Woven Natural Fibre Polymer Composites

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These woven materials are flexible, able to be tailored to the specific needs and have better mechanical properties due to their weaving structures.

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1. Introduction

Woven polymer composites have excellent mechanical strengths, i.e., rigidity, strength, and dimensional stability compared to unidirectional fibre composites for a number of applications in fibre reinforced polymer composites. The development of appropriate reinforcement is crucial to the achievement of optimum mechanical properties, in particular in the manufacturing of hybrid composites using natural fibre, in any forms, with a view to the manipulation of final composite properties. In the case of hybrid woven composites, textile engineering concepts are used. This can be accomplished by using the correct yarn size, where the correct choice of yarn size is capable to provide optimum force value and strength to withstand the deformation of the woven fabric and the good mechanical properties of the composites[1]. In addition to the properties of matrix and yarn, the strength and hardness of woven fabric strengthened composites are determined by the structural parameters of materials, i.e., the fabrics counts and weave designs.

2. Applications of Woven Natural Fibre Polymer Composites

High strength synthetic fibres like Kevlar, carbon fibre, fibre-glass, Aramid and carbon nanotubes (CNTs) are commonly used in advanced composite structures as composite reinforcing materials. Nevertheless, the world is changing and green materials are in the vanguard due to the depletion and health concerns about inorganic materials, such as petroleum. In addition, the growing demand for natural fibre for composites has increased rapidly due to cost-effectiveness, low density, abundant, good thermal and insulating properties, renewability, biodegradability, high specific strength, etc. [2][3].

These successful benefits have stimulated the interest of numerous researchers in recent years in the development of natural fibres as reinforcement in polymer matrix composites such as kenaf fibre [4][5][6], oil palm fibre [7][8], sugar palm fibre[9][10], banana fibre[11][12], pineapple leaf fibre[13][14], flax[15][16], hemp[17][18], sisal[19][20], coir[21][22], jute[23][24], etc, as summarised in Table 4.

Table 4. List of reported study of natural fibre reinforced polymer composites.

Fibre Types	Matrix Type	Properties Remark	Ref.
Oil palm frond	Urea Formaldehyde	Composite with 50% of fibre showed higher flexural strength, modulus of electricity (MOE), and tensile strength of 1.43 MPa, 1248 MPa and 3.8 MPa, respectively.	[25]
Oil palm EFB	Polypropylene	Microwave-treated fibre-based composites showed improved mechanical and thermal properties. EFB fibres treated at 90 °C for 90 min were found to be suitable for better reinforcement into the composite in terms of mechanical, thermal, and crystalline properties. Moreover, onset degradation temperature and water absorption properties were also found to be changed apparently due to treatment.	[26]
Sugar palm	Unsaturated polyester	Increasing trends in the tensile strength, tensile modulus, flexural strength, and flexural modulus were shown in sugar palm yarn loadings of up to 30 wt%. However, maximum impact strength was achieved at 40 wt% of sugar palm fibre yarn loadings. Elongation at break increased with the increment of sugar palm yarn loading up to 50 wt%. The thermal stability of the composite decreased in accordance with onset and maximum temperatures, while the percentage of residue increased for higher fibre loadings	[27]

