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Plant Fiber Reinforcements as Alternatives in Pultruded FRP Composites Manufacturing: A Review

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ABSTRACT

Recent developments of green technology promote the rising attraction toward developing high-performance and environmentally friendly pultruded products from naturally derived resources. Some factors that attract attention to developing pultruded biocomposites are their lightweight properties, recyclability, and economical and environmentally superior alternatives to synthetic fibers in commercial applications. Researchers have studied that the environmental crisis caused by conventional synthetic materials can be reduced significantly by using sustainable materials instead. This paper aims to review the potential of plant fibers to be used in pultruded composite manufacturing to reduce and replace the use of synthetic materials in pultruded structures. It was found that kenaf and jute fibers have been extensively studied in pultruded plant fiber reinforced composites and pultruded glass/plant fiber reinforced hybrid composites for their mechanical and physical properties under various test parameters. Overall, pultruded PFCs have recorded good mechanical properties but have limitations in water absorption properties for outdoor applications. An overview of the optimum process parameters, limitations, and potential applications of pultruded PFCs are also outlined. Finally, this review summarizes the future scopes and expectations, providing researchers and industrialists with a vision for deeper investigation in developing pultruded PFCs.

摘要

绿色技术的最新发展促使人们越来越倾向于利用自然资源开发高性能、环保的拉挤产品。开发拉挤生物复合材料引起关注的一些因素是其轻质性能、可回收性以及商业应用中合成纤维的经济和环保替代品。研究人员研究表明，使用可持续材料可以显著减少传统合成材料造成的环境危机。本文旨在综述植物纤维在拉挤复合材料制造中的潜力，以减少和取代拉挤结构中合成材料的使用。研究发现，红麻和黄麻纤维在各种试验参数下的力学和物理性能已在拉挤植物纤维增强复合材料和拉挤玻璃/植物纤维增强混杂复合材料中得到广泛研究。总体而言，拉挤PFCs具有良好的机械性能，但在户外应用的吸水性能方面存在局限性。还概述了拉挤PFCs的最佳工艺参数、限制和潜在应用。最后，这篇综述总结了未来的范围和期望，为研究人员和实业家提供了在开发拉挤全氟氯化碳方面进行更深入研究的愿景。

KEYWORDS

Plant fiber composite (PFC); pultrusion; pultruded FRP composites; sustainable materials

关键词

植物纤维复合材料; 拉挤; 拉挤FRP复合材料; 可持续材料

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Introduction

Composites are produced through various manufacturing processes. Each process holds significant characteristics in producing composites that are different from one another. The recent composite processing techniques are categorized as open molding, closed molding, cast polymer molding and additive manufacturing (Rajak et al. 2019). The selection of processing techniques depends on various aspects, such as the resin type, reinforcement type and fiber placement in the composites (Balasubramanian, Sultan, and Rajeswari 2018).

Generally, a method that can be utilized with a large quantity of fiber reinforcements is theoretically responsible for producing composites with increased strength. Pultrusion is one of the most common closed molding processing methods for producing FRP profiles with high fiber volume and excellent strength, among other manufacturing processes (Pannu, Singh, and Dhawan 2019). Pultrusion is a continuous molding method used in numerous manufacturing sectors to produce structures and composite materials with uniform cross-sections. Pultruded structures and profiles used in various industries are mainly made from synthetic fibers like carbon and glass fibers. However, the excessive use of synthetic materials in composites has raised sustainability issues and adverse environmental effects. This is because synthetic fibers are made by processing petrochemicals and fossil fuels, which are energy sources that are not renewable. In addition, synthetic fiber is expensive, harmful to health, and takes a long time to decompose in materials if used excessively. Therefore, plant based natural fibers are proposed as alternatives to synthetic materials in developing sustainable composites for structural applications via pultrusion in this era of emerging green technology. Haag et al. (2017). studied and compared flax reinforced composites processed by three manufacturing techniques: twin-screw extrusion and injection molding, vacuum-assisted resin transfer molding (VARTM), and pultrusion. The research findings indicate that composites' highest performance was achieved using the pultrusion process compared to the other two techniques. Pultruded flax fiber reinforced composites consisting of high fiber volume fraction, high fiber orientation, and high fiber bundle length validated better mechanical performance than composites from other manufacturing techniques.

Plant fibers are not just chosen to solve problems with sustainability. Plant fibers are used in various composite manufacturing processes due to their lighter weight, lower cost, and superior strength-to-weight ratio. The properties of the fibers are influenced by factors like the physical and chemical morphology, the growth and structure of the lumens, cells, and cell walls, and cross-sectional dimensions (Juliana et al. 2018). Cellulose, hemicelluloses, and lignin typically make up plant fiber's chemical composition as illustrated in Figure 1 (Chokshi et al. 2022). In the form of cellulosic microfibrils in the inner layer of the primary wall, cellulose is one of the primary components of plant fibers. Cellulose is a linear chain of 1,4-linked D-glucose units. It is the main component of plant

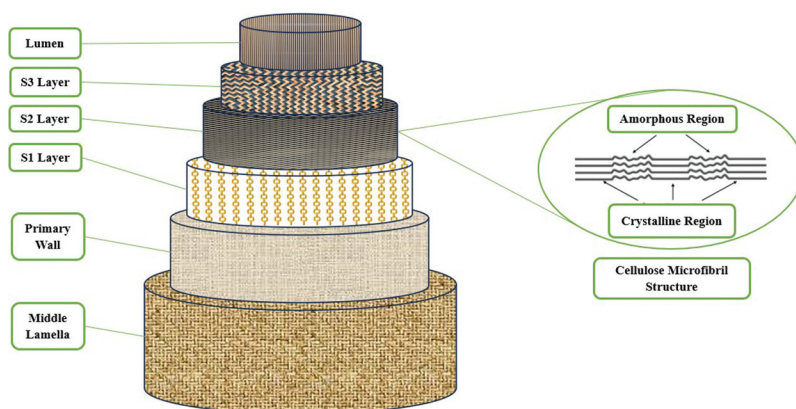


Figure 1. Hierarchical structure of plant cell wall and cellulosic structure (Fornari et al. 2022; Strauss et al. 2023).

cell walls and gives them a stiff and rigid structure. The multiple hydroxyl (OH-) groups on the glucose residues hydrogen bond with one another to form microfibrils, securing the chains in place and contributing to their high tensile strength (Ravindran, Sreekala, and Thomas 2019). Generally, the reinforcing efficiency of plant fibers in composites depends on the cellulose content and their crystallinity (Manivel et al. 2022). The crystalline structure in cellulose provides good strength in plant fibers, making it applicable in load bearing composites. Plant fiber composites typically have better tensile properties with high cellulose content and a low fibrillar angle.

