solvent-retted fibres were measured in a controlled humidity chamber by Eqs. 1, 2. Pressley Fibre Bundle Strength Tester was used for this purpose. The pre-factor determination technique in Eq. 2 and the tensile strength equation (Eqs. 3) was based on the work of Shuvo et al. [16].

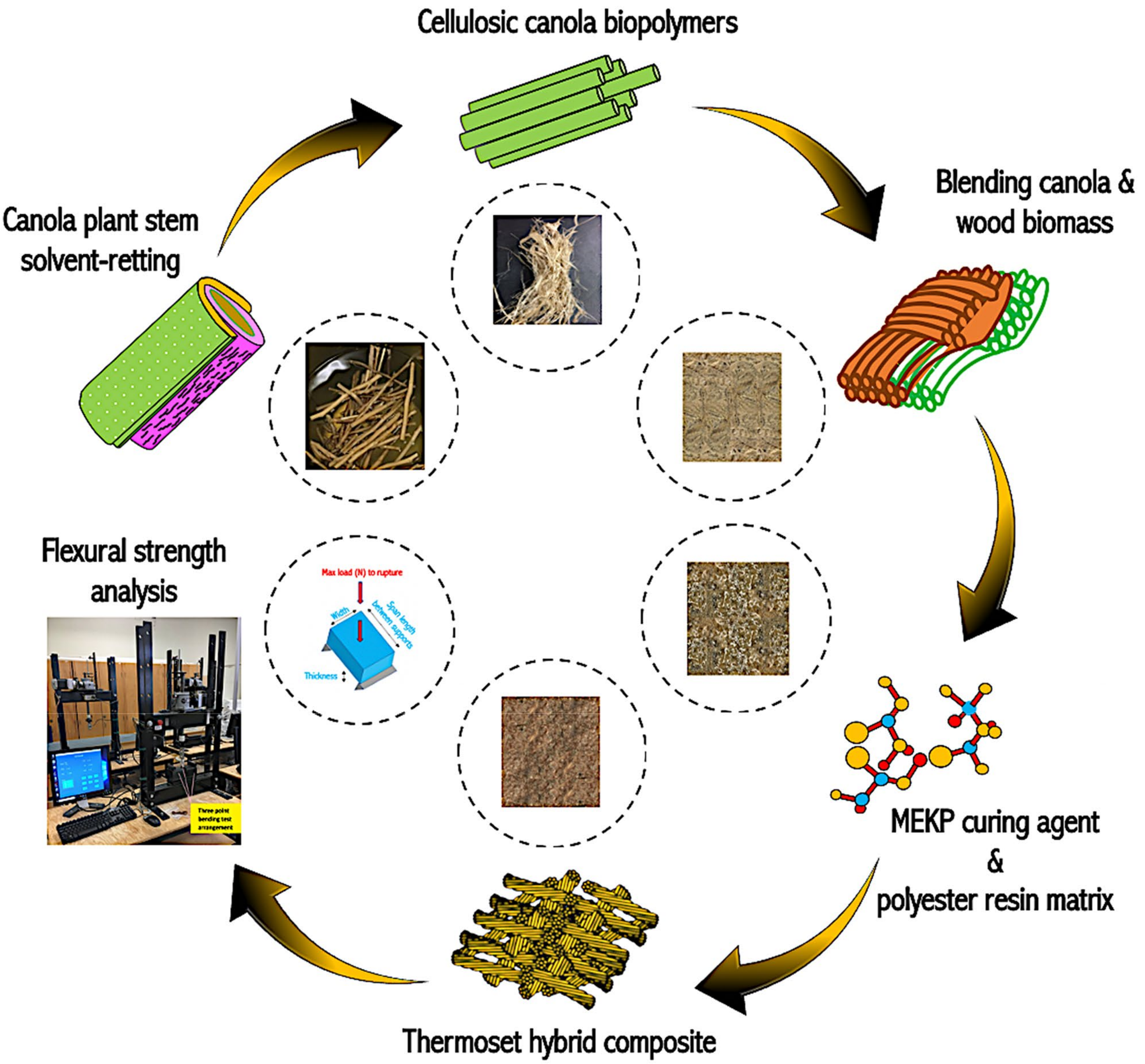


Fig. 1 Experimental framework from canola fibre extraction (post solvent-retting) to canola-wood reinforced hybrid composite fabrication using unsaturated polyester resin and MEKP agent (for ambient curing)

Table 1 Three composite sets (PCW, 2.5 CW, 5 CW) and their biomass content %

Composite set labels	Composite constituents		Polymer fraction (%)		Resin matrix	Response
(N = 5)	Type	Composition	Canola (%)	Wood (%)		
PCW	Pristine	Wood + UPE	–	–	3% MEKP mixed resin	Flexural performance
2.5 CW	Hybrid	Canola + Wood + UPE	2.5	25		
5 CW	Hybrid	Canola + Wood + UPE	5	25		

$$\text{Strength Index}\left(\frac{\text{lb}}{\text{mg}}\right) = \text{Breaking Load (lb)/Mass of specimen (mg)} \tag{1}$$

$$\text{Breaking Tenacity}\left(\frac{\text{gram.force}}{\text{tex}}\right) = 6.42 \times \text{Strength Index} \tag{2}$$

$$\text{Tensile strength(MPa)} = 9.807 \times \text{Fibre density}\left(\frac{\text{gm}}{\text{cc}}\right) \times \text{Breaking tenacity}\left(\frac{\text{gram.force}}{\text{tex}}\right) \tag{3}$$

To better analyze the fibre properties employed for composite fabrication, the canola fibres were further treated and investigated for fibre diameter and density analysis, based on the working procedure of Shuvo et al. [16]. FibreShape was used for fibre diameter analysis and a gas pycnometer measured the fibre density.

Flexural Strength of Composite Specimens

ASTM D3410M [38] test method and a Tension frame were used for conducting three-point bending tests of composite specimens. At a loading rate of 5 mm/min, the Tension frame exerted compressive force on the composite specimens to determine failure points. In a three-point bending setup, the maximum flexural strength (FS) (MPa) of a rectangular composite sample under applied compressive loading (N) is given by Eq. 4.

$$\text{Flexural strength (F.S.)} = \frac{3\text{Pl}}{2\text{bh}^2}(\text{Pa}) \tag{4}$$

where,F.S. = Maximum flexural strength (MPa),P = Breaking load (N)l = Span of support specimen (m)b = Specimen width (m)h = Specimen thickness (m)

Scanning Electron Microscopic (SEM) and Optical Microscopic Analysis

Furthermore, the cross-sections were also imaged with scanning electron microscopy (SEM) (FEI Quanta 650 FEG ESEM from Thermo Fisher Company, USA) with an acceleration voltage of 20 kV and a current of 10 µA. Before conducting the SEM, the samples were coated with Au (gold) for making the material conductive. The Denton Gold Sputter deposition system was used to put a thickness of 16 nm. Digital images were taken using an optical microscopy.

