REVIEW ARTICLE

Synergistic Utilization of Flax Fiber Polymer Composites: A Review

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The application of flax fiber is vast in the various fields in the world, the well-known in the area of as textiles many of the countries they used the flax fiber mixture with linen, traditionally used for making of bed sheets, underclothes and table linen. The specific properties of flax fiber responsible for the potential platform to next-generation structural applications in automobile and other consumer works. Due to its mechanical properties, flax fiber composites possess good strength and durability. In this review paper, the various proportion on evaluation of work done to know about the amount of research undergone with flax fiber composite in various fields. From this review paper, the utilization of flax fiber has gap in variety of applications in various fields. To identify the research gap and its utilization, quantum of work to be done in the all of the areas was analyzed in that 36% of work done on mechanical property, 30% in novel performance work like simulation and model analysis, 18% of work going on marine, aeronautical related applications and only 16% work carried out in structural related applications using flax fiber composite, flax fiber composite products are potentially used because of their lighter weight and lower cost. Most of the automobile components are replaced by flax fiber composite, these composite components are sound in the capability to reduce the weight for fuel efficiency. Other developing market applications such as tiles, marine piers and flower pots are now a day manufactured from flax fiber composite. In the future, the flax fiber will reduce the utilization of synthetic fiber, by producing an eco-friendly environment in all type of products, wherever replacement is possible with some synergic property.

Introduction

The presence of natural Fiber in this earth crust may contain the enormous number of properties that help to utilize by the human begins mainly in addition to and some replacement of synthetic Fiber over natural Fiber with similar properties. The high usage of more performed engineering polymers has their applications as the plasma-based surface-treated Fibers. To improve the mechanical properties of thermoplastic eco-friendly natural composites used as alternatives, here they used epoxy as a matrix. The European society for composite material [**1**] has explained about two major drawbacks of matrix and reinforcement materials and the high energy needed for mechanized and the recycling of the thermoset composite of their life. These drawbacks were addressed by using natural Fibers to the combination with thermoplastics matrix material. [**2**] made a comparison of flax fiber and glass fiber, the flax fiber has more concept than glass fiber due to its cellulose microfibrils local misalignment inside the fiber. Flax fiber also has good fracture strength than glass fiber due to its concentric rings of microporous structure [**3**] investigated the mechanical properties of thermally treated flax fiber composites. It was concluded that the decline of the mechanical properties and improves the bonding between the interfaces. The stiffness of the composites varies due to its unstable circumstance of stress-strain during starting of the loading. Mechanical properties of flax fiber composites comparison with glass fiber on water aging was investigated [**4**]. The flax fiber composites strongly affected by water aging than glass fiber composites. Water aging was conducted at 300ºC and glass fiber composite's tensile modulus and maximum stress were slightly affected it was decreased by 37% of modulus and 34% by ultimate stress. In the case of saline-treated flax fiber composite, the modulus was reduced by 9%. It was noticed that the physicochemical with mechanical modifications are important factors while gone with this kind of water immersion for mechanical properties [**5**] have studied the effect of water aging on their mechanical properties. The variation in bending moduli of composites from one to four % due to the different water aging up to four days' immersion of water, which may cause the swelling of the work piece. However, the better findings, they keep the underwater immersion up to 180 days. This property increases for unaged fiber composites with a small crack. The explosive growth of composite material products in the world with different applications, especially flax fibers are promising materials for structural, automotive, mechanical and consumer applications. With the small introduction about the flax fiber composites and their works, help us to deep study of understanding about the works carried out in past and future, supports us to give the idea to make the reports

as different headings and perform and evaluate the study. According to the different headings in various fields of work are presented as follows. These are some of the statements of different novel approaches of flax fiber-reinforced composites with various analyses for detailed study with the concentration on the desired area, with a variety of functional and some other applications of natural fiber-based composite materials especially flax fiber composites.

Structural analysis of flax fiber reinforced composite

The structural analysis of the flax fiber has been analysed in this section. The flax fiber composites were fabricated with polypropylene and epoxy composites for simulation analysis. The moulded model is considered with tinned damage mechanics [**6**] made a discussion about crack initiation to breakage with non-elastic tensile behaviour of these fibers mainly seen in the bundle zone of the interfaces which have the first-class relation during the failures. The isentropic hardening law states the elastic property of nonlinear tensile stress-strain curves up to ultimate strain as an important factor for the application-oriented utilizations the flax fiber is used more than other fibers in hybrid structure for different engineering structural applications. Deformability of nonwoven flax fiber composites was studied [**7**]. Finding advanced products using composites is widely grown with the impact of the materials in the lifecycle in the environment. The nonwoven fabric forming which depends muscularly on the fiber density of fabrics and blank holder pressure. This is responsible for structural based application this is due to the specific behaviour of non-woven fabric modelling and its testing day today purposes. Different plant fiber has differences in structures and morphologies [**8**]. Sisal fiber and flax fiber was compared for the tensile modulus and it is inferred from the experimental results that flax fiber is having more modulus than that of sisal fiber. It is obtained that mostly for short fibers the tensile modulus will be delicate. In study on assessment of 3D moisture diffusion parameters on flax/epoxy composites, [**9**] have studied the experimental and analytical parameter of moisture diffusion to quasi- unidirectional and twill flax fiber reinforced epoxy composite. The morphology and anisotropy study of flax reinforced composite reported mainly about the relationship between the effects of moisture with aging of fiber. Using unidirectional flicks model as a predictor of property in the three different aging conditions, they suggested the direction of the fiber is more responsible for the water absorption of the fiber. [**10**] have investigated fiber-matrix interface adhesion of flax fiber composites. Fiber sizing is only the variable, one with sizing and one without sizing and compared flax and carbon fiber laminates [**11**]. Natural fibers like flax have good interface between the matrix and reinforcement it results in the morphological and good damage resistance towards the failures hence they can be used to produce good component for structural loading bearing material compared to the synthetic fiber. This above evaluation of structural analysis of flax and their constituent's fibers can have very less amount of implementation only. This is due to the less life cycle environment of the fiber and more amount of pressure fixed environment also in the some morphological and aging of fibers due to damage are some of the highlighted areas of these results. **Table 1** shows the structural applications of flax fiber with different studies by the researchers.