As a result of its renewable and sustainable nature, plant fibers are gaining more attention for application in composite materials and structures. Hence, this paper reviews the research progress and potential of plant based natural fibers to be implied in pultruded composite manufacturing to reduce and replace the use of synthetic materials in pultruded structures. In raising awareness of developing environmentally friendly and high-performance materials for structures and infrastructure facilities, this paper aims to provide an overview of the prospects of plant fibers to be applied in pultruded FRP composites.

Pultruded FRP composites

Utilizing reinforcing fibers, resin, a catalyst, fillers, pigments, and a release agent, pultrusion is known for producing fiber-reinforced polymer composite profiles with a uniform cross-section, such as flat bars, rods, beams, channels, and solid and hollow sections (Qi et al. 2023). The highly automated process can produce continuous and high fiber volume composites, making it ideal for structural profile production with an excellent strength-to-weight ratio. The pultrusion process does not only limit its scope in producing open-section geometries, but also single- or multi-celled close-shaped profiles can be manufactured through this process (Strauss et al. 2023). Moreover, besides producing conventional linear profiles, efforts and research have also been carried out in developing curved parts using modified pultrusion technologies (Aranberri et al. 2021; Liu et al. 2021; Struzziero et al. 2021; Tang et al. 2022; Tonatto, Tarpani, and Amico 2021; Zhao et al. 2022). Figure 2 shows examples of commonly fabricated and applied structural components made by pultrusion.

This technology is emerging in the composites industry due to continuous production at a high rate and low labor cost, which leads to cost-effective manufacturing (Volk et al. 2022). Composites with glass and carbon fiber reinforcements of synthetic fibers are frequently made using pultrusion (Correia 2023; Hofmann et al. 2023). However, plant fiber reinforcements like hemp, flax, kenaf, and jute are also gaining attention in the current generation of structural composites (Mahesh and Mahesh 2023; Scheibe, Urbaniak, and Bledzki 2023). Commercially, the reinforcing materials usually used in pultruded FRP composites are fiberglass continuous strand mats, continuous fiberglass roving and chopped strand mats. The unidirectional roving provides longitudinal reinforcement of the profile, while woven fabrics give transverse strength (Pirchio et al. 2023). A surfacing mat enhances the composite surface appearance and protects the layer from chemical and weather conditions. The fiber arrangement and stacking sequence vary according to the pultruded composite's application. Figure 3 shows an example of a stacking sequence in a C-channel pultruded profile.

There are two steps in the pultrusion processing: impregnation and curing as shown in Figure 4 (Landesmann, Seruti, and Batista 2015). The process starts with the fiber creel to easily pull the fibers without a knot. The fiber reinforcement is then drawn into a resin bath and thoroughly impregnated with the resin mixture. The impregnated fibers will be pulled through a pre-former into a heated die. The die configuration determines the product's shape, and the resin is then cured. Conventionally, the heating zones varied along with the die and were controlled depending on the type of resin, pulling speed, and the length of the die. The pultruded parts are pulled throughout the process using a pulling device which controls the processing speed. A sawing system is equipped at the end of the pultruder to cut off the cured continuous profiles at the desired length.

Generally, several process control parameters are essential in producing pultruded composites, such as the pull speed, resin viscosity, fiber volume fraction, heating temperature in the die, and

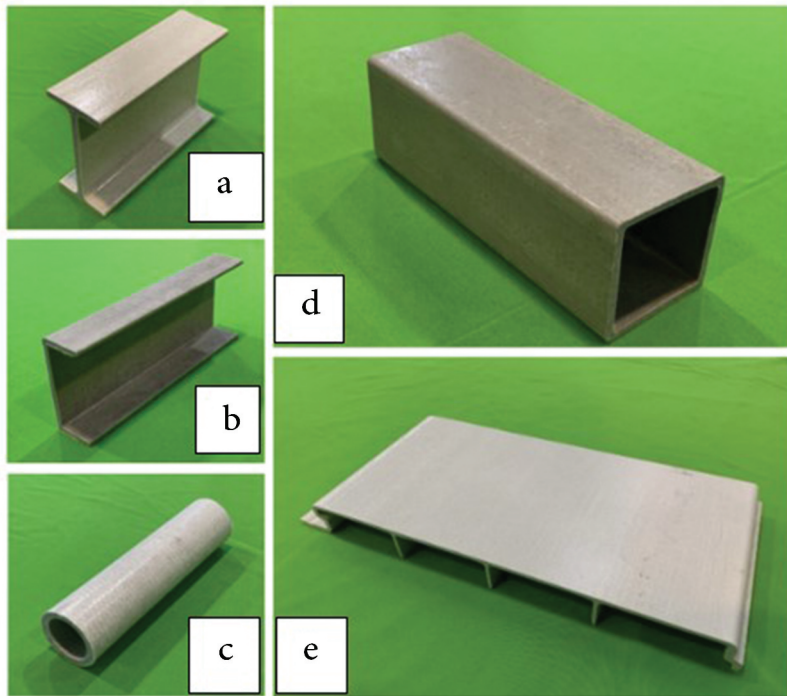


Figure 2. Pultruded components (Mahesh and Mahesh 2023): (a) I beam (b) C channel (c) round tube (d) square tube (e) deck (Top FRP Manufacturer and Supplier in Malaysia - Mui Fatt Marketing Sdn Bhd 2022).