Failure and Reliability Analysis Using Two-Parameter Weibull Distribution

Natural fibre-based composite structures suffer from different variations due to the intrinsic anisotropic behaviour of natural fibres. A predictive analysis of breaking load point under compression could be effective for studying composite design-process. Hence, a two-parameter Weibull method was used for constructing probability distribution curves for failure/reliability analysis. The following Weibull equations were employed for this purpose:

$$\text{F} = 1 - e^{\left(\frac{-\sigma_f}{\sigma_o}\right)^{m}} \tag{5}$$

Reformulating by taking natural logarithm,

$$\Rightarrow \ln\left(\ln {}^{1}/_{1-\text{F}}\right) = \text{m}\ln\left(\sigma_f\right) - \text{m}\ln\left(\sigma_o\right) \tag{6}$$

By linearizing, Y = mX + b if,

$$\text{Y} = \ln\left(\ln {}^{1}/_{1-\text{F}}\right);$$

$\text{X} = \ln\left(\sigma_{\text{f}}\right)$; $\text{b} = -\text{m}\ln\left(\sigma_{\text{o}}\right)$ Where, m = Shape parameter (slope); σ_{f} = Breaking load at failure; σ_{o} = Scaling parameter or characteristic strength; F = Probability of failure for variable σ_{f} (F > 0) (F = 0.5 means 50% failure whereas 0 means no failure); R = Probability of survival for variable σ_{f} (R is also known as reliability); m = σ_{o} = Constant for specimens(m also known as Weibull modulus)

Alternatively, the two-parameters (m and σ_{o}) could be used for measuring R by applying the following Eq. 7:

$$\text{R} = e^{\left(\frac{-\sigma_f}{\sigma_o}\right)^{m}} \tag{7}$$

Results and Discussions

Canola Biopolymers

Canola stems (Fig. 2) are thin and strong. Fibres are readily available in bundle-form after extraction from the solvent-retted plant stems. Further fibre surface modification process allows fibre individualization.

Like cellulosic canola fibres, the wood biomass also contains xylan (arabino-4-O-methylglucuronoxylan). Besides mechanical strength, the wood particles add an important feature to the overall thermoset composite structures, which is the improvement in resistance against hydrolysis reaction [39]. While the canola fibres exhibit a low-density, its length also assists in forming the reinforcement network by interfacial adhesion with the resin matrix. This extra-ordinary

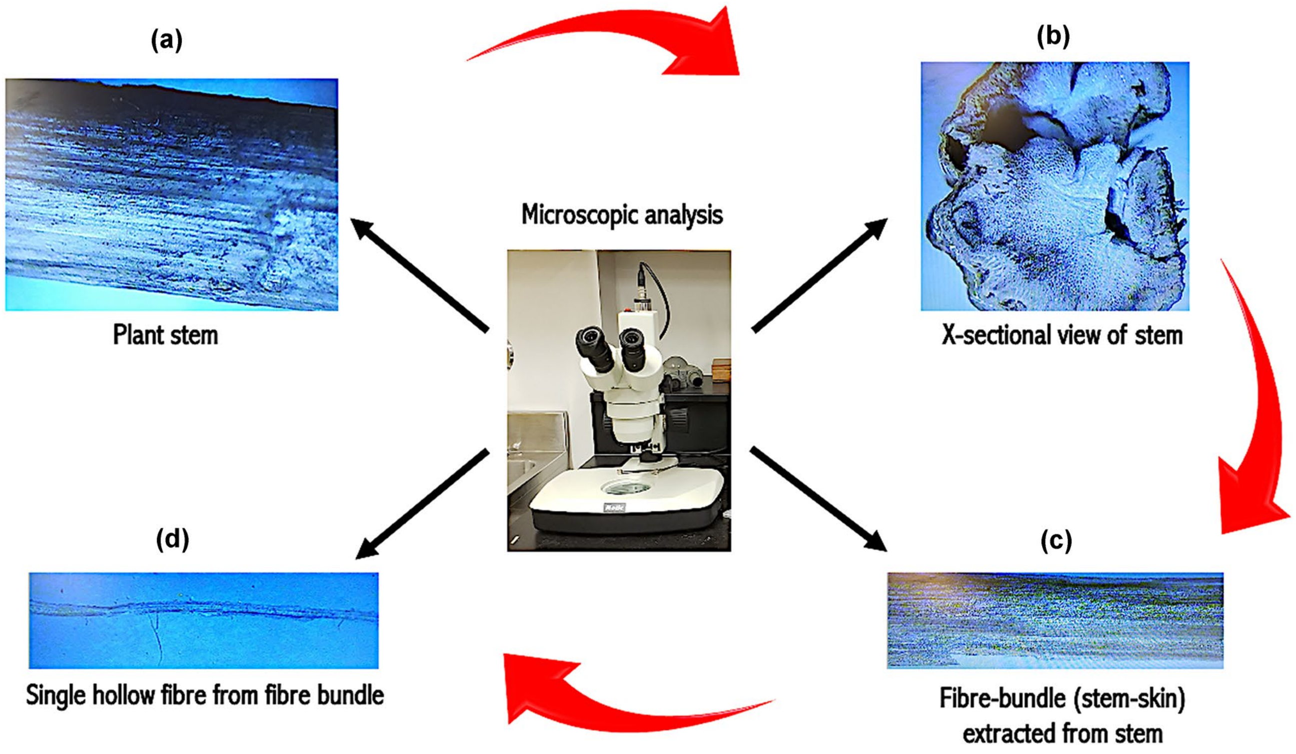


Fig. 2 Microscopic images of canola stems and fibre polymers: **a**, **b** plant stems are solvent-retted; **c** fibre bundles are manually extracted from the stem surface after retting process is completed; **d** single hollow fibre entity separated from the fibre bundle

Table 2 Mechanical properties of canola plant-based bast fibres

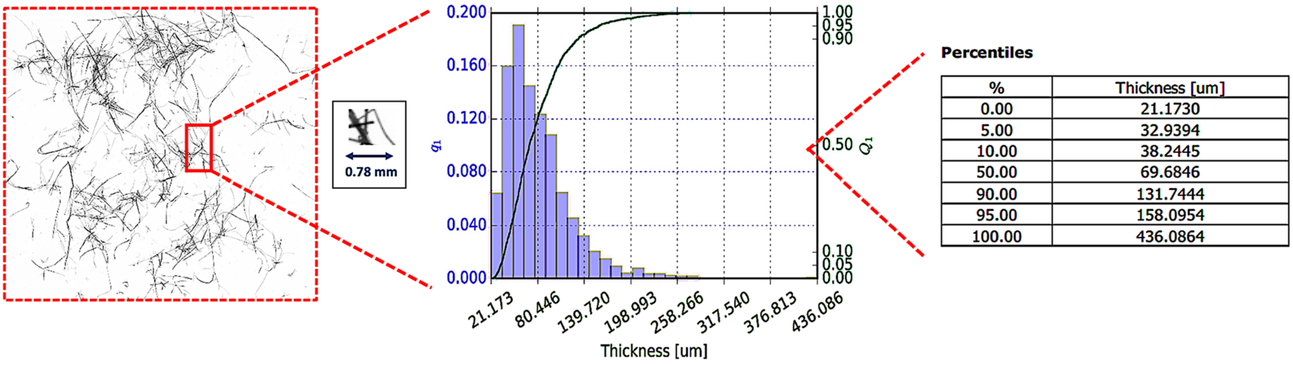
Canola fibre	Density (g/cc)	Breaking tenacity (g-force/tex)	Tensile strength (MPa)
Average	1.34	13.31	174.93
± 1σ	0.0014	4.59	60.29
N	10	5	5

feature of hollow fibre configuration could be harnessed to construct self-healing composites and laminate by integrating self-healing agents though these hollow reinforcements. The hollowness of canola fibres will eventually facilitate the healing chemicals to flow through its interior and fill the fractured regions during any external impact or damage propagation process.