Table 1. Structural applications of flax fiber.

Ref. No	Type of structur		Method of fabrication			Mate (Fabric)	Whiskers	Flakes	Property Evaluated		
	Experimental Model	Simulation model	Compression Moulding	Bag Moulding	Layup methods				Tensile Strength	Impact Strength	Hardness
1		✓	✓				✓		✓		
2	✓					✓	✓			✓	
3	✓			✓	✓			✓	✓		✓
4		✓			✓	✓				✓	
5		✓	✓			✓			✓		✓
6	✓				✓	✓			✓	✓	✓

Mechanical property evaluation and its characterization

In the case of natural fibers, the water absorption and water saturation does not humiliate the monotonic tensile strength of flax-epoxy composites. This leads to an increase in the fatigue strength for a high number of cycles this will responsible for the significant increase of damping ratio, decreases with the dynamic elastic modulus about 50% at 70º C hydrothermal conditions. It exhibits diffusion of kinetic one-dimensional fickian behaviours in the composites [**12**] made a comparison between the studies about the glass with flax fiber in-plane shear behaviour of flax/epoxy and glass/epoxy uni-directional laminates and reported due to increasing use of flax fibers in the polymers composite, the flax reinforcement is considered as an alternative to glass fibers. This is about the low failure strain of flax composites shows that 2% strain limit must be chosen for a suitable comparison of flax and glass composites shear strength. Due to the microstructure, flax fiber shows a clear anisotropy that considered a drawback for composite reinforcement. The shear property of the flax fibers identified using a model formation with back-calculation techniques evaluated the study to find out the micro bond test with interfacial bonding and shear strength of this composite which has low shear strength due to this property. However, this will control the residual thermal stress responsible for hydrogen bonding. The higher shear strength improves the practical adhesion which is mainly seen by Van der Waals bonding structure among that thermoplastic polymers are used for manufacturing [**13,14**] examined the mechanical properties of impregnated yarns or fabrics with multi-scales. The alignment with natural Fiber is more difficult than with continuous synthetic fibers. The tensile result of this flax