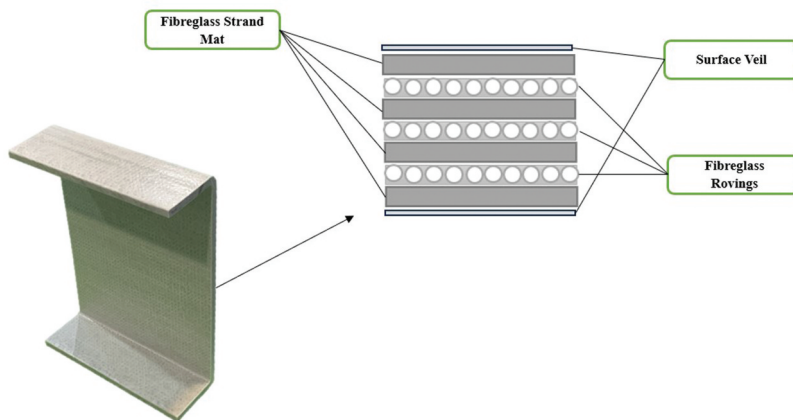


Figure 3. Stacking configuration in pultruded profile.

preform plate area ratio (Li et al. 2002; Paciornik 2003; Chang et al. 2019). For instance, the viscosity of the matrix determines the processing temperature and speed to ensure a high quality of the fully cured end product (Sandberg et al. 2021; Tian et al. 2023; Li et al. 2023). Typically, thermosets, such as unsaturated polyester resin, vinyl ester resin, epoxy resin, and phenolic resin, are used as the matrix system. However, thermoplastic composites are also gaining significant attention in the pultrusion industry (Bechtold, Wiedmer, and Friedrich 2016; Esfandiari et al. 2022; Wilson and Buckley 2016; Zhang et al. 2023). Pultrusion technology and pultruded FRP composite have steadily emerged in many development areas and are still open to market challenges.

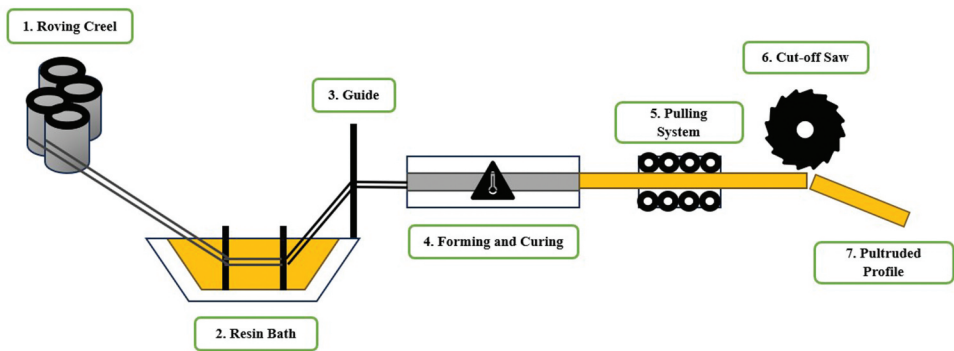


Figure 4. Pultrusion process (Sandberg et al. 2021).

Plant fibers in Pultrusion

Plant fibers can be classified as plant fibers, animal fibers and minerals. Among these types, plant fibers have been widely used as reinforcing fibers in composites lately (Sanjay et al. 2019). Generally, plant fibers can be classified into bast fibers, core fibers, seed fibers, leaf fibers and reed fibers (Keya et al. 2019; Vayabari et al. 2023). Popular plant fibers are extensively researched and applied in various composite applications especially bast and core fibers (Figure 5) (Karimah et al. 2021; Sadrmanesh and Chen 2018; Vinod, Sanjay, and Siengchin 2023). Plant-based natural fibers offer several advantages to reducing and replacing conventional synthetic fibers in pultruded FRP composites. Besides providing good relative mechanical and lightweight properties, plant fiber-reinforced composite (PFC) also solves sustainability issues by reducing the energy required for production (Asyraf et al. 2023; Roy et al. 2019; Shalwan and Yousif 2013). According to Wu et al (Wu et al. 2018), 20% of environmental issues were reduced by producing kenaf-reinforced composite compared to the fiberglass-reinforced composite. Although plant fiber offers several

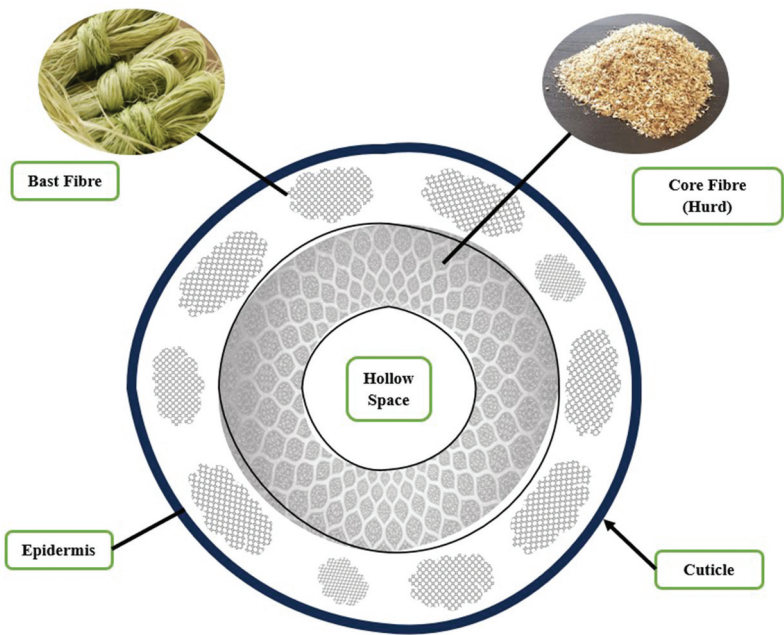


Figure 5. Anatomy bast and core fibres (Angelov et al. 2007; El-Abbassi et al. 2020; Khoo et al. 2023; Liganiso et al. 2013).