Diameter, Density, and Tensile Strength of Canola Fibre Polymer

Density of the canola fibre was 1.34(± 0.0014) g/cc, comparatively lower than cotton (1.54 g/cc), hemp (1.48–1.49 g/cc), flax (1.54 g/cc), and jute (1.44–1.50 g/cc) [40, 41] (Table 2) but closer to different controlled and commercial canola cultivars [16]**.** Also, canola fibres exhibited a breaking tenacity and tensile strength of 13.31(± 4.59) g-force/tex and 174.93 (± 60.29) MPa. It can be seen that although canola fibre is lower in density than other major bast fibres, it is mechanically weaker compared to them. Cotton, jute, hemp, and flax typically display a breaking tenacity of 41.30–61.10, 18–56.70, 27–63, and 23.40–72 g-force tex, respectively; their tensile strength range is 573–849, 393–800, 690, and 345–1500 MPa [41–43]. However, the low-density of the canola fibres make it a suitable choice for fabricating lightweight composite structures.

The diameter of canola fibres extended between 21.17 and 436.09 µm with an average value of 79.80 (± 41.31) µm (Fig. 3). According to ISO 9276-1 and ISO 9276-2, the size, shape, and optical parameters were weighted by the Geodesic length using the FibreShape flatbed scanning method. The diameter of canola bast fibres are comparable to different bast fibres including jute (25–200 µm), hemp (25–500 µm), and flax (40–600 µm) [41, 42]. Canola nonwoven mat produced with the mixture of fine and coarse fibres—entangled between them—influenced the flexural performance of hybrid canola composite specimens.



Percentiles

%	Thickness [um]
0.00	21.1730
5.00	32.9394
10.00	38.2445
50.00	69.6846
90.00	131.7444
95.00	158.0954
100.00	436.0864

Fig. 3 Diameter (thickness) of canola bast fibres (N = 1529)

Obukuro et al. demonstrated that fibres with less than 16 µm causes an inefficient fibre-resin interfacial bonding and fibres with ≥ 20 µm contributes in improving flexural performance of composite structures [44]. Interestingly, the diameters of canola fibres are suitable for a strong interfacial adhesion with the resin matrix and displaying a satisfactory level of flexural strength in a composite configuration.

Load–Deflection Curves of Hybrid Canola-Wood Composites

Maximum flexural strength of cellulosic bagasse fibre (extracted from sugar cane stalk) reinforced composite structures can be increased by 37% and 44% by adding only 2% and 4% of bagasse fibres [45]. Similarly, the authors found that, 2% inclusion of wheat fibres reduces the flexural strength of wheat fibre reinforced composites, whereas 4% inclusion of wheat fibres increases the strength. Hence, the current study took a similar approach of using minimal amount of canola fibre fraction by combining the two observed studies: bagasse and wheat fibre reinforced composites. The current research study utilized a fibre proportion of 2.5% (> 2%) while fabricating the canola-wood hybrid composite structures. Additionally, the impact of increasing the fibre content up to 100% on the compressive strength of composites was also observed by fabricating hybrid composites with 5% canola fibres.

The load–deflection behaviour of pristine and hybrid canola composites was investigated in this study, which

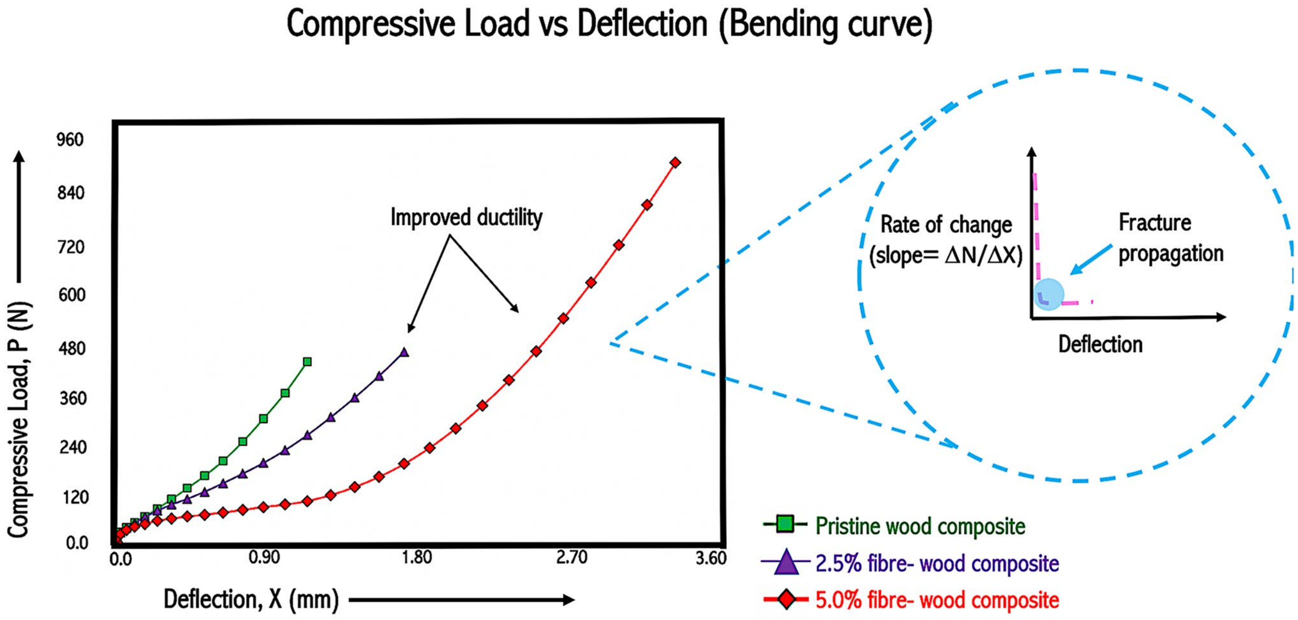


Fig. 4 Load–deflection curves of pristine wood and canola-wood hybrid composites

is demonstrated by Fig. 4. The curves represent the three-point bending test of the composite specimens that differ in biomass polymer content (%). It can be seen that the load–deflection curve for the PCW, 2.5 CW, and 5 CW composite specimens display an almost linear behavior once the specimens undergo a deflection of ~ 0.70, ~ 1.10, and ~ 2.30 mm. The linear behaviour continues up to a peak point until the PCW, 2.5 CW, and 5 CW composite specimens reach the breaking point at ~ 460 N, ~ 480 N, and ~ 890 N, respectively against the deflection thresholds of ~ 1.20 mm, ~ 1.70 mm, and ~ 3.40 mm, respectively. The inception of linearity or the gradients, refer to a faster distribution of compressive loading with respect to deflections, from the resin matrix to the fibre network; this linearity rapidly gives rise to debonding mechanism that ultimately propagates the cracking and fracture process. However, the nature of static fractures of the pristine wood composites (PCW) is brittle, whereas, the static fracture of the fibre reinforced hybrid canola-wood composite structures (2.5 CW and 5 CW) is ductile. The deflection as well as the breaking load values between the hybrid structures increases with the increase of fibre fraction. The deflection load at failure of the 2.5 CW and 5 CW hybrid structure are about ~ 1.5 and ~ 2.8 times higher than the control PCW structures without cellulosic canola fibre, when the fibre fractions are 2.5 and 5 wt%.