Fibre Types	Matrix Type	Properties Remark	Ref.
Sugar palm	Epoxy	Increasing flexural and torsion properties of the non-hybrid composite at fibre loading of 15 wt% were 7.40% and 75.61%, respectively. For hybrid composites, the experimental results revealed the highest flexural and torsion properties that was achieved at the ratio of 85/15 reinforcement and 60/40 for the fibre ratio of hybrid sugar palm yarn/carbon fibre-reinforced composites. The different ratio between matrix and reinforcement had a significant effect on the performance of sugar palm composites.	[28]
Kenaf	Epoxy	The kenaf composite was found to withstand a maximal temperature of 120 °C. The tensile and flexural strengths of the aligned kenaf composites (50 and 90 MPa, respectively) were three times higher than those of the commercialized Product T (between 39 and 30.5 MPa, respectively) at a temperature range of 90 to 120 °C.	[29]
Kenaf	Polylactic acid (PLA)	The acetylation treatment was effective for improving the performance of PLA/kenaf composites. This behaviour was found to relate to the surface cleaning of acetylated kanaf, in addition to the efficient modification of the hydrophilic characteristics of kenaf.	[30]
Banana fibre	Epoxy	The mechanical analysis indicated that 6% NaOH treatment with a two-hour immersion time gave the highest tensile strength. It was found that 6% NaOH treatment with a two-hour immersion yielded the highest interfacial shear stress of 3.96 MPa. The TGA analysis implied that alkaline treatment improved the thermal and heat resistivity of the fibre.	[31]
Banana fibre	Epoxy	The best mechanical performance was achieved in the composite specimen of 10 mm fibre length and 15% fibre loading.	[32]
PALF	Epoxy	The continuous and aligned fibres significantly increased flexural strength. Revealed by Weibull statistics, the PALF reinforcement, above 10–30 vol%, followed a linear increase to a value of flexural strength around 120 MPa.	[33]
PALF	Epoxy	It was found that the change in fibre orientations will have a great influence on storage modulus and loss tangent along with other mechanical properties investigated in this study, as the evidence from the table that maximum variance in storage modulus at frequencies of 0.1, 1 and 10 Hz were approximately 3.86, 4.26 and 4.23 GPa, respectively and the corresponding variance in loss factor values were 0.16, 0.12, and 0.09, respectively.	[34]
Flax	Epoxy	The unstitched and stitched flax composites showed that while delamination was not the predominant damage mode in both laminates, stitching did facilitate the propagation of in-plane cracks. The findings revealed that stitching with thicker yarn (flax) led to a lower ratio of absorbed energy per area of damage as well as the energy absorbed for full penetration.	[35]
Flax	Vinyl ester	The results at two different impact energies (25 J and 50 J) confirmed the fact that the flax specimens can absorb more energy during the impact event, but they tended to show greater damage extension at lower energy levels compared to the glass/flax specimens. The hybridisation of the flax reinforced natural fibre composite revealed a much higher impact performance, exhibiting greater perforation and penetration resistance with the benefits of having a lower environmental impact than glass fibre laminates without hybridisation.	[36]
Hemp	Polyurethane (PU)	Increasing fibre volume content to 40%, flexural strength enhanced 193.24%. Additionally, 15 mm hemp fibre was found to be the optimum fibre length, where flexural strength at 40% fibre volume was further increased to 274.3%.	[37]
Hemp	Unsaturated polyester	The results suggested a significant effect of chemical treatment in terms of increasing mechanical and dynamic mechanical properties and decreasing in water absorption properties. The benzoylation treatment showed a better impact among all three chemical treatments (benzoylation, alkali treatment, and sodium bicarbonate).	[38]
Sisal	Epoxy	The results indicated that storage modulus and loss modulus were found to be high for the composite having 15 mm length of fibres.	[39]
Jute	Epoxy	Composites prepared from chemically treated (acid pretreatment, alkali pretreatment, and scouring) jute fibres were found to be better than the raw jute composites in terms of tensile strength, elongation at break, void fraction, and interfacial adhesion. The findings suggested the chemical treatment of jute fibres could enable better matrix–fibre adhesion due to improvement in interfacial bonding with polymer matrix, which consequently improved the tensile properties of the composites.	[40]

The development of loose natural fibre into a woven form improved the natural fibre's potential and usefulness as a reinforcement in the advanced composite structure. In recent years, an increasing interest in textile composites has been observed. They are progressively used in the fabrication of high mechanical performance structures in many fields as listed in Table 5.

Table 5. Applications of woven natural fibres composites in field scales.

Fibres	Reinforcement	Applications	Ref.
Bamboo fabric	**Polylactic acid**	**Packaging**	[41][42]
Woven jute and glass fibre	**Polyester**	**Solar parabolic trough collector**	[43]
Twill weave woven flax fabric	**Polypropylene**	**Marine composite**	[44]
Woven kenaf bast and oil palm EFB	**Polyhydroxybutyrate (PHB)**	**Construction and building materials**	[45]
Flax fabric	**Carbon nanotubes**	**Supercapacitor electrode**	[46]
Sisal fabric, flax fabric and glass fibre	**Epoxy**	**Wind turbine blades**	[47]
Woven cotton fabric	**Polylactic acid**	**Antibiotic delivery device**	[48]
Plain hemp fabric	**Epoxy**	**Electronic racks**	[49]
Woven kenaf and Kevlar fabric	**Epoxy**	**Ballistic armour materials**	[50][51]
Sugar palm yarn	**Polyester**	**Automotive component**	[28][52][53][54][55][56]

The woven-fibre composite denotes the type of textile composite in which strands form through the weaving process; they are interlaced with each other and impregnated with a resin material in two mutually orthogonal (warp and weft) directions. Particularly, in the form of short and random, composite materials reinforced with woven fabric have better out-of-plane rigidity, strength, and durability properties than laminate composites, although the geometry of this composite class is complex and there is no limit to the choice of possible architectures and components. Many parameters of woven-fibre composite materials can be altered, such as the geometry of microstructures, weave type, and hybridisation or choice of components (e.g., geometric and mechanical parameters of strands and resins)[57]. Thus, their mechanical performance should be taken into account in the preliminary study for the selection of woven fibre composites with the right blend of weight, cost, toughness, and strength properties.