advantages, such as low weight, low cost, abundant availability, and sustainable and environmentally friendly properties, it comes with some limitations, such as high moisture absorption (Kumar, Manna, and Dang 2022; Madhu et al. 2019). Generally, the property of PFC depends on the constitution of plant fibers such as cellulose, hemicellulose, lignin, fiber distribution and fiber surface roughness (Rajesh et al. 2021). Besides that, the mechanical characteristics of PFCs highly depend on interfacial bonding between the fiber and matrix. Chemical processing is often applied to plant fibers to reduce the hydrophilic properties of fibers and enhance the fiber-matrix adhesion to improve the mechanical properties of PFC, which can be applied to pultruded structural applications (Karthi et al. 2020; Sahu et al. 2023; Setswalo et al. 2023). The poor dimensional stability and high hydrophilic nature are the significant disadvantages limiting plant fiber use in different applications. Therefore, chemical treatments are essential to improve the surface properties of plant fibers before being applied to composites (Koohestani et al. 2019; Setswalo et al. 2021). The common chemical treatments applied are alkaline, silane, acetylation, and maleate coupling treatments (Edeerozey et al. 2007).

To produce pultruded profiles from reinforced plant fibers with similar properties to GFRP, the processing parameters, fiber preforms in yarns and woven fabrics, and resin must be adapted to each other. Hence, research on optimum processing parameters, fiber size and loadings, and characterization of pultruded plant fiber composites is important to develop eco-friendly pultrudes for commercial structural applications. To limit investments in new machinery, producing plant fiber profiles should be made possible in the same production plants and manufacturing setups as conventional GFRP profiles. For instance, parameters such as pulling speed, preheating conditions, the heating temperature in the die, and the cooling rate need to be adapted for the pultrusion of PFC profiles in the manufacturing industry (Barkanov et al. 2021; Joshi, Lam, and Win Tun 2003). Angelov et al. (2007). have conducted a study on pultruded flax/polypropylene yarn, and their findings indicated that under certain conditions of speed and temperature, the pultruded profiles show good mechanical performance similar to composites fabricated using compression molding. Linganiso et al (Linganiso et al. 2013). stated that at higher die temperatures (290°C) and lower pulling speeds (0.5 m/min) during the process, the mechanical properties of pultruded flax-reinforced thermoplastic composites have improved. The improvement is due to the increased penetration within the reinforcement resulting from better melting and lower matrix viscosity at high temperatures and low pulling speed during the process.

Similarly, efforts have been taken by (Fairuz et al. 2015a). to find the optimum process parameters for the pultrusion of kenaf reinforced composite through analysis of variance. The findings revealed that a pulling speed of 0.4 m/min, gelation temperature at 120°C and curing temperature at 180°C were the best combination of processing parameters for kenaf fibers. During pultrusion, it is essential to ensure that a low-viscosity resin is used to facilitate ease of resin penetration into fiber yarn. Besides that, voids inside pultruded PFCs are generally higher than pultruded synthetic fiber composites (Fairuz et al. 2015b). It occurs due to high moisture content and poor wetting of plant fibers. Hence, the resin is formulated to contain the filler to reduce the use of resin and to fill in the porosity inside the composites. Table 1 shows several research works using plant fibers such as kenaf, jute and hemp. The significant findings based on the various test parameters used to study the properties of pultruded PFCs are highlighted in the literature review. Table 1 shows that characterization in mechanical and physical properties has been analyzed on pultruded PFCs. Mechanical properties such as tensile, compressive, and flexural studies have been conducted, while moisture absorption has been studied for physical properties.

Mechanical properties of pultruded plant fiber composites

Researchers investigating the mechanical properties of plant fiber composites have stated that the composites are suitable for low-load applications (Parbin et al. 2019; Saba, Paridah, and Jawaaid 2015). Hence, introducing plant fibers in conventional pultrusion manufacturing would lead to cost-effective

Table 1. Research on the characterization of plant fiber reinforced pultruded composites.

Year	Author	Raw materials	Tested variable	Parameters of variable	Test analysis	Obtained data		Volume percentage of eco-friendly material content
						Best parameter composition	Results	
Mechanical properties								
2023	Zakaria et al. (2023)	Kenaf	Fiber orientation and fabrication method	0° fiber orientation (pultrusion)/ 45° fiber orientation (filament winding)	Tensile strength	0° fiber orientation via pultrusion	39.16 MPa	-
2019	Gupta et al. (2019)	Jute + Unsaturated Polyester	Composition of hybrid filler	Bagasse/Carbon black/CaCO3 (g)	Tensile strength Flexural strength	Bagasse 25 g/CB 5 g/CaCO3 5 g Bagasse 35 g/CB 5 g/CaCO3 50 g	61.39 MPa 155.48 MPa	40–50% of jute fibers
2018	Hedayati Velis, Golzar, and Yousefzade (2018)	Jute + Thermoplastic starch and high-density polyethene (HDPE)	Matrix system and filler	Jute/thermoplastic starch, Jute/HDPE, & Jute/HDPE/wood flour	Tensile strength Tensile modulus	Jute/HDPE Jute/HDPE/10% wood flour	81.9 MPa 8.27 GPa	35–40% of jute fibers
2016	Fairuz et al. (2016)	Kenaf + Vinyl Ester	Filler loading (%)	20/30/40/50/60%)	Tensile strength Tensile modulus Flexural strength Flexural modulus Compressive strength	50% 50% 30% 50% 40%	150–155 MPa 10000 MPa 180 MPa 2000 MPa 80–85 MPa	40% of kenaf fibers
2016	Zamri, Akil, and Mohdshak (2016)	Kenaf + Unsaturated Polyester	Yarn size (Tex) Fiber loading (%)	1400/2200/3300 (Tex) 60/65/70%)	Flexural strength Flexural modulus Compressive strength	Tex 1400/70% Tex 1400/70% Tex 1400/70%	350–400 MPa 35–40 MPa GPa	70% of kenaf fibers 70% of kenaf fibers
2014	Osman et al. (2014)	Kenaf	Concentration of chemical treatment (%)	3%, 6% and 9% M Sodium hydroxide (NaOH)	Compression modulus Tensile strength Tensile modulus Flexural strength Flexural modulus	6% of NaOH 6% of NaOH 6% of NaOH	70–80 MPa 3.5–4.0 GPa 200–250 MPa 14–16 GPa 250–300 MPa 14–16 GPa	