Crack propagates where fibres are minimally present, causing composite failure under a low level of applied loading condition. Hence, in a composite design, a larger fibre fraction can uniformly distribute within the matrix system [45], forming a strong interfacial adhesion with the matrix. Consequently, the flexural performance of a composite structure will be improved. The current work demonstrated that, by increasing fibre fraction, compressive strength of the composite structures can be improved. It was revealed that breaking load could be improved by nearly 46% if the use of cellulosic canola fibre fraction is increased, from 2.5 to 5%. The finding of the current study resembles with a recent of work of Xie et al. i.e., deflection and fracture toughness (to withstand applied loading) increases with increased content of cellulosic fibres [46]. However, further work is necessary to calculate the optimal use of canola fibres in the composite specimens since flexural strength could be decreased due to fibre agglomeration from overuse of fibre fractions [46, 47]. Interestingly, it was also demonstrated that by replacing half of the wood content with substantially low amount of canola fibres, a comparable deflection value and breaking load could be achieved. As a result, a lightweight and superior hybrid composite structure was developed using the canola fibres. Hence, the current work demonstrated that wood-based composites containing 2.5–5% of cellulosic canola fibre improve compressive strength and reduce composite weight than those of control pristine PCW specimens.

Further, canola is intrinsically a low-density cellulosic fibre with a low fibre diameter. As a result, nonwoven or composite structure with high packing density can be designed with cellulosic canola fibres, which would ultimately reduce the porosity and permeation. These attributes

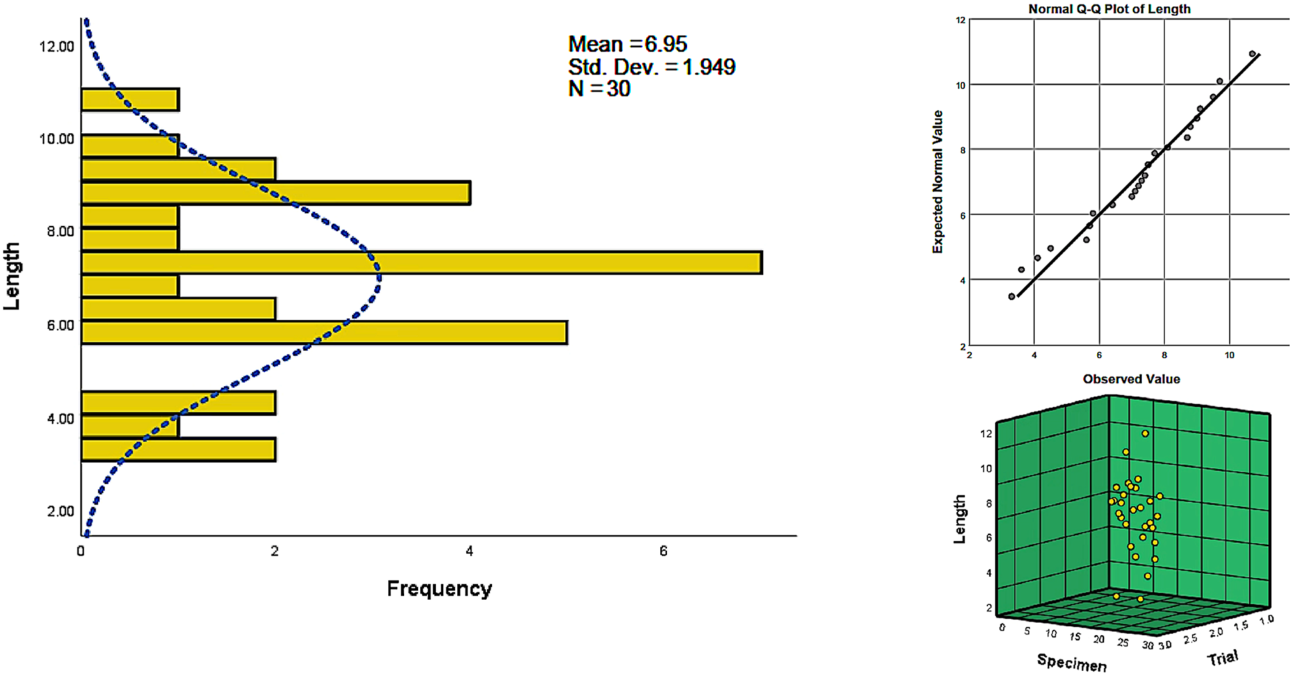


Fig. 5 Fibre length of canola bast fibres (N = 30)

of canola fibre could facilitate towards building composite structures with satisfactory resistance to freeze-thraw effects.

To summarize, the improvement of the compressive strength of the hybrid canola composite structures is associated with several key factors including fibre diameter, fibre length, fibre density, fibre volume fraction, and interfacial adhesion between fibre and the resin matrix system. The average fibre length of canola fibres was ~ 7 cm (Fig. 5), which produces a high aspect ratio for canola fibres due to its microlevel diameters. As a result of the aspect ratio, canola fibre network generates an adaptive environment for forming composite structures with the resin matrices. The low-density of canola fibres favours a high-volume fraction and a compact packing density of reinforcements. As a result, a high surface area is produced by fibre reinforcements inside the composite structure to spread the fibre-resin interfacial loads, allowing the canola hybrid composite structures to withstand external load or impact. Consequently, the canola hybrid composites portray a strong flexural performance.

Maximum Flexural Strength of Hybrid Canola-Wood Composites

When a crack propagates in service under compressive loading, fracture in a composite structure occurs with a little or zero plastic deformation. Composites with strong FS could resist such crack initiation, and the unstable/failure propagation process. According to the “weakest link” theory, the weakest link of a chain is responsible for initiating the fracture process in a material [48]. Voids in a nonwoven is one of the weak links, which, however, could be solved by increasing the reinforcements. Composites with higher amounts of reinforcements will achieve higher fracture toughness, [49] and thereby, improved flexure performance. Additionally, by employing longer fibre length flexural property could be improved. Once load is applied on a composite, the load is transferred from matrix to the fibre; as a result, debonding can take place at the fibre-resin interface, pulling the fibre out through the resin. Short fibres are more prone to such frictional energy unlike the longer fibres. Canola fibres, due to their longer length, could perform well against the debonding load and exhibit a satisfactory level of FS.