Fiber yarn was very good while compared with impregnated fabrics this is due to the waving methodology and location of Fiber within the constraint. Here in this paper they also made micrological studies through the Scanning Electron Microscope (SEM) image for both single and twisted yarn. Then they concluded that the difference in their density shows various levels of strength to the Fiber, high twist increases the internal stress of the yarn this influences the mechanical behaviour of the Fiber. Mechanical and fracture mechanical behaviour of composites reinforced with unidirectional aligned flax Fibers was experimentally investigated. The main point here is to determine the crack paths in the fatigue loading conditions to find the stress intensity factor. They suggested two approaches on the different loading directions of fiber. Both the different orientation gives enhanced results that flax fibers were reinforced by the composites, which are semi-finished products such as yarn and twisted yarn [**15**]. Traditional fiber such as E-glass one can be used with vegetable fibers, such as flax, hemp or jute in composites make it possible to consider hybridization as an intermediate step for the substitution. By changing the sequence of the fiber produces composites with the predominant tensile properties which can have used for the evaluation of the hybridization effects. Another parameter that is important to evaluate the impact resistance of a laminate called a damage degree, which means the ratio between the absorbed energy and incident energy. The ternary hybridization of carbon, basalt and flax Fibers fabricated by using hand lay-up techniques to make the stacking with help of vacuum bag molding. The study subjected to the tensile, flexural also with interlaminar shear with different energies. The pure form of Fiber has less property while comparing with the others due to the proneness but the sequential enhancement of the fiber laminates good properties with all of the modifications [**16**]. Mechanical properties of flax-Fiber-reinforced epoxy composites were investigated. The damage condition of the specimen was observed through SEM micrograph. The repeated load and unload given to the composites and was progressively monitored with the increasing load. The loading intervals of this Fiber can consider as the chief parameter of this computational model of research analysis that produces a good identity for flax epoxy [**17**]. The stiffness of the different plant fibers exposed to monotonic loading, low-cycle, repeated progressive loading, and fatigue loading. For single loading conditions, a low strain is observed, the low cycle fatigue condition improves up to 20% with degradation this made the superior quality over glass fiber. This non-linear transformation of fiber will produce the competing low magnitude for mechanisms in composites [**18**]. There will be a need should take for plant fiber when designing for structural applications. The impact strength of carbon and glass fiber composites was studied by using two different impact test methods Drop-weight and Charpy test [**19**]. The ductility index decreased as the composite thicknesses increased were noticed. Carbon and glass fiber composites have been the most studied under Impact loading. The impact resistance of natural fiber increases because of the impact force and Hertzian forces were slightly a considerable factor, also the ductility decreases due to the increasing thickness of the composite. They reported that thickness as a considerable factor responsible for the property changing of composites, larger thickness possesses more energy than the smaller one. [**20**] have studied the behaviour of flax fiber in the industrial applications. This study utilizes the unidirectional reinforcement of fiber in thermoset. These results demonstrate that the glass fiber reinforced composites can be replaced with the of bio fiber materials in vehicle applications. This result showed that higher volume content has low durability and the transverse test results in improved property. The microscopic image shows this is due to the low-stress levels in the adhesion in the matrix interface of mechanical property. [**21**] experimentally studied on the tensile properties of flax fiber/epoxy composite laminates by in the double cantilever beam test. The results revealed that cotton thread stitch does not necessarily improve the interlaminar fracture toughness of the composite, however, stitching with flax yarn can improve it by at least 10% at the lowest stitch fiber areal fraction. The imperfection was due to the stitching of the materials, but the tensile performance of flax fiber may raise at least percentage. Greater energy dispersion in the laminates helps to understand the fracture toughness of stitched to tolerate in the tome of crack birding and to produce support to the high tensile loading conditions [**22**] have studied the dynamic mechanical properties and wettability of the flax and basalt fiber reinforced epoxy composite. The composite was fabricated by stacking of ten layers of flax fiber and other with replacing the first and last layer with the basalt fiber to establish a hybrid epoxy composites and Analysis of variance (ANOVA) was performed to check the influence of two parameters like aging condition and material for the consideration of surface properties and mechanical properties. It is observed from the work that interfacial adhesion is comparably good for flax-basalt composite and wettability property is being affected after 15 days of aging. [**23**] investigated the neat flax fiber as reinforcement to the newly synthesized resin from lactic acid, alkyl alcohol, and pentaerythritol and basalt fiber was added to it for hybridization. Both composites were compared for their mechanical and thermal properties. Dynamic Mechanical Analysis Test (DMAT) and Thermo gravimetric analysis (TGA) were done for thermal analysis of the prepared composites. Fiber loading happens with varying fiber weight percentages like 40%, 50%, and 60%. It was obtained from the experiment that the hybrid flax basalt reinforced composite showing enhanced mechanical as well as thermal properties after aging with flax fiber combination [**24**] flax, sisal and jute reinforced composite material were considered as the perfect alternative for the glass fibers. These natural fibers have good mechanical properties rather than glass fibers

but they suffer a disadvantage of absorption of water, which results in a reduction in the mechanical properties. When the temperature increases more than 55^0C it showed major negative effects so it is recommended to utilize the hybrid composite for lesser temperature application. Aging behaviour of flax fiber composite on their mechanical properties was reported [**25**]. The major effects due to the environment manipulate of the Fiber is mainly squabble about the mechanical stress, temperature and moisture, this study helped to understand the behaviour of flax with lactic acid for different percentage. Finally, stated that under creep load condition, the elastic property decreases also due to the strong synergic effect and because of water immersion leads to losses in the stiffness. When compared to other fibers flax could have minimum environment cracking this will show a long time with the stand of Fiber in different mechanical loading conditions. The physical properties of two bio composites, flax/bio-based epoxy and flax/Polyurethane were investigated and compared [**26**]. The post-cured bio composites were taken for the curing process with 90% relative humidity at 30^oC temperature for a period of 720 hours. Plasticizing effect due to the water took long time for flax/polyurethane composite than for flax/bio-based epoxy composites with the mechanical properties enhanced due to the stronger interface between the hydroxyl groups of the fibers. The stiffness analysis on the second layer of the flax nano cell walls has to be identified for the technical measurement of nano indentation on the cell wall in the cross-section of the fiber has more interface cohesion [**27,28**] have studied the mechanical behaviour of flax fiber in yarn cloth and laminate form were investigated for their density, tensile behaviour, cross-sectional area and fiber volume fraction. Individually all the parameters were investigated. Their overall work was aimed to understand the influence of flax fiber for reinforcement with the composite and inferred from the work that shape of the fiber is to be elliptical. Therefore, that it gives good mechanical performance [**29**] tensile and flexural properties of mat and flax yarns was measured with different damage modes. For the evaluation to reduce the propagation of crack while the load applied on the fiber the mat can give good result damages due to the lack of adhesion between the materials. Mechanical performances of flax fiber with various combinations by different researchers were tabulated in **Table 2**. The mechanical properties are most widely considered and highly dominant property ever in all the fields of applications, in flax fibers too here the different stands of the properties like fickian behaviour and stress due to hydrogen bonding between the materials. With different loading conditions with more effect due to the Hertzian, force some of the studies with the basic mechanical properties with different loading conditions also discussed in this section.

Table 2. Mechanical behaviour of flax fiber.