Biocomposites must have useful characteristics (high-quality performance, durability, and reliability standards) in order to replace synthetic fibre-reinforced composites and extend into other industrial applications, such as traditional petroleum plastics used in automotive applications in particular[58][59][60][61]. The quest for lightweight vehicle parts, together with good end-of-life disposal, has indirectly opened a gateway to solve the issue of fuel consumption in the automotive sector and thus, reduced greenhouse gas emissions[62]. With this in mind, the European Commission has implemented the “European Guideline 2000/53/EG” which set the objective of improving the vehicle’s recyclability to 85% by weight in 2005. This percentage was increased to 95% by 2015[62].

Longest fibres, such as jute, can be formed into flexible fibre mats that can be produced by physical entanglement, nonwoven needling, or thermoplastic fibre melt matrix technologies. The two major types are carded and needle-punched mats. In carding, the fibres are combed, mixed and physically entangled in a felted mat. Geotextiles have a wide range of applications. It can be used as a mulch around the freshly planted seedling. With good moisture retention and promoting seed germination of jute fibre mats, low-and medium-density fibre mats can be made and used for soil stabilisation around new or existing constructions to stop soil slopes without roots from soil erosion and topsoil loss. As natural separators between various materials, medium and high-density fibre mats can also be used underground in road building and other forms of construction. Woven jute is commonly used as a “gunny” and tote bag because of the long and strong properties of jute fibre.

Morris et al.[63] investigated woven natural fibre-reinforced composites materials for medical imagery. The various woven natural fibre materials, such as silk, cotton, lyocel, bamboo, and carbon fibre (as control), were integrated into a range of various resin materials appropriate for such applications. From examining a variety of resins and natural fibre materials in combination and testing their performance in terms of MRI and X-Ray imaging, the result showed that a woven cotton material impregnated with a two-part epoxy resin increased the passage of X-Rays by 15% and had no effect on the MRI signal (unlike the 40% MRI signal attenuation from carbon fibre) while maintaining a flexural modulus up to 71% of that of carbon fibre. These findings showed that natural fibre composites generated using such materials have attractive properties for use in patient care and positioning devices for multi-modal imaging without the need to substantially compromise the strength of the material.

In biomedical applications, Bagheri et al.[64] suggested flax sandwiched with thin carbon sheets on either side for use as an orthopaedic long bone fracture plate because the hybrid's mechanical properties are closer to the human cortical bone than the clinically used orthopaedic metal plates, rendering the material a possible candidate for long bone fracture fixation. A sandwich-structured composite in which two thin sheets of carbon fibre/epoxy are attached to each outer surface of the flax/epoxy core, resulting in a unique structure compared to other bone plate composite plates. The findings of the mechanical testing showed a significantly high final strength in both tension (399.8 MPa) and flexural loading (510.6 MPa) with a higher elastic modulus in bending tests (57.4 GPa) relative to tension tests (41.7 GPa). In both tension and bending tests, the composite material suffered a brittle catastrophic failure. Compared to clinically use orthopaedic metal plates, current CF/flax/epoxy findings were similar to human cortical bone, making the material a possible candidate for long bone fracture fixation.

In sporting good uses, a multitude of flax preforms have been used: woven flax prepregs, containing epoxy resin, were combined with carbon prepregs in the hybrid material concepts used in tennis rackets, bicycles, fishing rods, or ski. Glass fibres are still used in the latter and in one particular technology[65], the core of the ski sandwich structure is reinforced with strips ± 45° flax, located in the thickness direction of the core (balsawood), facilitating more weight reduction and damping capability improvement. In ski poles, braided flax is used, making them a bio-based and light alternative to poles reinforced with carbon or glass fibre.

Wambua et al.[66] found that flax composites had higher energy absorption compared with hemp and jute composites. However, the ballistic qualities of hemp composites were improved greatly when a mild steel plate was used to protect and support the body armour. Radif et al.[67] noticed that the use of a woven ramie Kevlar-reinforced polyester composite as a material to manufacture body armour, in particular, to reduce the amount of Kevlar used, created a potential cost-effective product and could also contribute to a reduction in its cost of production. Furthermore, the armour was comparable to the third level of protection of the ballistic limits in accordance with the International Standard of the National Institute of Justice (NIJ).

A multilayer armour system (MAS) in which traditional Kevlar^{TM} was substituted by either an epoxy matrix composite reinforced with 30 vol% jute fabric or a plain epoxy plate following an NIJ trauma limit after ballistic testing with 7.62 mm ammunition was manufactured and characterised by Luz et al.[68]. Within the statistical deviation, the ballistic output for the three investigated MAS second layer materials were found to be identical. Generally, lesser energy was dissipated by the aramid fabric in perforating individual ballistic tests, while the jute fabric composite and the plain epoxy were more effective. While not indicative of what happened in the MAS tests, the energy dissipated by each particular substance led to the exploration of the ballistic significance of the epoxy rupture mechanism. Referring to them, evidence of the massive collection of post-impact fragments by the composite of jute fabric and also the aramid fabric, which has also been recently reported, has been suggested as the main mechanism for energy dissipation. Additional fragment capture and brittle epoxy spalling (plain or composite matrix) contributed significantly to the dissipation of post-impact energy. Despite comparable ballistic efficiency and a negligible difference in weight, the considerably lower cost associated with environmental and societal advantages of natural fibre in practice favoured the replacement of jute fibre composite for both aramid and plain epoxy in MAS.