Increased fibre polymer fraction in a fibre reinforced composite structure increases the overall FS—a phenomenon, marked in the current study. Figure 6 displays superior FS of canola-wood hybrid composites (2.5 CW, 5 CW) compared to the pristine wood PCW composites. While the pristine PCW composites exhibited a maximum FS of 49.25 (± 9.44) MPa, hybrid 2.5 CW and 5 CW composites exhibited 59.6 (± 30.18) and 89.58 (± 27.65) MPa, respectively by consuming less wood fraction. Adding a little amount of fibre fraction substantially increased the FS of

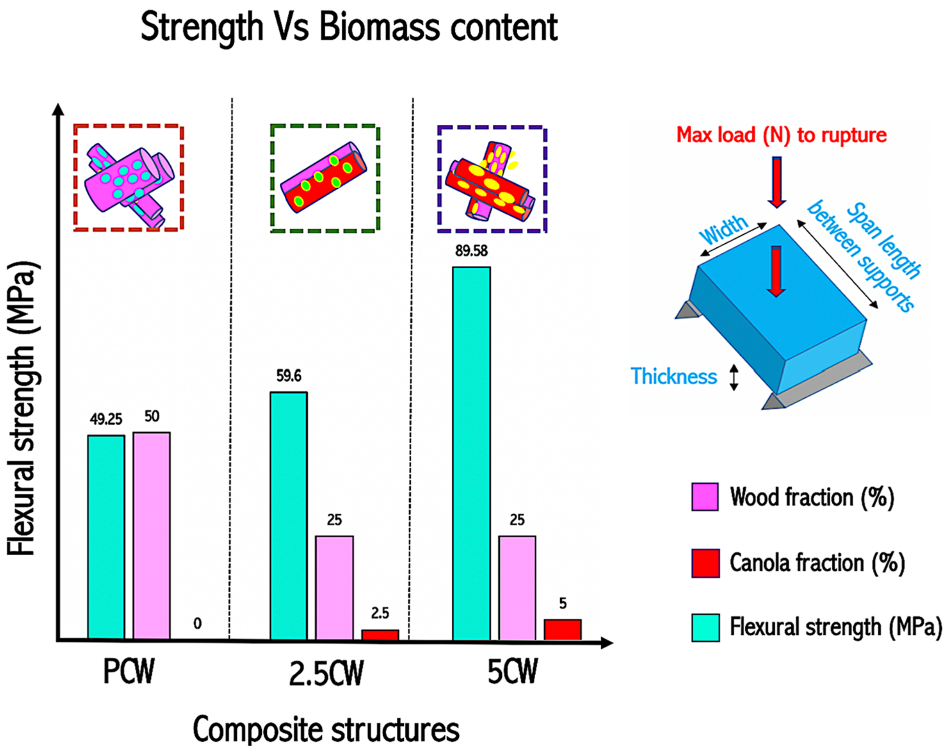


Fig. 6 Comparative analysis of average maximum flexural strength between hybrid canola-wood composites (2.5 CWs and 5 CWs) and pristine wood composites (PCWs)

the hybrid composites—up to a 50% increase in FS with superior lightweight performance. The FS standard deviation of the composite structures were quite high, ranging between ~ 10 and ~ 30 MPa, probably as a consequence of heterogenous cracking due to the shrinkage during drying. However, no statistically significant variation was noticed among the pristine wood and hybrid canola composite structures ($\alpha = 0.19 > 0.05$). The apparent increase in the FS of the canola hybrid composites could be associated to a network of well-distributed longer canola fibres within the resin matrices, and therefore, the load bearing capability. Composites with 4% sisal weight fraction and 4% banana weight fraction exhibited a FS of 16.5 and 15.5 MPa [49], which is lower than the values obtained from the current research work, probably due to the canola fibre length. The fibre length of canola fibres (mean: ~ 7 cm) was much higher than the sisal (0.165 cm) and banana (0.195 cm) fibres.

Interestingly, the canola-wood hybrid composites displayed a larger FS than different hybrid composites, for example, hybrid composites of rice husk and walnut shell (13.3 MPa) [50] or coconut shell (13.1 MPa) [50] powder (Fig. 7). Similarly, the FS of banana-cotton (60.4 MPa) [36] or jute-oil palm fibre (49 MPa) [51] hybrid composites are lower compared to the FS of canola-wood hybrid composites. By increasing the biomass fraction, it is possible to design canola hybrid composite structures with higher FS like jute-hemp (109.5 MPa) [52] hybrid composites. The possible design of canola-glass fibre reinforced hybrid composites may also display higher values of FS like *cissus quadrangularis* stem-glass fibre (143.9 MPa) [53] or bamboo-glass fibre (132 MPa) [54] hybrid composites; however, a research work needs to be conducted to investigate this hypothesis.

Surface Morphology and Fracture Modes

As the performance of the composites largely depends on the interfacial characteristics that transfer external load from matrix to the fibrillar network, an analysis of the failure mode at the fibre-matrix interface must be given a due emphasis. Here, four main contributing parameters are discussed for the improved mechanical performance of the hybrid canola-wood composites, in the form of elevated flexural strength and higher capacity of energy absorption: (1) superior fibre breaking-tenacity (or tensile properties), (2) improved fibre volume fraction from low fibre density, (3) high aspect ratio for high fibre length and low fibre diameter, (4) interfacial adhesion between the fibre reinforcements

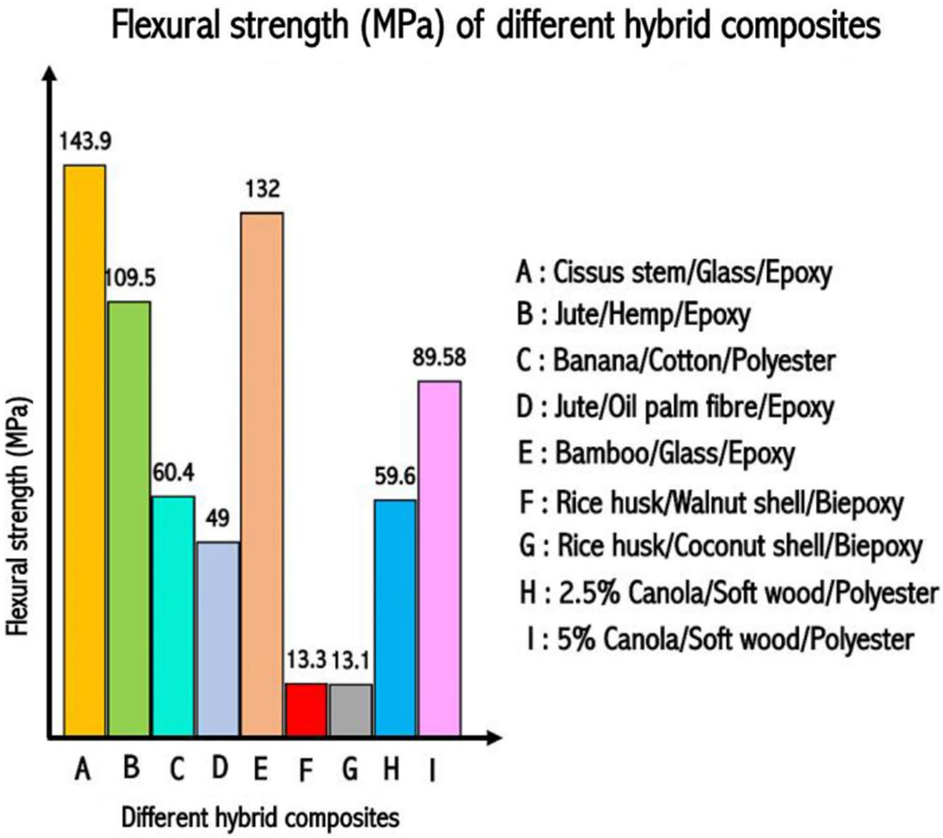


Fig. 7 Comparison of flexural strength (MPa) among different kinds of hybrid composites (**A** [53]; **B** [52]; **C** [36]**; D** [51]; **E** [54]; **F/G** [50]; **H/I** current work)