Reference No	Type of approach		Optimal Combination				Mate	Whiskers	Flakes	Property Evaluated /Characterization			
	Experimental Model	Simulation Model	Flax/Epoxy	Flax/Glass	Glass/Epoxy	Flax/other fibers				Tensile/Shear behaviour	Impact/Stress behaviour	Hardness/ Fatigue behaviour	SEM/Others
7	✓		✓					✓					/✓
8		✓	✓		✓			✓		/✓			
9	✓					✓				/✓			
10	✓					✓	✓			✓/	✓/	✓/	✓/
11	✓					✓		✓			/✓		
12	✓			✓			✓			/✓			
13	✓		✓						✓	✓/	✓/	✓/	✓/
14		✓	✓				✓					/✓	
15		✓				✓		✓			✓/		
16	✓				✓	✓	✓						/✓
17		✓					✓	✓		✓/			
18		✓				/✓	✓						
19		✓				/✓		✓			✓/		
20		✓		✓						✓/	✓/	✓/	
21	✓					✓		✓		✓/	✓/	✓/	
22		✓				✓							/✓
23		✓		✓			✓			✓/	✓/	✓/	✓/
24	✓	✓					✓			✓/			
25	✓					✓	✓		✓	✓/✓			

Novel performance of flax fiber composites

The failure criterion of flax fiber reinforced with the matrix of polypropylene composite, which is treated under different water-absorbing loading conditions were reported [**30**]. With the help of the stress-strain ratio they determine the failure analysis but this failure analysis can have applied for the woven fabricated natural fiber which has the unique property of eliminating the path dependency effect. The influence of moisture content of environment during the development of new cobalt-free up matrix reinforced with flax fibers. The moment of crack initiation was studied under the humid condition to characterize the interfacial shear stress by using differential scanning calorimetry and x-ray photon spectroscopy. The fiber reinforced in longitudinal direction composite has less strength and more moisture absorption which causes degradation of fibers. This exhibits the low curing rate in the presence of water with high humid conditions [**31**] investigated the several compositions of flax fibers which have made them chiefly eye-catching to the automobile industries. Synthetic fibers like glass fibers and carbon fibers have been utilized as reinforcements in composite materials of various automotive components. The response surface methodology (RSM) helps to study about the moisture processing content to analysis the curing temperature, flexural strength and modulus, ultimately it is optimized by using ANOVA software to find the better results. With the assistance of Risk and Safety Management (RSM) design 20% of moisture content, at 170ºC with curing time for 180 seconds can produce the better optimized value for highest yield flexural strength and modulus. In the amendment of ANOVA, we easily determine the correct form of processing conditions reduced by cost with material saving time [**32**] have studied the mechanical properties of unidirectional flax fabric polyamide composites fabricated using hot press moulding. The various process parameters, and composite constituents were studied by different configuration for this unidirectional fiber. Three temperatures value are combined with a three-pressure level simultaneously. This configuration leads to the young's modulus value of 36 GPa and tensile strength of 174MPa, the porosity study is carried out by measurements of a differential calorimeter and rheological methods. The point of protection from the environment with the reduced use of plastic-based and petroleum products. The temperature with a standing capacity of these natural fibers showed the good impregnation. The speedy growth in research and modernism in the natural fiber composite area has been found recently that improvement in the mechanical properties for the wide range of applications. By Comparing the other materials attention is justified, such as synthetic fiber composites [**33**]. Because of the low environmental impact, cost and support their potential across the applications for specific uses the low density of this fiber shows the dramatic change in fire retardancy, leads to the positive move in this area of research and extended application [**34**] experimentally analysed the data of the flexural strength of the fiber which deviate negatively from the hypothetical calculation, exhibited lower values than the predicted ones. In adding together, the mechanical testing indicates the judo's choice and potential behaviour of characterized fiber to produce new hybrid composites used in an application where stiffness and vibration damping are critical importance to the improved damping properties of the fiber. The bacterial cellulose was one of the effective binders to produce rigid and robust natural fiber nonwoven without the need for polymer binders [**35**], recently reported in an invention of thermally bonding of materials. In the case of lower thicknesses of flax, fiber has poor binder but it is good in efficiency while comparing with highly compacted fiber. Since the fiber binder, exhibits the poor tensile property and it is submerged in the water for 21 days the nano cellulose stable in water. The natural fiber has an environmentally sustainable property that makes the attention towards application-oriented inventions, studying the flexural, impact and some other mechanical properties with the disturbance of shock wave tube test to study the behaviour on shock wave and the failure analysis [**36**]. Flax fiber cross-ply reinforced polypropylene has greater shock wave proof observances up to 0.6 MPa than the unidirectional fibers, this may implant in the shock-based replacement in automobile used applications. Bidirectional flax fabric as a primary layer with basalt mat as outer secondary layer to fabricated a flax reinforced epoxy composite [**37**]. This composite is kept in a salt-fog surrounded condition. A 3D microscope was used to analyse the fracture surface of the samples tested for water absorption and observed aging resistance was also improved when hybridization of basalt fiber to flax fiber composites. [**38**] have studied the overview of basalt fiber reinforced composite to overcome the demerits like poor interfacial adhesion, bad thermal resistivity, and poor resistance to environment. The poor interfacial bonding and thermal stability are bottlenecked in composite materials. The overview from the work says usage of basalt fiber has provided environmental and cost-effective than flax fiber. New composites with L-Poly Lactic Polybutylene succinate (PLLA PBS) flax bio composite, which is considered as a fully biodegradable composite. Due to the addition of flax reinforcement, there is an increase in mechanical properties and recycling after three to four cycles, the degradation decreases because of the flax element present in the PLLA PBS bio composites [**39**]. Study on cement stabilised soil, focuses on reinforcing flax fiber to cement-based material to improve the tensile strength and the toughness of the product material. The comparison made for the addition of flax by casting and extrusion process reported the improvement in properties of flax reinforced cement soil as composite [**40**]. The tow behaviour-based approach was used for investigation of the dependent statistical parameters on factors including sample size and selection, method of