(Continued)



Table 1. (Continued).

Year	Author	Raw materials	Tested variable	Parameters of variable	Test analysis	Obtained data		Volume percentage of eco-friendly material content
						Best parameter composition	Results	
2011	Zamri et al. (2011)	Kenaf + Unsaturated polyester	Fiber loading (%)	50/60/65/70/75%)	Flexural strength	70%	225–250 MPa	70% of kenaf fibers
2011	Safee et al. (2011)	Jute + Unsaturated polyester	Jute-reinforced unsaturated polyester pultruded rod	PJFRC	Compressive strength Compressive modulus Flexural strength Flexural modulus	-	149 MPa 7.4 GPa 890 MPa 2.6 GPa	70% of jute fibers
2010	Omar et al. 2010).	Kenaf and Jute + Unsaturated polyester	Dynamic mechanical properties	Pultruded kenaf and jute composites	Dynamic compressive strength Strain-rate sensitivity at lower strain-rate condition Strain-rate sensitivity at higher strain-rate condition	Jute reinforced composite Kenaf reinforced composite Jute reinforced composite	150.6 ± 5.9 MPa 4.2 MPa 150.6 MPa	70% of kenaf and jute fibers
2012	Peng et al. (2012)	Hemp (wool)	Matrix system	Polyester/Vinyl Ester/ Polyurethane	Tensile strength Compressive strength Flexural strength	Polyurethane Polyurethane Polyester	122.66 MPa 50–60 MPa 180 MPa	30% of hemp and 5% of wool fibers
2001	van de Velde and Kiekens (2001)	Flax + Polypropylene	Comparison of mechanical properties	Pultruded Flax/PP and Glass/PP composites	Tensile strength Flexural strength	Flax/PP Glass/PP Flax/PP Glass/PP	145 MPa 515 MPa 101 MPa 135 MPa	38% of flax fibers
<i>Physical properties</i>								
2012	Peng et al. (2012)	Hemp (wool)	Matrix system	Polyester/Vinyl Ester/ Polyurethane	Highest percentage of water absorption (%)	Polyurethane	17.83%	30% of hemp and 5% of wool fibers
2009	Akil et al. (2009)	Jute + Unsaturated polyester	Immersion environment	Distilled water/Sea water/acidic solution	Highest moisture content, Mm (%) Diffusion coefficient, D (mm ² /s)	Distilled water (flexural) Distilled water (compressive) Distilled water (flexural) Distilled water (compressive)	10.71% 14.32% 6.54 × 10 ⁻⁶ (mm ² /s) 2.67 × 10 ⁻⁵ (mm ² /s)	-
2010	Nosbi et al. (2010)	Kenaf + Unsaturated polyester	Immersion environment	Distilled water/Sea water/acidic solution	Highest moisture content, Mm (%) Diffusion coefficient, D (mm ² /s)	Distilled water (compressive) Distilled water Distilled water	(mm ² /s) 25.30% 19.83 × 10 ⁻³ (mm ² /s)	70% of kenaf fibers

and sustainable products for low-load structural applications. Generally, several factors affect the mechanical properties of plant fiber composites, such as moisture absorption, fiber alignment, fiber treatments, fiber distribution and the use of additives (Vedernikov et al. 2021). According to Table 1, plant-based fibers such as jute, kenaf, flax and hemp are studied in developing pultruded composites. However, studies on pultruded kenaf and jute fiber composites have been extensively researched. From the literature study, different plant fiber reinforcement types have demonstrated different mechanical and physical properties. Such a circumstance is due to the difference in plant fiber properties such as cellulose content, degree of polymerization and micro-fibrillary angle, which results in the different interface between the fiber and matrix. In this context, (Omar et al. 2010). found comparable dynamic mechanical properties between two different types of plant fiber reinforcements by analyzing the dynamic compressive strength and strain rate properties of pultruded kenaf fiber reinforced composites and pultruded jute fiber reinforced composites. Jute fiber reinforced composites recorded higher dynamic compressive properties and better performance at high strain rate loading than kenaf fiber reinforced composites due to higher cellulose content and lower microfibril angle in jute fibers. However, kenaf reinforcements recorded higher values at low strain rate loading. Zakaria et al. (2023). compared kenaf fiber composites fabricated using pultrusion and filament winding under varying fiber orientation. Based on the investigation, 0° fiber orientation via pultrusion recorded higher tensile strength compared to filament winding.