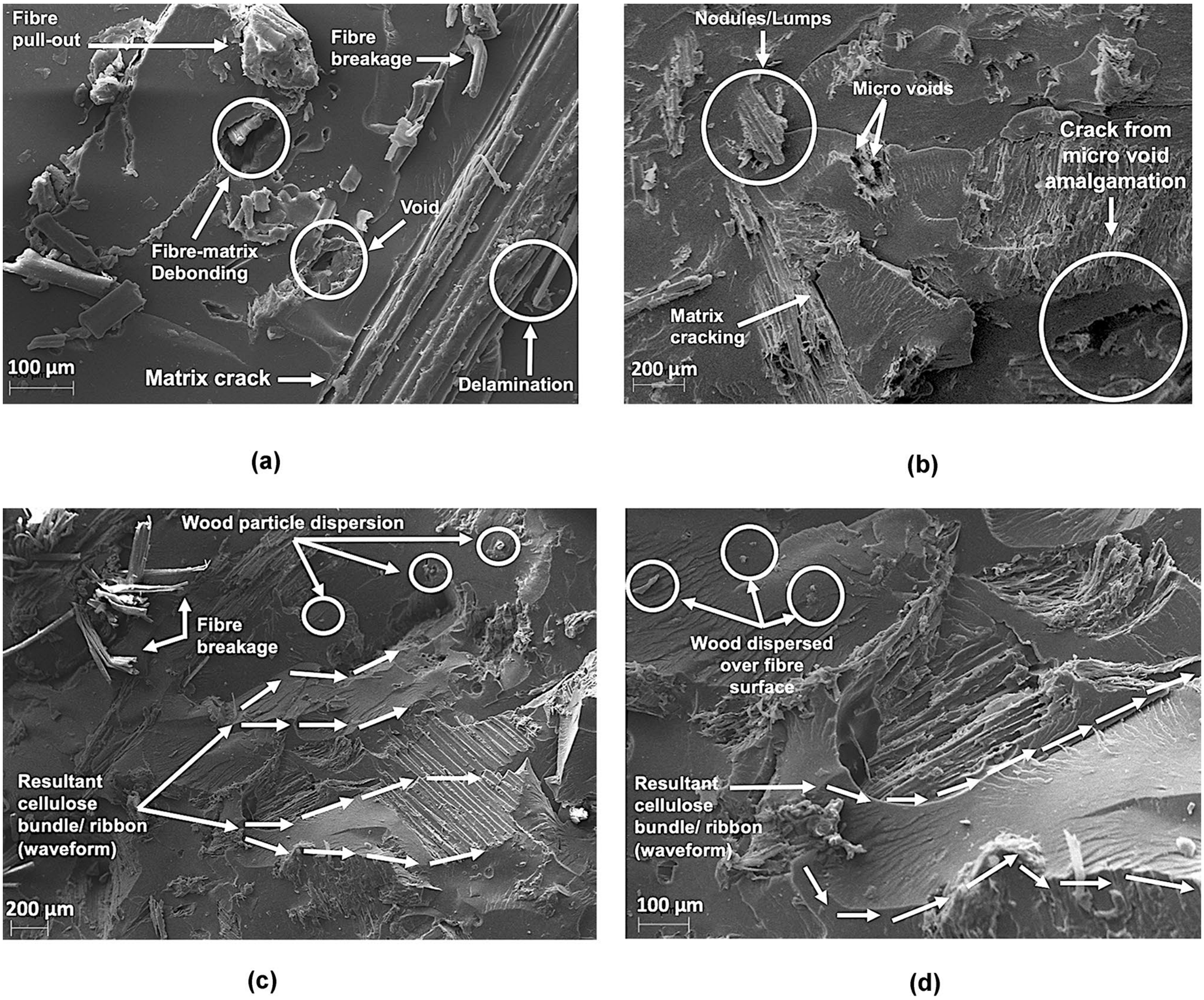


Fig. 8 SEM micrographs on the fractured cross-section of the flexural tested composite specimens (a: 100% canola reinforced pristine composite; b: PCW 100% wood reinforced pristine composites; c: 2.5 CW hybrid fibre-wood composite; d: 5 CW hybrid fibre-wood composite)

and resin matrix. The synergetic effect of low fibre density, compact packing of fibres, and high aspect ratio permitted an appropriate level of interfacial bonding between fibre reinforcements and resin matrix for composite fabrication. Further, the superior tensile properties of canola fibres and their high aspect ratio confirmed resistance to fibre-fracture/breakage and fibre pull-out, yet at the same time facilitated a chemical environment for interfacial bonding between canola and resin-matrix, which is a primary toughening mechanism in composite materials.

Figure 8 displays the SEM micrographs of the fractured cross-section of the composite specimens (for comparative analysis, we also posited the fractured surface of 100% canola made pristine composite). The available hydroxyl groups could have been primarily responsible for the overall interfacial adhesion between the biomass and matrix fractions [55]. The SEM micrographs confirm the random orientation of cellulosic elements within the composite architecture (Fig. 8a–d). The complex interior of the composite architecture is vastly susceptible to mechanical failure arising from fibre fracture/breakage and delamination [56]. Fibre-matrix debonding is another critical reason for structural failure [57]. Cellulosic fiber reinforced polymer composites are also vulnerable to fiber pull-outs, resin deformation debris or matrix cracks [58]. Combining these mechanisms could fail a composite specimen—a phenomenon that was predominant in the composites made of 100% canola fibres (Fig. 8a). Fibre breakages were largely visible in the pristine canola composites. Also, fibre-matrix debonding generated few openings on the surface**.** Delamination, on the other hand, was marked to be one of the critical failure modes that separated the adjacent fibre plies by weakening the interfacial chemical bonds. One possible reason for the delamination mode could be associated with the low-thickness strength of the composites made with 100% canola fibres [59]. Furthermore, the presence of different sizes and contents of the void was a significant defect as matrix cracks are sensitive to the presence of voids [60]. However, such defects were less prevalent for canola-wood hybrid composites 2.5 CW and absent for 5 CW, as the void spaces among the fibre network were, at least in part, filled in by wood particles, contributing towards a dense network of woody and non-woody biomass, and ultimately, lowering the voids and increasing the breaking load threshold (Fig. 8c, d). As a result, the hybrid composites did not display any interfacial delamination or debonding along with the interfaces of the canola fibres, resulting in an effective dissipation of compressive loading at a lower wood fraction. Although the SEM image (Fig. 8c, d) of the hybrid composite specimen did not show any debonding behaviour, it showed a compressive waveform (both for 2.5 CW and absent for 5 CW) of the resultant cellulose bundle/ribbon made of a long chain fibrillar network. However, the ribbons were longer and thicker for 5 CW than the 2.5 CW composites, confirming the increased concentration (%) of fibres. The ribbons could be the outcome of an improved intermolecular attractive and intra-molecular coalescence among the polyester matrices and the cellulosic elements they housed. As a result, the resultant bond-strength of the cellulose ribbons augmented the incident stress transfer properties of the strength bearing fibres by minimizing the fibre pull-outs, delamination, and debonding. The superior tensile strength/fibre breaking-tenacity could have played a pivotal role in minimizing the fibre fractures/breakages. Although, 2.5 CW exhibited few fibre breakages (Fig. 8c), 5 CW did not demonstrate any (Fig. 8d), which may suggest 5 CW could be the optimum concentration factor to achieve the best mechanical performance; however, it is recommended to test this hypothesis in future works. To summarize, the hybrid composite structures (both 2.5 CW and 5 CW) were superior and differentiated themselves from the 100% canola composites as they are more prone to mechanical and surface defects, making them inappropriate for engineering or industrial applications.