experimental data analysis. The elementary filaments in bundles were held together by a pectin-based interface and the more attention received by the fibers are elementary fibers and technical fibers. Flax filament will have higher strength and strains compared with the other fiber [**41**]. Study on damage mechanism by acoustic emission [**42**] investigated about the acoustic properties, which need to be improved for that purpose there is a necessity of very large porosity volume fraction roughly up to 60%. When increasing the porosity level from 5 to 60% tensile strength drops drastically. It was inferred that these fabricated composites definitely would have good mechanical and acoustics properties. The numerical model accounting for the heterogeneous mechanisms involved during aging such as water diffusion and the resulting swelling and plasticizing of polymers are implemented [**43**]. The purpose of this paper is to present the development and the results of the numerical model that enable to predict the long-term properties of bio-composites. With various fibers, contents and different hydrothermal aging condition [**44**] the good elongation property of the flax fiber can help to implement it as useful films in the packaging industry the nanofilm obtained through 15 days magnetic stirring and the microscopic observation. Transmission electron microscopy (TEM), Scanning Electron Microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), Differential scanning calorimetry (DSC), (Product Object Model) POM are the various study reported by numerous researchers for the identification of different novel performance of under various microscopic observations. **Table 3** describes the novel performance of flax fiber as explained by various researchers. The absorbing quality of the flax fiber is the unique property that represents various levels and it involves and takes over the introduction of new novel research. In this section discuss the novelist areas which improve the thrust of the research in the field of acoustic, X ray-photon spectroscopy with some of the microscopic depiction for morphological studies.

Application oriented flax fiber composites

The flax fibers, hemp fibers have been used increasingly as reinforcement in polymer composites because of its enormous stiffness like glass fibers [**45**]. In an overview of the technical arguments given, they possessed high damping properties for both the flax and hemp-based composites. Since 1960s carbon fiber composites have been used later in the 1970s they have not been noticed as a breakthrough in new material until their appearance in sporting goods by the general public based on sporting goods and aerospace application the visibility of composites material has not been limited. In 1960, s designers discovered the potential called fiberglass already. In 1948 the designers designed the furniture which was designed for improving stability and different humid conditions responsible for the artisanship of consumer goods lead to automotive and aero applications. In the alternative with the synthetic, this piece of writing presents the characterization of an eco-composite consisting of a thermoplastic matrix reinforced by flax fibers by considering its mechanical properties. By discussing uniaxial tensile loading and their mechanical behaviours by a different configuration of specimens were tested. The technique that has been often used for the identification and characterization of micro failure mechanisms in composites is the acoustic emission (AE) technique. Matrix cracking and matrix /matrix friction are several phenomena that can be distinguished. The relation between the mechanical effects in the acoustic emission can be reviewed with variable sentry functions. [**46**] have studied the fatigue behaviour of flax fiber-reinforced composites. They are used to replace their conventional, synthetic counterparts slowly. A quantity of an interesting application as follows, printed circuit board substrates based on bio-based materials have been recently proposed to produce and tested by quite a lot of researchers. To specify the applications in electronic ways, some of the functional units of $1m^2$ of printed circuit boards. Subtracts used in this comparative study as cradle to the gravity of life cycle assessment with the incineration used in the recovery of energy as the end of life as a scenario. In addition, its durability improves the application particularly in automotive oriented applications. The bio-based PCB can have good lifetime as 13-15 years it also

Table 3. Novel performance of flax fiber.

Reference No	Novelty analysing methodology		Nature of the fibre		Plasticizing / acoustic properties	Moisture absorbing/ shock proof quality	Software Optimization Techniques/ thermal Aging	Microscopic Depiction/property Enhancing quality
	Experimental Model	Simulation model	Treated	Un-treated				
26	✓		✓			✓/		/✓
27		✓	✓		/✓			✓/
28	✓			✓			✓/	
29	✓			✓				/✓
30		✓		✓				/✓
31	✓					/✓		✓/
32	✓		✓					✓/
33		✓		✓		/✓	✓/	
34	✓		✓			✓/		✓/
35		✓	✓				/✓	
36	✓			✓	/✓			✓/
37	✓			✓		✓/		✓/
38		✓	✓					/✓
39	✓		✓		/✓	✓/		
40	✓			✓	✓/		/✓	
41	✓			✓			/✓	✓/

cost-effective comparing with glass fiber composites [**47**] have studied the damage tolerance of the laminated flax fiber using the four-point bending, and dropping the weight by impact resistance to act as a hindrance to the crack propagation in the work piece surfaces. The tensile property of the laminates was monitored with peculiar failure modes in the hybrid laminates. The hybridization of carbon with flax gives better impact performance, also maintain satisfactory flexural stiffness compared with carbon laminates, the propagation of crack mostly due to the delamination in the hybrid stacking sequences. There is an increasing interest in the production of laminates in recent days from the waste gained from the industrial or agricultural process, this kind of replacement will lead to environment-friendly manufacturing in the field of the composite as well cost-effective since there is the utilization of waste [**48**]. By lifecycle, analysis (LCA) it is recommendable that both matrix and fiber obtained from by-products may be fully used as a replacement for artificial materials. This work fully revealed the possibility of getting both matrix and reinforcement material from the renewable resources [**49**] have studied the characterization and evaluation of the fatigue behaviour of flax epoxy composites. In the composites industries the use of flax fibers is increasing, thanks to their advantageous characteristics such as good acoustic and thermal insulation and renewability. The flax fibers reinforced composites were made by complying with a thermoset epoxy matrix with nine flax textiles configuration.