Osman et al. (2014). studied the effect of alkali treatments at different concentrations of sodium hydroxide (3%, 6%, and 9% M) on the mechanical properties of pultruded kenaf fiber reinforced polyester composites. The researchers recorded that 6% of sodium hydroxide as the best treatment parameter as the tensile and flexural properties of the composites have significantly improved. Chemical treatments improve the surface roughness of the fibers for better mechanical interlocking (Ahmad, Hamid, and Osman 2019). It also enhances cellulose exposure on the fiber surface, increasing the number of possible reaction sites. Safiee et al. (2011). analyzed the compressive and flexural properties of jute fiber-reinforced unsaturated polyester rods fabricated using pultrusion. The pultruded jute rods with 70% fiber content recorded 149 MPa and 890 MPa for compressive strength and flexural strength, respectively. The composite rod demonstrated major failure modes: matrix yield, shear failure, fiber micro buckling, and pure fiber compressive failure. Another study was conducted by (Hedayati Velis, Golzar, and Yousefzade 2018). where jute, high-density polyethylene, wood flour and starch were used as raw materials to develop pultruded tube profiles. The researchers compared the tensile properties by varying the matrix systems using jute fibers as reinforcement. The study introduced thermoplastic starch as a biopolymer matrix system and compared it with a high-density polyethylene (HDPE) matrix system. The study revealed that jute/HDPE tubes have higher tensile strength and modulus when compared to other jute/thermoplastic starch tubes. Additionally, wood flour was tested as a filler in jute-reinforced HDPE composites. Adding 10% of wood flour filler to jute/HDPE improved the tensile modulus up to 8.27 GPa. However, the tensile strength of jute/HDPE decreases when wood flour is added due to the weak interface between the filler and matrix.

Research on filler loading, filler composition, fiber loading, yarn size, matrix system and immersion environment as tested parameters in pultruded PFCs has been demonstrated, and the best parameters from the tests are also highlighted. Similar findings on the optimum fiber loading (70%) for kenaf fiber reinforced pultruded composites were recorded by (Zamri, Akil, and MohdIshak 2016). and (Zamri et al. 0000). where the composites recorded the highest mechanical performance. (van de Velde and Kiekens 2001; van de Velde, van Langenhove, and Kiekens 1998) studied thermoplastic pultruded profiles using flax fiber as reinforcement and compared its mechanical properties with pultruded Glass/Polypolypropylene composites. The flexural and tensile properties of pultruded Flax/PP round profiles showed good values, although lower than those of Glass/PP rectangular profiles. The findings have proven the possibility of developing pultruded plant fibers using a thermoplastic matrix with good mechanical properties at a lower density ($0.08 \pm 0.04 \text{ g/cm}^3$).

Peng et al. (2012). stated that hemp/wool fiber reinforced pultruded composite using a polyurethane resin system had higher tensile and compressive properties than vinyl ester and

polyester resin systems. However, polyester composites show better flexural strength. The study gave an overview of the importance of fiber impregnation and fiber – matrix adhesion between plant fibers and different matrix systems to ensure better mechanical and physical properties for applications of pultruded PFC as structural components. Additionally, studies on filler loadings and filler composition in pultruded PFCs were also conducted by (Fairuz et al. 2016). and (Gupta et al. 2019). respectively. Typically, fillers are used in composites to reduce costs and improve properties. This is proven by (Fairuz et al. 2016). when the tensile, compressive, and flexural properties of kenaf-reinforced pultruded composites have improved with the increase of filler loading in the composite. However, the optimum amount of added filler loading is also necessary to avoid the resin getting too viscous with too high filler composition, resulting in voids and poor wettability in the composites.

Physical properties of pultruded plant fiber composites

The physical properties of plant fiber composites must be investigated to ensure the composites' longevity and durability. For instance, a high moisture absorption would lead to poor interfacial bonding between the fiber and matrix, resulting in mechanical failure in composites (Zakikhani et al. 2014). Besides analyzing the mechanical properties of different resin systems, (Peng et al. 2012). also studied the physical properties by investigating the water absorption properties. As a result, hemp/wool fiber-reinforced polyurethane samples recorded the highest water absorption rate due to the presence of voids. Nosbi et al. (2010) researched the water absorption properties of pultruded kenaf-reinforced unsaturated polyester composites. The composites displayed the highest absorption in distilled water, followed by acidic solution and seawater. The findings also indicated the decay in compressive properties with an increased water absorption rate. The failure properties of the composites were explained due to the formation of hydrogen bonding between the water molecules and cellulose presence in kenaf fibers.

Similarly, (Akil et al. 2009). evaluated the physical properties of pultruded jute fiber reinforced composites by testing the water absorption properties of the composites. The results revealed maximum water absorption in the samples immersed in distilled water, followed by acidic solution and seawater. They also recorded that the flexural and compressive properties decreased with an increasing water absorption rate. However, compared to the study conducted by (Nosbi et al. 2010), pultruded jute fiber composites show a lower water absorption rate than pultruded kenaf-reinforced composites. This condition could be attributed to the better fiber matrix interface in jute-reinforced composite than kenaf-reinforced composite. Overall, the studies indicated that pultruded PFCs have limitations in application in aqueous environments, resulting in swelling and failure of the structure. However, further research on coatings and surface engineering on pultruded PFCs could widen the prospects of the material for outdoor applications.

The literature review has given an overview of research progress on pultruded PFCs over the years. The efforts taken by researchers to study the process parameters and characterization in mechanical and physical properties of pultruded PFCs have validated the prospects and limitations for the development of commercial low load-bearing structural and non-structural products. Although the properties offered by pultruded PFCs are not as good as those of conventional fiberglass profiles, the composites showed better mechanical properties than some of the conventional plastics used in low-load structural and non-structural applications. Besides that, the optimum amount of plant fibers used in pultrusion could reach as high as 70% compared to other composite fabrication methods. This also shows that a large portion of synthetic materials (glass fiber reinforcements and plastics) in structures could be potentially replaced by plant fiber reinforcements via pultrusion. PFC pultruded profiles can be used in architectural and construction applications with relatively low loads (Furtos et al. 2021, 2022). For instance, they can be used in window and door frames, curtain wall systems, decorative elements, handrails, and lightweight structural components that do not carry significant loads. Besides that, various types of plant fibers offer different properties that can be studied in the future by implementing them into pultruded FRP composites. Hence, there is still a massive scope in designing

and manufacturing pultruded products with PFCs. The world's concern to “go green” encourages researchers and industrialists to develop eco-friendly materials with good performance and sustainable properties.