Woven bamboo fabric is similar to silk in softness. The fibres, which are not chemically treated, are generally smoother and more round without sharp spurs to irritate the skin making bamboo fabric hypoallergenic and ideal for people who have allergic reactions to other natural fibres like wool or hemp. A comparative analysis by Tausif et al. [69] on their comparative study of bamboo viscose fibre as an eco-friendly alternative to cotton fibre in knitted polyester-cellulosic blends was performed. Conventional cotton is not known to be eco-friendly, since it needs a significant quantity of water and pesticides during its processing. The eco-friendly quality of bamboo viscose is subjected to the manufacturing process used. Polyester-bamboo (PB) and polyester-cotton (PC) blended yarns were prepared using open-ended spinning techniques and the yielded yarns were single jersey weft-knitted. The results indicated that the PB blend outperformed the PC blend in mechanical properties and demonstrated lower thermal resistance than the PC blend, which is advantageous for summer clothing. Although at higher proportions of bamboo viscose fibre in the PB blend, the moisture management characteristics of PB blended fabrics were expected to be comparable to those of PC blended fabrics.

3. Challenges and Future Perspective on Woven Natural Fibre Composites

Under the Industrial Revolution 4.0 (IR4.0), the development of woven natural fibre composites remains in a very high challenge. The woven polymer composites are normally fabricated with thermoset matrices, although thermoset composites are well-known for their superior strength[70]. However, the fabrication processes in innovative ways are hardly ever reported[71]. Additives manufacturing (AM) coves the 3D printing production from a thermoplastic polymer, ceramic to metal materials. It reduces waste materials, labour monitoring and energy used[72]. The insertion of natural fibre reinforcements in powders and yarn forms, into PLA polymer composites, were reported as FDM or SLS 3D printing materials[73]. Unfortunately, there is no room is available for woven natural fibres composites in additives manufacturing, at least not to date. From a future perspective, woven natural fibres should be involved in AM to produce strong composites at a minimum cost.

Despite the intense research conducted on woven natural fibre composites, the use of woven natural fibre in aircraft interior components are not yet seen. Aircraft components have strict regulations on their durability and performance, especially with regards to flame retardancy[74]. However, woven natural fibres behave similarly as wood materials, with high flammability and low thermal stability in general[75]. Although numerous treatments and flame-retardant fillers were included in the woven natural fibre composites' design and enhanced thermal and flame properties were achieved, but compliance with aviation materials' requirements seems still challenging. Therefore, pushing the woven natural fibre composites as the alternative aircraft interior materials would be a prior task that needed to be done instead of continuous research without commercialisation.

As commercialization is a part of the future schedule, the popularisation of woven natural fibre composites is important. Without knowing and understanding from the public, commercialising woven NF composite products shall be a tough challenge. Publicity on the woven natural fibre composites should be a collaborative effort between universities, government and industrial partners. Woven natural fibre composites have been innovative materials among researchers for at least decades, however, the public has zero or limited information about these woven natural fibre composite materials. This makes it challenging for companies to use woven natural fibre composites in their products. This is because consumers are not going to select the products with which they are not familiar or confident. Hence, the government should take the initial step to introduce and promote the achievements of woven natural fibre composites conducted by local universities, via social media and newspapers. Through this approach, good products made from woven natural fibre composites can be delivered to consumers.