The hydrothermal aging of natural fiber composites using extrusion/injection molding techniques with modification of PLA and PLA/flax fiber was studied [**50**]. The numerical model was compared with experimental results were limited at 300°C and but significant result at 500°C. [**51**] the growing of flax community around the world which has a variety of applications exist in the plant composite study for the manufacturing-oriented applications also with the different orientation of fibers with some mechanical properties [**52-54**]. Regarding the application of flax fibers has various diversions with different proposals due to the stiffness and controlled crack propagating property it is used in sports goods manufacturing, also in the PCB boards production [**55**]. The light weight performance of flax fiber and their unique property of shock absorbing capability produce an additional support for flax fiber composite to transform as a commercial product [**56,57**]. Requirement of new material for the world is necessary to reduce the environmental hazard, the introduction of flax fiber based natural fiber composite has the ability to build eco-friendly products in all areas. The highlighted property was the fabric and easy texture changes of fiber used in the textile industry as mixing with linen cotton cloths [**58**]. In **Table 4**, various applications of flax fiber composite were tabulated separately.

Table 4. Various applications of flax fiber.

Reference No	Type of combination			Some other useful Applications	Electrical applications	Marine based Applications	Aerospace Applications	Acoustic Applications	Textile Applications
	Flax	Synthetic fibre	Other Natural Fibre						
42	✓	✓		✓					✓
43	✓			✓				✓	
44	✓	✓			✓				
45	✓	✓				✓	✓		
46	✓		✓					✓	
47	✓	✓		✓	✓		✓		✓
48	✓	✓	✓			✓		✓	
49	✓			✓					✓
50		✓			✓			✓	
51	✓		✓				✓		
52	✓	✓						✓	
53		✓		✓			✓		
54	✓	✓				✓			✓
55	✓				✓				
56	✓	✓				✓	✓	✓	
57	✓	✓				✓	✓	✓	
58	✓	✓							✓

Conclusion

Structural analysis of flax fiber reinforced composites

- Non-elastic and absolute tensile property of the flax fiber made into many of the structural applications in the form of beams and columns as construction parts, the energy absorption quality of this flax and interfacial bonding this is the best replacement for carbon fiber in all the structural fields.
- In most of the countries, natural fibers are expansively accessible with low-density and biodegradable, renewable, hazardous and non-abrasive properties.
- Flax Fiber also has the excellent possible grouping of low cost, lightweight and high strength and stiffness for structural application with different lengths of the fiber has a good length to diameter ratios, among all the natural fibers this was the best also a better replacement for glass fiber structural applications.

Mechanical property evaluation and its characterization

- Good tensile, impact, flexural, wear, shear and some other mechanical behavior of flax fiber made this one as distinct achiever over other natural fibers.
- The unique intrinsic property of flax fiber like biodegradability, environment friendliness, low stiffness, good stress intensity factors during fatigue loading conditions.
- Interlaminar shear made the flax fiber the strongest replacement for especially glass and other synthetic fibers.
- All types of natural polymers are good in the mechanical areas while considering the water adsorption the fiber moisture decrease the properties this will see in the SEM and other characterization of this kind of mechanical behavior.

Novel performance of flax fiber

- Novelty is the property always shows and produces single identification of the fiber the water-absorbing quality was less for flax and but this will reflect in the critical mechanical loading conditions.
- Acoustic and thermal behavior of flax fiber was good and it has more intensity to withstand in higher temperatures than other natural fibers.
- The origin of the plant it has their quality by nature as interfacial strength, fiber orientation, and dispersion made a dramatic change in all of the areas in the thermoset and thermoplastic flax polymers due to the better cell wall thickness in different working conditions.
- Filaments also as a numerical model to state different hydro aging of excellent quality of withstanding for flax fiber.

Application of flax fiber composites

- The fabrication of new fibers especially in the part of the natural availability of this fiber to implement in any one of the application-oriented works.
- In the era of composite materials, the usage of carbon fibers was more in all fields. This is because of its unique withstanding quality in all types of conditions flax fiber possessed good damping property than carbon or glass fibers.
- The Cradle to grave assessment we can use this flax for PCB instead of silicon boards. The crack withstands and energy absorption property of flax enhances the usage for LCA in the replacement as artificial materials.
- In addition, texture property of flax's major application in the textile fields. In some of the Asian countries in the glass manufacturing industries, they reduce the usage of Polyolefin has successfully replaced by flax due to its unique unidirectional strain in the time to produce a good design.