Hybridizing plant fibres with synthetic fibres via Pultrusion

Composites using two or more types of reinforcement or matrix are known as hybrid composites (Sanjay and Yogesha 2017), which can be made from a combination of plant and synthetic fibers, synthetic and synthetic fibers, or plant fiber and carbonaceous materials (Nurazzi et al. 2021). Although plant fibers have advantages in pultruded composite production, the combination of plant fibers alone is insufficient to provide good mechanical properties. PFCs have several disadvantages, such as their low impact strength, high moisture absorption, low fire resistance and high temperature when compared with synthetic fiber reinforced composites, requiring them to be combined with synthetic fibers to enhance the mechanical performance and water-resistant properties. The hybridization of plant fibers with synthetic fibers could reduce the limitations of both plant and synthetic fibers individually while producing materials with eco-friendly and durable advantages (Safri et al. 2018).

The three main factors affecting the properties of the hybrid composites are the selection of materials, preparation methods and the interaction between fiber and matrix (Mochane et al. 2019). Other factors that should be considered while designing hybrid PFCs are the mechanical and physical properties, recyclability, environmental sustainability, disposability, cost, treatments, and test methods according to the intended applications. The three most used hybrid configurations are interlayer (layer by layer), interlayer, and inter yarn (Prabhu et al. 2021). Lackey et al. (2007). have successfully fabricated hemp/glass-reinforced pultruded composites using unidirectional hemp yarn and woven hemp fabrics. The study used pull speeds of 2.03 cm/s (48–60 in/min) and a die temperature of 177°C (350°F) to process hemp fiber without damage, as hemp could withstand 177°C processing temperature during pultrusion. The researchers also stated that the processing temperatures during the pultrusion of plant fibers are limited. Hence, a suitable process temperature is essential to avoid damage to the plant fibers. Volumetric composition, such as volume fractions of fibers, matrix and porosity, is also one of the factors affecting the performance of the pultruded hybrid composites, such as mechanical, physical and thermal properties. Typically, the volumetric composition of composites is controlled during manufacturing of composites. However, a different approach has been conducted by Madsen, Hashemi, and Tahir. to control the volumetric composition in pultruded hybrid composites. The researchers studied the volumetric composition in pultruded kenaf/glass-reinforced hybrid composites by developing a generic model and validating it with experimental data. The model can be used to control and design the volumetric composition in pultruded hybrid composites. This method effectively saves time and cost in finding the best composition in pultruded composites.

Most of the research on plant/synthetic fiber reinforced hybrid composite involves finding the best parameters to improve its mechanical and physical properties as a function of fiber loading, fiber preforms (length, shape and size), fiber orientation, stacking sequence, chemical treatments, fiber and matrix selection and adhesion between fiber and matrix (Karthi et al. 2020). The mechanical properties of hybridized composites depend on factors such as fiber loading, fiber orientation, stacking sequence, hybrid ratio and fiber-matrix interfacial strength (Neto et al. 2022, 2019). Research has been carried out on the hybrid plant/glass fiber composites using pultrusion processing, presented in Table 2. Mechanical, physical and tribological properties have been investigated on pultruded plant/glass fiber reinforced hybrid composites. Glass fibers have been used as the synthetic component, whereby kenaf and jute as plant fibers develop pultruded composites.

Mechanical properties of pultruded hybrid plant/glass fiber composites

All studies have validated that hybrid composites demonstrate better mechanical properties than pure PFCs. Zakaria et al. (2020); Hashemi et al. (2015); Malek et al. (2014). have compared the mechanical

Table 2. Research on the characterization of plant/synthetic fiber reinforced hybrid pultruded composites.

Year	Author	Composite materials	Tested variables	Parameters of variables	Test analysis	Obtained data	
						Best parameter composition	Results
<i>Mechanical Properties</i>							
2021	Kumar, Wallia, and Angira (2021a)	Jute/Glass + Polyester	Hybrid filler loading (Wt. %)	0/3/6/9/12/15	Impact strength Tensile strength Compressive strength	0 Wt.% 9 Wt.% 9 Wt.%	731.91 J/m 88.37 MPa 56.13 MPa
2020	Zakaria et al. (2020)	Kenaf/Glass + Unsaturated Polyester	Various types of pultruded composites	KFRP/GFRP/HFRP/KFRPC4/KFRPO4	Flexural strength retention and recovery (Room Temp) Flexural strength retention and recovery (Hygrothermal)	HFRP HFRP	73.83% and 79.08% 46.04% and 47.90%
2019	Naga Kumar, Prabhakar, and Il Song (2019)	Jute/Glass + Polyester	Variation in weight percentage of filler (Wt. %)	Coconut coir ash/carbon black/eggshell ash	Tensile strength Compressive strength	9% carbon black filler 15% egg shell filler	76 MPa 99.44 MPa
2015	(Hashemi et al. 2015)	Kenaf/Glass	Hybrid fiber mixing ratio (β)	0.00/0.09/0.22/0.38/0.63/1.00	Interlaminar shear strength	0.09 β	14.5 MPa
2014	Malek et al. (2014)	Kenaf/Glass + Resol type phenolic	Different ratios of glass/kenaf hybrid FRP composites with and without additives	Glass: Kenaf, 0:100/20:80/40:60/60:40/80:20/100:0	Bending strength Bending modulus	60:40 (With additives) 80:20 (With additives)	110–120 MPa 900–1000 MPa
2013	Memon and Nakai (2013b)	Jute Spun Yarn/PLA/Glass	Different braided preforms, pultrusion temperature, filling ratio	GF520/GF600/GF720/GF1150	Bending strength Bending modulus	Braided preform = GF720 Temperature = 205°C Filling Ratio = 120%	31.83 MPa 10.40 GPa
2010	Akil et al. (2010)	Jute/Glass + Polyester Kenaf/Glass + Polyester	Type of pultruded glass/plant hybrid fiber composites	Pultruded jute/glass and kenaf/glass hybrid polyester composites	Flexural strength Flexural modulus	Jute/Glass Jute/Glass	325–350 MPa 20–25 GPa
<i>Physical Properties</i>							
2022	Alaseel et al. (2022)	Kenaf/Glass + Polyester	Volume fraction of kenaf and glass fibers	20KGPE/30KGPE/40KGPA/GUPE	Reduction of flexural property due to water absorption (%)	30KGPE hybrid	24%
2020	Bassam et al. (2020)	Kenaf/Glass + Polyester	Volume fraction of kenaf and glass fibers	20KGPE/30KGPE/40KGPA/GUPE	Dielectric strength (kV/mm)	30KGPE hybrid	2.73 kV/mm