On the other hand, due to the absence of long-chain canola fibre polymers, the tiny 100% wood particle reinforced pristine composites (PCW) (Fig. 8b) displayed a lower ductile behaviour with a trace of a lower deflection (Fig. 4). In contrast, at a lower wood content (both 2.5 CW and 5 CW), the hybrid composites exhibited evidence of plastic deformation. The SEM image (Fig. 8b) of the pristine wood composites (PCW) exhibits few major nodular (or lumpy) structures on the cross-section of the fractured surface, together with minor solidified woody tissues and micro-voids. These micro-voids could amalgamate and form secondary cracks over the time against minimal loading [61]. The nodular network could arise from self-aggregation of the wood particles [62], possibly due to rapid solidification by the MEKP curing agent. However, these nodules are less visible in the SEM image (Fig. 8c, d) of the hybrid canola-wood composites (both 2.5 CW and 5 CW), indicating a homogeneous incorporation of the canola and wood biomass in the polyester resin matrices. In particular, these observations indicate that the wood particles were also homogeneously incorporated on the surface of the fibrillar network, contributing to their mutual cooperative coalescence and uniformly adhered to the resin matrices between the cellulose bundles. This suggests that the tiny cellulosic wood particles are assembled as a multiphase system within the hybrid composite configuration (both 2.5 CW and 5 CW)—firstly, integrated within the long-chain cellulose bundles, and secondly, dispersed in the surrounding resin matrices. This binding effect could be attributed to the superior flexural performance of the hybrid composites, confirming a robust interfacial adhesion and fine dispersion of the cellulosic materials (both canola and wood) into the polyester matrices.

To summarize, this current work successfully developed strong, and tough canola fibre reinforced hybrid composites. At room temperature and under applied compressive loading, the mechanical performance of the pristine wood composites could be significantly improved by incorporating natural canola biopolymers at a reduced wood fraction or lightweight composite configuration. Solvent-retted canola fibres that nicely balance stiffness, superior strength to weight ratio, and toughness of compressive loading clearly differentiate themselves from other industrial fibres. Consequently, the extended use of canola fibres for next-generation biocomposites could inspire novel designs of lightweight engineering structures.

Weibull Distribution for Probabilistic Reliability Analysis

Figure 9 portrays the Weibull distribution curves for failure and probabilistic reliability analysis of canola-wood hybrid composite structures against a wide range of bending loads (N), for a fibre fraction between 2.5 and 5%. It can be seen that, the 50% survival probability for the hybrid canola composites lies below 735.10 N (using Eq. 6 as shown below). It refers that the current hybridization design-process, utilizing 2.5–5% fibre fraction, could possibly construct composite structures with canola and wood fractions that would display a 50% probability to survive against a 735.10 N compressive load.

$$\ln\left(\ln {}^{1}\!/_{1-0.5}\right) = 3.40X - 22.79$$

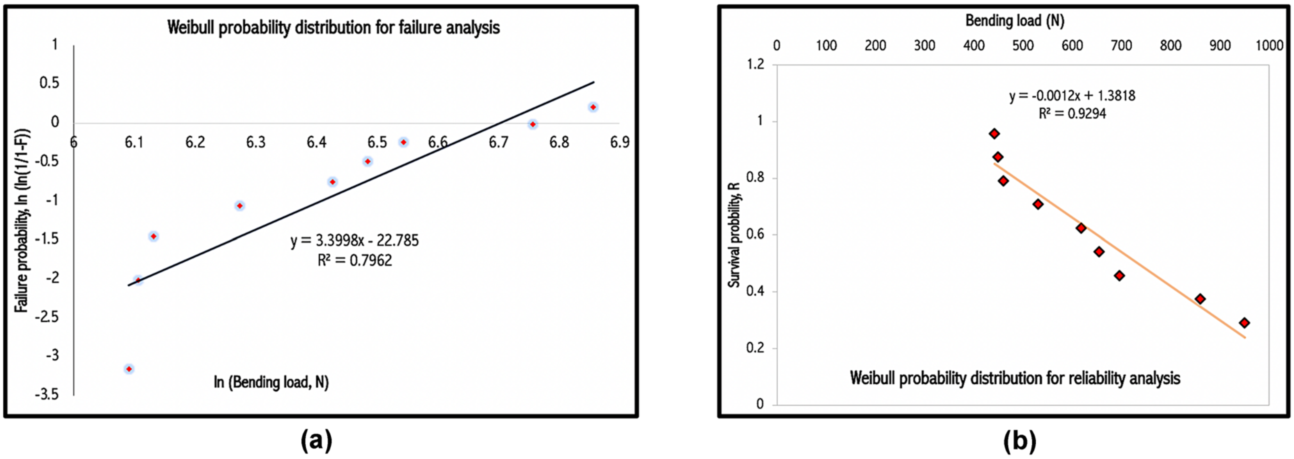


Fig. 9 Weibull distribution for failure **a** and probabilistic reliability **b** analysis of the canola-wood hybrid composite structures against bending load (N)

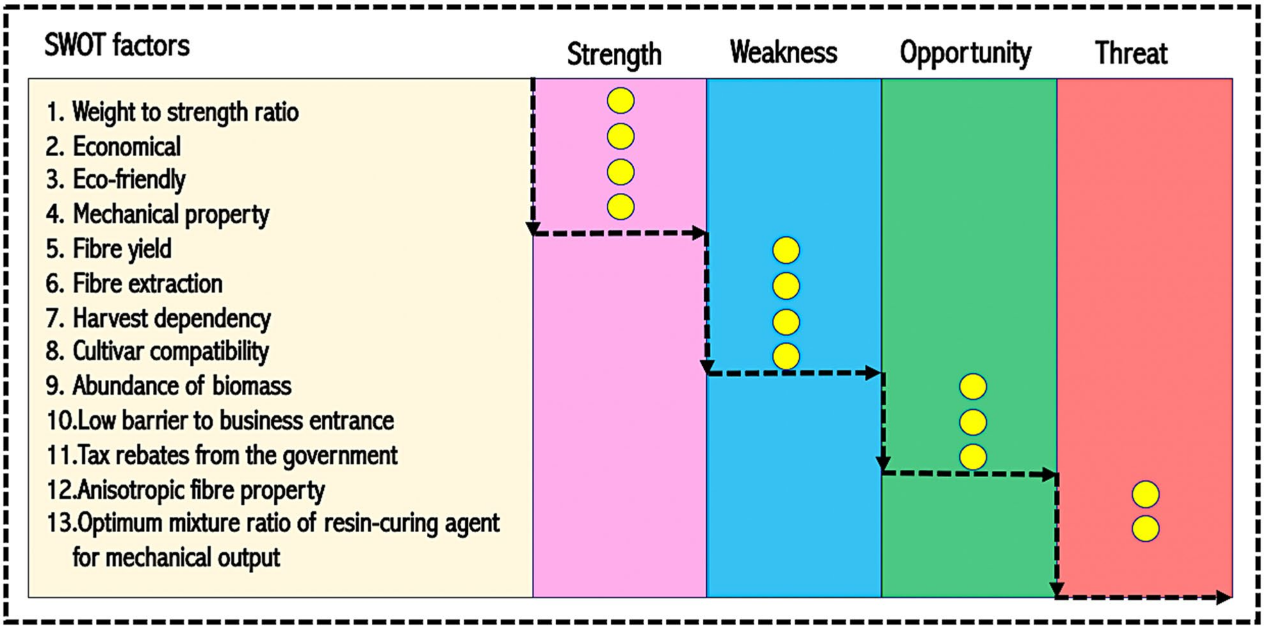


Fig. 10 Summary of SWOT analysis for natural fibres concerning the bio-composite fabrication and commercialization process (from backward to forward linkage industries)

$$\Rightarrow X = 6.60$$

$$\Rightarrow \ln\left(\sigma_{\mathrm{f}}\right) = 6.60$$

$$\Rightarrow \sigma_{\mathrm{f}} = 735.10\mathrm{N}$$

The difference between experimental average (~ 629 N) and Weibull average breaking load (~ 735 N) is < 17%; the R-squared value is pretty high (> 0.92) at 95% confidence interval. Hence, for predicting breaking load, the two-parameter Weibull probabilistic distribution could be used for the canola-wood hybrid composite structures. Similarly, the failure probability could also be calculated using Eq. 6.