References

1. Wahab, M.; Rejab, M.; Saiman, M.P. Analysis of mechanical properties for 2D woven kenaf composite. In Applied Mechanics and Materials; Trans Tech Publication: Freienbach, Switzerland, 2014.
2. Ahmed, K.; Vijayarangan, S.; Naidu, A.C.B. Elastic properties, notched strength and fracture criterion in untreated woven jute–glass fabric reinforced polyester hybrid composites. Mater. Des. 2007, 28, 2287–2294.
3. Mohd Nurazzi, N.; Khalina, A.; Sapuan, S.M.; Dayang Laila, A.H.A.M.; Rahmah, M.; Hanafee, Z. A Review: Fibres, Polymer Matrices and Composites. Pertanika J. Sci. Technol. 2017, 25, 1085–1102.
4. Aisyah, H.A.; Paridah, M.T.; Sapuan, S.M.; Khalina, A.; Berkalp, O.B.; Lee, S.H.; Lee, C.H.; Nurazzi, N.M.; Ramli, N.; Wahab, M.S.; et al. Thermal Properties of Woven Kenaf/Carbon Fibre-Reinforced Epoxy Hybrid Composite Panels. Int. J. Polym. Sci. 2019, 2019, 1–8.
5. Manap, N.; Jumahat, A.; Abd Rahman, N.; Ain Abd Rahman, N. NaOH treated Kenaf/Glass hybrid composite: The effects of nanosilica on longitudinal and transverse tensile properties. J. Phys. Conf. Ser. 2020, 1432, 12046.
6. Sanjay, M.R.; Arpitha, G.R.; Senthamaraikannan, P.; Kathiresan, M.; Saibalaji, M.A.; Yogesha, B. The Hybrid Effect of Jute/Kenaf/E-Glass Woven Fabric Epoxy Composites for Medium Load Applications: Impact, Inter-Laminar Strength, and Failure Surface Characterization. J. Nat. Fibers 2019, 16, 600–612.
7. Yusof, N.S.B.; Sapuan, S.M.; Sultan, M.T.H.; Jawaid, M. Conceptual design of oil palm fibre reinforced polymer hybrid composite automotive crash box using integrated approach. J. Cent. South Univ. 2020, 27, 64–75.
8. Amir, S.; Sultan, M.; Jawaid, M.; Safri, S.N.; Shah, A.U.; Yusof, M.R.; Naveen, J.; Mohd, S.; Salleh, K.A.; Saba, N. Effects of layering sequence and gamma radiation on mechanical properties and morphology of Kevlar/oil palm EFB/epoxy hybrid composites. J. Mater. Res. Technol. 2019, 8, 5362–5373.
9. Edhirej, A.; Sapuan, S.M.; Jawaid, M.; Zahari, N.I. Cassava/sugar palm fiber reinforced cassava starch hybrid composites: Physical, thermal and structural properties. Int. J. Biol. Macromol. 2017, 101, 75–83.
10. Norizan, M.N.; Abdan, K.; Ilyas, R.A. Effect of water absorption on treated sugar palm yarn fibre/glass fibre hybrid composites. In Proceedings of the Prosiding Seminar Enau Kebangsaan 2019, Bahau, Malaysia, 1 April 2019; pp. 78–81.
11. Zin, M.H.; Abdan, K.; Norizan, M.N. The effect of different fiber loading on flexural and thermal properties of banana/pineapple leaf (PALF)/glass hybrid composite. In Structural Health Monitoring of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites; Elsevier: Amsterdam, The Netherlands, 2019; pp. 1–17.