The percentage of utilization of fiber relevant to their fields. Similarly, we convert the amount of usage into a percentage for each content. From the reference of pieces of literature, we studied the maximum of papers and works related to mechanical property and their performance in various areas as a property evaluation and analysis as 36%. The next to this a novel and different testing study performance holds 30% to the total 100% stag this kind of approach has to be the difference in the field of emerging research. In the end of this review study, the structural studies have less exposure as 16% the only minimum of work done on this vicinity, with the extend the flax fiber combinational synthetic fibers are used as very less as 18% of work only done in that application orient purposes. Utilization of flax fiber in area of application-oriented products reduces the usage of synthetic fiber. Flax fibers are cost effective and they are potential replacement for glass fibers, by changing the orientation of flax fiber shows improved performance and strength. Flax fiber with bio-degradable polymer matrices provide promising application purposes. There is a wide opening for flax fiber in the shock absorbing capability in the time of applying sudden loading on the materials and low velocity related applications. The major limitation of flax fiber as reinforcement in the composite for incompatibility results is poor fiber arrangements, less interfacial bonding between fiber/matrices and manufacturing methods. The appropriate selection of methods and chemical treatment increases the application of composite in various fields. Future work to be done with flax fiber is potentially more, by considering the environmental assessment, chemical treatment and further improvements in resistance to moisture absorption. Additionally, proper utilization of tribology modifications and novel manufacturing methods used is need for further development for future application.

Keywords

Flax fibers, hybrid composites, novel techniques, mechanical properties, structural applications, application of fiber.

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References

1. Woigk, W.; Rion, J.; Hegemann, D.; Fuentes, C.; Van Vuure, A. W.; Masania, K.; Dransfeld, C.; Proceedings of the 17th European Conference on Composite Materials, European Society for Composite Materials, **2016**.
2. Madsen, B.; Aslan, M.; Lilholt, H.; *Composites Science and Technology*, **2016**, *(8) 123*,151.
3. Bourmaud, A.; Le, Duigou A.; Gourier, C.; Baley, C.; *Industrial Crops and Products*, **2016**, *(1) 84*,151.
4. Apolinario, G.; Ienny, P.; Corn, S.; Léger, R.; Bergeret, A.; Haudin, J.M.; Effects of water ageing on the mechanical properties of flax and glass fiber composites: Degradation and reversibility. In Natural fibers: Advances in science and technology towards industrial applications, **2016**, *(23)58*, 183.
5. Cheour, K.; Assarar, M.; Scida, D.; Ayad, R.; Gong, X.L.; *Composite Structures*, **2016**, *(15) 152*, 259.
6. Sliseris, J.; Yan, L.; Kasal, B.; *Composites Part B: Engineering*, **2016**, *(15) 89*, 143.