Interestingly, the shape of the failure and reliability curves resemble with the work of Roy et al. and Sayeed and Paharia [63, 64].

SWOT Analysis

SWOT analysis (Fig. 10) summarizes an overview of this current work, which could be studied for any natural fibre-based composite structures, either solo or in a hybrid configuration. Strength of the natural fibres (like canola) lies in producing lightweight composite structures, which is economical, environmentally friendly, and exhibits a satisfactory level of mechanical properties. Fibre yield or nature of retting method could be a challenge. A slow retting method or manual extraction process is detrimental for the industrial production process, which hinders a fast turn-over process and eventually hampers the forward linkage industries. Hence, automation of the extraction process is mandatory without damaging the fibre surface. Chemical extraction process could be a solution that doesn't involve any mechanical combing like the primitive decortication process. One such example is the alkaline retting of cattail fibre, which only involves agitation in a chemical bath using Launder-Ometer [65]. Similar technologies should be explored and developed for fibre production at industrial level. Cultivar compatibility with resin matrices or polymer fractions during the hybridization process could be a challenge. Rigorous research works need to put forward for an in-depth analysis of response behaviours of different cultivars. Natural fibres originate from nature, and thereby, production processes and the sourcing processes could be severely affected by a bad harvesting period. Further, the conservation of biomass and waste streams require a regulated climate chamber and a clean environment to prevent a microbial attack. However, natural fibre provides immense opportunities for business development due to their abundance in nature around the globe. Further, the governments of different countries offer rebate and tax benefits for natural fibre-based industries to encourage enterprises to invest in this sector. Surprisingly, the barrier to market entrance is also low due to government policies and growing consumer demands for reducing carbon footprint. Anisotropic characteristics of natural fibre is a major threat for fabricating homogeneous nonwoven mats or composites, which could be addressed by proper choice of nonwoven manufacturing techniques or developing new ones. For example, computer machine learning algorithms could provide better solutions to better the mat quality by optimizing the automated fibre deposition processes than the hand lay-ups. Also, if a proper blend of resin-curing agent ratio is not maintained or formulated, the mechanical properties of the product may not suffice the end-choice applications.

Conclusion

Cellulosic canola fibres are envisaged for applications in diverse grounds. The current study hypothesized the possible improvement of flexural strength of wood-based pristine composite structure by incorporating cellulosic canola fibre. Utilizing a facile composite fabrication technique, hybrid composite structures of canola and wood biomass were produced in this current study. Canola fibre exhibits a mean breaking tenacity and tensile strength of 13.31 g-force/tex and 174.93 MPa. The average length (7 cm) of canola fibre generates a suitable aspect ratio for composite application, mostly due to its fine micro-level diameters. The minimum diameter (~21.17 microns) of canola is above 20 microns, making it suitable for an improved interfacial adhesion with synthetic resin matrix. The canola-wood hybrid composite structures exhibited a maximum flexural strength of 89.58 MPa, nearly double the value of pristine wood composites.

Interestingly, the density (1.34 g/cc) of canola is fibre lower comparative to major bast fibres like jute, flax or hemp. As a result, canola affects the overall weight of a composite structure. Thereby, a higher efficiency could be obtained by using lightweight canola reinforced composites for interior panels in automotive or aerospace industries, probably due to higher fuel or energy efficiency. The carbon footprint will be also low. Also, the composite structure benefits from the higher packing density of canola fibres due to its intrinsic low-density profile.

The composite interface is of paramount importance that affects the overall performance of canola composite structures. Therefore, future work should focus on investigating the strength of interfacial adhesion between fibre and unsaturated polyester matrix. The nature of interaction of between different chemical groups of the composite structure could be analyzed by FTIR (Fourier-transform infrared spectroscopy). Integrating saline coupling agents may improve interfacial adhesion and hinder the debonding at the interface.

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Author Contributions IS wrote the manuscript, designed the study, fabricated the composites, conducted all the mechanical experiments, and performed the statistical data analysis. MdS and LK participated in the morphological experiments. MdSH helped IS to draft the morphological study.

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Availability of Data and Materials All data generated or analyzed during this study are included in this article.

Declarations

Conflict of Interests The authors state that there are no conflicts of interest to disclose.

Ethics Approval and Consent to Participate This research does not contain any studies on human participants or animals performed by the author.

Consent for Publication I, Ikra Iftekhar Shuvo (IIS), the author, hereby declare that it is my study, and I developed the manuscript titled 'Flexural strength and load–deflection behaviour of hybrid thermoset composites of wood & canola biopolymers'. The study was conducted at the University of Manitoba and Composites Innovation Centre (CIC Engineering, Canada).

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Ikra Iftekhar Shuvo Currently exploring flexible electronics for a broad spectrum of applications, including wearables and smart electronic textiles, Ikra Iftekhar Shuvo is taking an interdisciplinary approach – combining electronics, biomedical science, and computer science – to studying physiological biosignals of the human body. After completing his BSc (BUTEX) and MSc (University of Manitoba), Ikra worked at different Canadian companies, including BOEING Canada and Stern Partner's WH1. Through formal MITACS internships, Ikra also had the opportunity to collaborate with major technology transfer and R&D centres in Canada, including Composites Innovation Center (Manitoba) and Groupe CTT (Quebec).

Md. Saiful Hoque is pursuing his PhD in Textile and Apparel Science at the University of Alberta, Canada. His primary research area involves investigating the performance of protective clothing and the applications of smart materials for protective textiles. Previously, he completed his BSc in Textile Engineering from the University of Chittagong, Bangladesh, and worked several years in the textile manufacturing industries. After developing a strong passion for research works, he moved to academia in the realm of textile science and engineering.

Md. Shadhin is currently pursuing PhD in Biosystems Engineering at the University of Manitoba, Canada. His research work is focused on the manufacturing and characterisation of fibre-reinforced composite materials for the Canadian transportation industries. The work is a joint collaboration between Composite Materials and Structures Research Group, Dept. of Mechanical Engineering and the Dept. of Biosystems Engineering at the University of Manitoba. Previously, he pursued MSc in Biosystems Engineering from the University of Manitoba and a BSc in Textile Engineering from the Bangladesh University of Textiles.

Lovely K. M. Khandakar With a major in Microbiology and a minor in Chemistry, Lovely Khandakar completed her BSc degree from the University of Manitoba, Canada. Currently, she works as a Senior Microbiology Technician at FSNS – a US-based safety and testing company in Alberta, Canada.