12. Srinivasan, V.; Rajendra Boopathy, S.; Sangeetha, D.; Vijaya Ramnath, B. Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite. Mater. Des. 2014, 60, 620–627.
13. Mittal, M.; Chaudhary, R. Development of PALF/Glass and COIR/Glass Fiber Reinforced Hybrid Epoxy Composites. J. Mater. Sci. Surf. Eng. 2018.
14. Uma Devi, L.; Bhagawan, S.S.; Thomas, S. Dynamic mechanical analysis of pineapple leaf/glass hybrid fiber reinforced polyester composites. Polym. Compos. 2010, 31, 956–965.
15. Morye, S.S.; Wool, R.P. Mechanical properties of glass/flax hybrid composites based on a novel modified soybean oil matrix material. Polym. Compos. 2005, 26, 407–416.
16. Fiore, V.; Valenza, A.; Di Bella, G. Mechanical behavior of carbon/flax hybrid composites for structural applications. J. Compos. Mater. 2012, 46, 2089–2096.
17. Panthapulakkal, S.; Sain, M. Studies on the water absorption properties of short hemp-glass fiber hybrid polypropylene composites. J. Compos. Mater. 2007, 41, 1871–1883.
18. La Rosa, A.; Cozzo, G.; Latteri, A.; Recca, A.; Björklund, A.; Parrinello, E.; Cicala, G. Life cycle assessment of a novel hybrid glass-hemp/thermoset composite. J. Clean. Prod. 2013, 44, 69–76.
19. Amico, S.C.; Angrizani, C.C.; Drummond, M.L. Influence of the Stacking Sequence on the Mechanical Properties of Glass/Sisal Hybrid Composites. J. Reinf. Plast. Compos. 2010, 29, 179–189.
20. Idicula, M.; Malhotra, S.K.; Joseph, K.; Thomas, S. Dynamic mechanical analysis of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites. Compos. Sci. Technol. 2005, 65, 1077–1087.
21. Hamouda, T.; Hassanin, A.H.; Kilic, A.; Candan, Z.; Safa Bodur, M. Hybrid composites from coir fibers reinforced with woven glass fabrics: Physical and mechanical evaluation. Polym. Compos. 2017, 38, 2212–2220.
22. Saw, S.K.; Sarkhel, G.; Choudhury, A. Preparation and characterization of chemically modified Jute-Coir hybrid fiber reinforced epoxy novolac composites. J. Appl. Polym. Sci. 2012, 125, 3038–3049.
23. Clark, R.A.; Ansell, M.P. Jute and glass fibre hybrid laminates. J. Mater. Sci. 1986, 21, 269–276.
24. Ramesh, M.; Palanikumar, K.; Reddy, K.H. Comparative evaluation on properties of hybrid glass fiber-sisal/jute reinforced epoxy composites. Procedia Eng. 2013, 51, 745–750.
25. Richard, B.D.; Wahi, A.; Nani, R.; Lling, E.; Osman, S.; Ali, D.S.H. Effect of fiber loading on the flexural and tensile strength of oil palm frond fiber reinforced polymer composite. Int. J. Integr. Eng. 2019, 11, 122–128.
26. Islam, M.; Gupta, A.; Rivai, M.; Beg, M. Characterization of microwave-treated oil palm empty fruit bunch/glass fibre/polypropylene composites. J. Thermoplast. Compos. Mater. 2017, 30, 986–1002.
27. Norizan, M.N.; Abdan, K.; Salit, M.S.; Mohamed, R. Physical, mechanical and thermal properties of sugar palm yarn fibre loading on reinforced unsaturated polyester composites. J. Phys. Sci. 2017.
28. Baihaqi, N.M.Z.N.; Khalina, A.; Nurazzi, N.M.; Aisyah, H.A.; Sapuan, S.M.; Ilyas, R.A. Effect of fiber content and their hybridization on bending and torsional strength of hybrid epoxy composites reinforced with carbon and sugar palm fibers. Polimery 2021, 66, 36–43.
29. Radzuan, N.A.M.; Tholibon, D.; Sulong, A.B.; Muhamad, N.; Che Haron, C.H. Effects of High-Temperature Exposure on the Mechanical Properties of Kenaf Composites. Polymers 2020, 12, 1643.
30. Chung, T.-J.; Park, J.-W.; Lee, H.-J.; Kwon, H.-J.; Kim, H.-J.; Lee, Y.-K.; Tai Yin Tze, W. The improvement of mechanical properties, thermal stability, and water absorption resistance of an eco-friendly PLA/Kenaf biocomposite using acetylation. Appl. Sci. 2018, 8, 376.
31. Zin, M.H.; Abdan, K.; Norizan, M.N.; Mazlan, N. The effects of alkali treatment on the mechanical and chemical properties of banana fibre and adhesion to epoxy resin. Pertanika J. Sci. Technol. 2018, 26, 161–176.
32. Karthick, R.; Adithya, K.; Hariharaprasath, C.; Abhishek, V. Evaluation of mechanical behavior of banana fibre reinforced hybrid epoxy composites. Mater. Today Proc. 2018, 5, 12814–12820.
33. Glória, G.O.; Teles, M.C.A.; Neves, A.C.C.; Vieira, C.M.F.; Lopes, F.P.D.; de Gomes, M.A.; Margem, F.M.; Monteiro, S.N. Bending test in epoxy composites reinforced with continuous and aligned PALF fibers. J. Mater. Res. Technol. 2017, 6, 411–416.
34. Doddi, P.R.V.; Chanamala, R.; Dora, S.P. Effect of fiber orientation on dynamic mechanical properties of PALF hybridized with basalt reinforced epoxy composites. Mater. Res. Express 2020, 7, 015329.
35. Ravandi, M.; Teo, W.S.; Tran, L.Q.N.; Yong, M.S.; Tay, T.E. Low velocity impact performance of stitched flax/epoxy composite laminates. Compos. Part B Eng. 2017, 117, 89–100.