7. Omrani F.; Wang P.; Soulat D.; Ferreira M.; Ouagne P.; *Composites Part B: Engineering*, **2017**, *(1)116*, 471.
8. Tanguy M.; Bourmaud A.; Baley C.; *Materials Letters*, **2016**, *(15) 167*, 161.
9. Saidane E.H.; Scida D.; Assarar M.; Ayad R.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 80*, 53.
10. Vanwalleghem J.; De Baere I.; Huysman S.; Lapeire L.; Verbeken, K.; Nila A.; Vanlanduit S.; Loccufier M.; Van Paepegem W.; *Polymer Testing*, **2016**, *(1) 55*, 269.
11. Berges M.; Léger R.; Placet V.; Person V.; Corn S.; Gabrion X.; Rousseau J.; Ramasso E.; Ienny P.; Fontaine S.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 88*, 165.
12. Baley C.; Kervoëlen A.; Le Duigou A.; Goudenhooft C.; Bourmaud, A.; *Materials Letters*, **2016**, *(15) 185*, 534.
13. Le Duigou A.; Bourmaud A.; Gourier C.; Baley C.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 85*, 123.
14. Omrani F.; Wang P.; Soulat D.; Ferreira M.; *Composites Part A: Applied Science and Manufacturing*, **2017**, *(1) 93*, 72.
15. Keck S.; Fulland M.; *Engineering Fracture Mechanics*, **2016**, *(1) 167*, 201.
16. Nisini E.; Santulli C.; Liverani A.; *Composites Part B: Engineering*, **2017**, *(15) 127*, 92.
17. Mahboob Z.; El Sawi I.; Zdero R.; Fawaz Z.; Bougherara H.; *Composites Part A: Applied Science and Manufacturing*, **2017**, *(1) 92*, 118.
18. Shah D.U.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 83*, 160.
19. Wang W.; Chouw N.; Jayaraman K.; *Journal of Reinforced Plastics and Composites*, **2016**, *(17) 35*, 1277.
20. Santamala H.; Livingston R.; Sixta H.; Hummel M.; Skrifvars M.; Saarela O.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 84*, 377.
21. Ravandi M.; Teo W.S.; Tran L.Q.; Yong M.S.; Tay T.E.; *Materials & Design*, **2016**, *(5) 109*, 659.
22. Fiore V.; Calabrese L.; Di Bella G.; Scalici T.; Galtieri G.; Valenza A.; Proverbio E.; *Composites Part B: Engineering*, **2016**, *(15) 93*, 35.
23. Bakare F.O.; Ramamoorthy S.K.; Åkesson D.; Skrifvars M.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 83*, 176.
24. Saidane E.H.; Scida D.; Assarar M.; Sabhi H.; Ayad R.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 87*, 153.
25. Regazzi, A.; Corn, S.; Ienny, P.; Bergeretn, A.; *Composites Part A*, **2016**, *130*, 300.
26. Cuinat-Guerraz N.; Dumont M.J.; Hubert P.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 88*, 140.
27. Bourmaud A.; Malvestio J.; Lenoir N.; Siniscalco D.; Habrant A.; King A.; Legland D.; Baley C.; Beaugrand J.; *Industrial Crops and Products*, **2017**, *(1) 108*, 1.
28. Blanchard J.M.; Sobey A.J.; Blake J.I.; *Composites Part B: Engineering*, **2016**, *(1) 84*, 228.
29. Wang, W.; Lowe, A.; Kalyanasundaram, S.; *The International Journal of Advanced Manufacturing Technology*, **2016**, *(4) 87*, 103.
30. Fuentes C.A.; Ting K.W.; Dupont-Gillain C.; Steensma M.; Talma A.G.; Zuijderduin R.; Van Vuure A.W.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 84*, 209.
31. Rasyid, M. A.; Salim, M. S.; Akil, H. M.; Ishak, Z. A. M.; *Procedia Chemistry*, **2016**, *19*, 469.
32. Lebaupin Y.; Chauvin M.; Hoang T.Q.; Touchard F.; Beigbeder A.; *Journal of Thermoplastic Composite Materials*, **2017**, *30(11)*, 1503.
33. Pickering K.L.; Efendy M.A.; Le T.M.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 83*, 98.
34. Le Guen M.J.; Newman R.H.; Fernyhough A.; Emms G.W.; Staiger M.P.; *Composites Part B: Engineering*, **2016**, *1 (5) 89*, 27.
35. Fortea-Verdejo M.; Lee K.Y.; Zimmermann T.; Bismarck A.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 83*, 63.
36. Huang K.; Rammohan A.V.; Kureemun U.; Teo W.S.; Lee H.P.; *Composites Part B: Engineering*, **2016**, *(1) 102*, 78.
37. Fiore V.; Scalici T.; Calabrese L.; Valenza A.; Proverbio E.; *Composites Part B: Engineering*, **2016**, *(1) 84*, 258.
38. George M.; Chae M.; Bressler D.C.; *Progress in Materials Science*, **2016**, *(1) 83*, 1.
39. Bourmaud A.; Åkesson D.; Beaugrand J.; Le Duigou A.; Skrifvars M.; Baley C.; *Polymer Degradation and Stability*, **2016**, *(1) 128*, 77.
40. Khelifi H.; Lecompte T.; Perrot A.; Ausias G.; *Materials and Structures*, **2016**, *(4) 49*, 1143.
41. Lamon, J.; R'Mili, M.; Reveron, H.; *Journal of Materials Science*, **2016**, *(2) 56*, 8687.
42. Monti A.; El Mahi A.; Jendli Z.; Guillaumat L.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 90*, 100.
43. Deng Y.; Paraskevas D.; Tian Y.; Van Acker K.; Dewulf W.; Duflou J.R.; *Journal of Cleaner Production*, **2016**, *(1) 133*, 427.
44. Sarasini F.; Tirillò J.; D'Altilia S.; Valente T.; Santulli C.; Touchard F.; Chocinski-Arnault L.; Mellier D.; Lampani L.; Gaudenzi P.; *Composites Part B: Engineering*, **2016**, *(15) 91*, 144.
45. Puglia D.; Sarasini F.; Santulli C.; Kenny J.M.; Manufacturing of natural fiber/agrowaste based polymer composites. In Green Biocomposites, **2017**, *(3) 69*, 125.
46. Bensadoun F.; Vallons K.A.; Lessard L.B.; Verpoest I.; Van Vuure A.W.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 82*, 253.
47. Oliver-Ortega H.; Granda L.A.; Espinach F.X.; Delgado-Aguilar M.; Duran J.; Mutjé P.; *European Polymer Journal*, **2016**, *(1) 84*, 481.
48. Pil L.; Bensadoun F.; Pariset J.; Verpoest I.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 83*, 193.
49. Merotte J.; Le Duigou A.; Bourmaud A.; Behlouli K.; Baley C.; *Polymer Testing*, **2016**; *(1) 51*, 174.
50. Regazzi A.; Léger R.; Corn S.; Ienny P.; *Composites Part A: Applied Science and Manufacturing*, **2016**, *(1) 90*, 559.
51. Chaudhary V.; Bajpai P.K.; Maheshwari S.; *Journal of Natural Fibers*, **2018**, *15*, 80.
52. Habibi M.; Laperriere L.; Lebrun G.; Toubal L.; *Composites Part B: Engineering*, **2017**, *(15) 123*, 165.
53. Prasath, K.; Arun, B.; Radha Krishnan; *International Journal of Mechanical Engineering*, **2013**, *(24) 12*, 279.
54. Prasath, K.A.; Amuthakkannan, P.; Manikandan, V.; Jegadeesan, R.; Selwin, M.; Novel topological approach in mechanical properties of basalt/flax hybrid composites, AIP Conference Proceedings, India, July 21-28, 2019.
55. Ramesh M.; *Progress in Materials Science*. **2019**, *102*, 109.
56. Prasath K.A.; Arumugaprabu V.; Amuthakkannan P.; Manikandan V.; Johnson R.D.; *Materials Research Express*, **2020**, *7*, 015317.
57. Prasath K.A.; Amuthakkannan P.; Arumugaprabu V.; Manikandan V.; *Materials Research Express*, **2019**, *6*, 115308.
58. Matykiewicz D.; Barczewski M.; *Composites Communications*, **2020**, 100360.