36. Barouni, A.K.; Dhakal, H.N. Damage investigation and assessment due to low-velocity impact on flax/glass hybrid composite plates. Compos. Struct. 2019, 226, 111224.
37. Haghighatnia, T.; Abbasian, A.; Morshedian, J. Hemp fiber reinforced thermoplastic polyurethane composite: An investigation in mechanical properties. Ind. Crops Prod. 2017, 108, 853–863.
38. Gupta, M.K.; Gond, R.K.; Bharti, A. Effects of treatments on the properties of polyester based hemp composite. Indian J. Fibre Text. Res. 2018, 43, 313–319.
39. Rana, S.S.; Gupta, M.K.; Srivastava, R.K. Effect of variation in frequencies on dynamic mechanical properties of short sisal fibre reinforced epoxy composite. Mater. Today Proc. 2017, 4, 3387–3396.
40. Wang, H.; Memon, H.; Hassan, E.A.M.; Miah, M.S.; Ali, M.A. Effect of Jute Fiber Modification on Mechanical Properties of Jute Fiber Composite. Materials 2019, 12, 1226.
41. Fazita, M.R.; Jayaraman, K.; Bhattacharyya, D.; Hossain, M.; Haafiz, M.K.; Khalil, H.P.S.A. Disposal Options of Bamboo Fabric-Reinforced Poly(Lactic) Acid Composites for Sustainable Packaging: Biodegradability and Recyclability. Polymers 2015, 7, 1476–1496.
42. Fazita, M.R.N.; Jayaraman, K.; Bhattacharyya, D. Formability Analysis of Bamboo Fabric Reinforced Poly (Lactic) Acid Composites. Materials 2016, 9, 539.
43. Reddy, K.S.; Singla, H. Optimization of woven jute/glass fibre-reinforced polyester hybrid composite solar parabolic trough collector. IOP Conf. Ser. Mater. Sci. Eng. 2017, 222, 012016.
44. Calabrese, L.; Fiore, V.; Scalici, T.; Valenza, A. Experimental assessment of the improved properties during aging of flax/glass hybrid composite laminates for marine applications. J. Appl. Polym. Sci. 2019, 136, 1–12.
45. Meysam, S.; Rostami, R.; Ismail, M.; Razak, A.; Ezekiel, B. Woven hybrid Biocomposite: Mechanical properties of woven kenaf bast fibre/oil palm empty fruit bunches hybrid reinforced poly hydroxybutyrate biocomposite as non-structural building materials. Constr. Build. Mater. 2017, 154, 155–166.
46. Zhang, Y.; Mao, T.; Wu, H.; Cheng, L.; Zheng, L. Carbon Nanotubes Grown on Flax Fabric as Hierarchical All-Carbon Flexible Electrodes for Supercapacitors. Adv. Mater. Interfaces 2017, 4, 1601123.
47. Kalagi, G.R.; Patil, R.; Nayak, N. Experimental Study on Mechanical Properties of Natural Fiber Reinforced Polymer Composite Materials for Wind Turbine Blades. Mater. Today Proc. 2018, 5, 2588–2596.
48. Macha, I.J.; Muna, M.M.; Magere, J.L. In vitro study and characterization of cotton fabric PLA composite as a slow antibiotic delivery device for biomedical applications. J. Drug Deliv. Sci. Technol. 2018, 43, 172–177.
49. Scarponi, C.; Messano, M. Comparative evaluation between E-Glass and hemp fiber composites application in rotorcraft interiors. Comp. Part B Eng. 2015, 69, 542–549.
50. Yahaya, R.; Sapuan, S.M.; Jawaid, M.; Leman, Z.; Zainudin, E.S. Measurement of ballistic impact properties of woven kenaf-aramid hybrid composites. Meas. J. Int. Meas. Confed. 2016, 77, 335–343.
51. Yahaya, R.; Sapuan, S.M.; Jawaid, M.; Leman, Z.; Zainudin, E.S. Effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf–aramid hybrid laminated composites. Mater. Des. 2015, 67, 173–179.
52. Mohd Nurazzi, N.; Khalina, A.; Sapuan, S.M.; Rahmah, M. Development of sugar palm yarn/glass fibre reinforced unsaturated polyester hybrid composites. Mater. Res. Express 2018, 5, 045308.
53. Norizan, M.N.; Abdan, K.; Ilyas, R.A.; Biofibers, S.P. Effect of fiber orientation and fiber loading on the mechanical and thermal properties of sugar palm yarn fiber reinforced unsaturated polyester resin composites. Polimery 2020, 65, 34–43.
54. Sapuan, S.M.; Bachtiar, D. Mechanical properties of sugar palm fibre reinforced high impact polystyrene composites. Proc. Chem. 2012, 4, 101–106.
55. Norizan, M.N.; Abdan, K.; Salit, M.S.; Mohamed, R. The effect of alkaline treatment on the mechanical properties of treated sugar palm yarn fibre reinforced unsaturated polyester composites reinforced with different fibre loadings of sugar palm fibre. Sains Malaysiana 2018.
56. Nurazzi, N.M.; Khalina, A.; Sapuan, S.M.; Ilyas, R.A.; Rafiqah, S.A.; Hanafee, Z.M. Thermal properties of treated sugar palm yarn/glass fiber reinforced unsaturated polyester hybrid composites. J. Mater. Res. Technol. 2019.
57. Scida, D.; Aboura, Z.; Benzeggagh, M.L.; Bocherens, E. A micromechanics model for 3D elasticity and failure of woven-fibre composite materials. Compos. Sci. Technol. 1999, 59, 505–517.
58. Ilyas, R.A.; Sapuan, S.M. The Preparation Methods and Processing of Natural Fibre Bio-polymer Composites. Curr. Org. Synth. 2020, 16, 1068–1070.

59. Ilyas, R.A.; Sapuan, S.M. Biopolymers and Biocomposites: Chemistry and Technology. Curr. Anal. Chem. 2020, 16, 500–503.

60. Mazani, N.; Sapuan, S.M.; Sanyang, M.L.; Atiqah, A.; Ilyas, R.A. Design and Fabrication of a Shoe Shelf from Kenaf Fiber Reinforced Unsaturated Polyester Composites. In Lignocellulose for Future Bioeconomy; Ariffin, H., Sapuan, S.M., Hassan, M.A., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 315–332. ISBN 9780128163542.

61. Ayu, R.S.; Khalina, A.; Harmaen, A.S.; Zaman, K.; Isma, T.; Liu, Q.; Ilyas, R.A.; Lee, C.H. Characterization Study of Empty Fruit Bunch (EFB) Fibers Reinforcement in Poly(Butylene) Succinate (PBS)/Starch/Glycerol Composite Sheet. Polymers 2020, 12, 1571.

62. Witayakran, S.; Smitthipong, W.; Wangpradid, R.; Chollakup, R.; Clouston, P.L. Natural Fiber Composites: Review of Recent Automotive Trends. In Encyclopedia of Renewable and Sustainable Materials; Elsevier: Amsterdam, The Netherlands, 2017; pp. 166–174.

63. Morris, R.H.; Geraldi, N.R.; Stafford, J.L.; Spicer, A.; Hall, J.; Bradley, C.; Newton, M.I. Woven Natural Fibre Reinforced Composite Materials for Medical Imaging. Materials 2020, 13, 1684.

64. Bagheri, Z.S.; El Sawi, I.; Schemitsch, E.H.; Zdero, R.; Bougherara, H. Biomechanical properties of an advanced new carbon/flax/epoxy composite material for bone plate applications. J. Mech. Behav. Biomed. Mater. 2013, 20, 398–406.

65. Pil, L.; Bensadoun, F.; Pariset, J.; Verpoest, I. Why are designers fascinated by flax and hemp fibre composites? Compos. Part A Appl. Sci. Manuf. 2016, 83, 193–205.

66. Wambua, P.; Vangrimde, B.; Lomov, S.; Verpoest, I. The response of natural fibre composites to ballistic impact by fragment simulating projectiles. Compos. Struct. 2007, 77, 232–240.

67. Radif, Z.S.; Ali, A.; Abdan, K. Development of a Green Combat Armour from Rame-Kevlar-Polyester Composite. Pertanika J. Sci. Technol. 2011, 19, 339–348.

68. Luz, F.S.D.; Junior, E.P.L.; Louro, L.H.L.; Monteiro, S.N. Ballistic test of multilayered armor with intermediate epoxy composite reinforced with jute fabric. Mater. Res. 2015, 18, 170–177.

69. Tausif, M.; Ahmad, F.; Hussain, U.; Basit, A.; Hussain, T. A comparative study of mechanical and comfort properties of bamboo viscose as an eco-friendly alternative to conventional cotton fibre in polyester blended knitted fabrics. J. Clean. Prod. 2015, 89, 110–115.

70. Aisyah, H.A.; Paridah, M.T.; Khalina, A.; Sapuan, S.M.; Wahab, M.S.; Berkalp, O.B.; Lee, C.H.; Lee, S.H. Effects of Fabric Counts and Weave Designs on the Properties of Laminated Woven Kenaf/Carbon Fibre Reinforced Epoxy Hybrid Composites. Polymers 2018, 10, 1320.

71. Mott, S. Five Forms of Thermoset Processing. Available online: https://blog.mar-bal.com/blog/five-forms-of-thermoset-processing (accessed on 13 January 2021).

72. Balla, V.K.; Kate, K.H.; Satyavolu, J.; Singh, P.; Tadimeti, J.G.D. Additive manufacturing of natural fiber reinforced polymer composites: Processing and prospects. Compos. Part B Eng. 2019, 174, 106956.

73. Le Duigou, A.; Correa, D.; Ueda, M.; Matsuzaki, R.; Castro, M. A review of 3D and 4D printing of natural fibre biocomposites. Mater. Des. 2020, 194, 108911.

74. Aravind Kumar, D.; Gokul Raj, G.; Shivaani, G.; Sreehari, V.M. Structural analysis of aircraft wings made of natural fiber reinforced composites. Int. J. Mech. Eng. Technol. 2018, 9, 1262–1268.

75. Lee, C.H.; Salit, M.S.; Hassan, M.R. A Review of the Flammability Factors of Kenaf and Allied Fibre Reinforced Polymer Composites. Adv. Mater. Sci. Eng. 2014, 2014, 514036.