(Continued)

Table 2. (Continued).

Obtained data						
Year	Author	Composite materials	Tested variables	Parameters of variables	Test analysis	Best parameter composition Results
2013	Osman, Akil, and Mohd Ishak (2013)	Kenaf/Glass	Type of pultruded glass/plant hybrid fiber composites	PKRC/PGRC/PKGRC	Maximum moisture content (%)	PKGRC (Flexural sp.) 3.789%
					Diffusion coefficient (m ² /s)	PKGRC (Compression sp.) 6.47%
						PKGRC (Flexural sp.) 2.256 × 10 ⁻¹¹ m ² /s
						PKGRC (Compression sp.) 3.290 × 10 ⁻¹¹ m ² /s
2011	Zamri et al. (2012)	Jute/Glass + Unsaturated polyester	Immersion environment	Distilled water/Sea water/Acidic water	Maximum moisture content (%)	Distilled water (Flexural sp.) 4.46%
					Highest diffusion coefficient (m ² /s)	Distilled water (Compression sp.) 5.16%
						Distilled water (Flexural sp.) 7.14 × 10 ⁻¹² m ² /s
						Distilled water (Compression sp.) 2.68 × 10 ⁻¹¹ m ² /s
Tribological Properties						
2021	Kumar, Wallia, and Angra (2021b)	Jute/Glass + Polyester	Hybrid filler loading (Wt. %)	0/3/6/9/12/15	Coefficient of friction (COF)	9 Wt. % 0.22
2014	Nasir and Ghazali (2014)	Kenaf/Glass	Type of pultruded hybrid plant fiber composites	Polypropylene/PSRP composite/pultruded glass-fiber/unidirectional glass-pultruded-kenaf	Lowest wear rate	Unidirectional glass pultruded kenaf 4.02 × 10 ⁻⁸ mm ³ /Nm
					Coefficient of friction (COF)	Unidirectional glass pultruded kenaf 3–4.5

properties of pultruded hybrid glass/plant fiber reinforced composites with pure pultruded PFCs. Pultruded hybrid glass/kenaf reinforced composites have outperformed pure pultruded PFC and GFC by recording higher bending strength and bending modulus at ratios of 60:40 and 80:20, respectively. According to (Zakaria et al. 2020; Akil et al. 2010), hybridized composites have shown better flexural strength and flexural modulus than pure pultruded PFCs. Hashemi et al. (2015). have proven that at 0.09 β of glass/kenaf-hybrid-fiber mixing ratio, the composite has improved its interlaminar shear strength. However, as the hybrid fiber mixing ratio increases, the ILSS of composites decreases due to the moisture absorption properties of kenaf fiber that limit the impregnation of the fibers in the composites, hence forming voids. A different approach was conducted by (Memon and Nakai 2013a, 2013b) when jute in the form of tubular spun yarn and polylactic acid (PLA) resin fibers were commingled and hybridized with glass fibers to fabricate pultruded composites. The bending properties were analyzed on the hybrid thermoplastic composites by varying the braided preforms and finding the composites' best processing temperature and filler ratio. The results revealed that the best bending properties were found at 205°C and 120% of processing temperature and filler ratio, respectively, for GF720 preform. (Kumar, Walia, and Angra 2021a). studied the influence of hybrid filler loading on jute/glass fiber reinforced hybrid pultruded composites. In their findings, the researchers stated that 9 Wt.% of hybrid filler loading is the optimum loading as the highest tensile and compressive strength is achievable by the composition. However, the highest impact strength is recorded when no filler is added to the hybrid composite.

Physical properties of pultruded hybrid plant/glass fiber composites

To analyze the physical properties of pultruded hybrid composites, (Osman, Akil, and Mohd Ishak 2013). studied the moisture absorption properties of pultruded glass/kenaf composites and compared the data with pure kenaf, and pure glass-reinforced pultruded composites. The findings indicated hybrid samples show lower moisture absorption properties than pure kenaf-reinforced composites. Although the hybrid composites were proven to absorb water at a slightly higher rate than pure glass composites, the difference was minimal. Zamri et al. (2012). analyzed the water absorption properties of jute/glass fiber reinforced unsaturated polyester pultruded hybrid composites. They found that the composites show maximum absorption rate in distilled water followed by acidic solution and seawater. They also validated that hybrid composites show significantly higher mechanical and water absorption performance than pure plant fiber composites. The investigation highlighted that through glass fiber hybridization, plant fibers tend to reduce their water absorption capacity. Both studies show that the flexural and compressive properties tend to decrease with increased water uptake. Therefore, a lower water absorption capacity is highly preferred for applying pultruded hybrid PFCs outdoors. (Bassam et al. 2020). mentioned that the dielectric strength of kenaf/glass-reinforced unsaturated polyester hybrid composites was higher than that of pure glass-reinforced UPE composites. Bundled kenaf close together raised dielectric strength because plant fibers have better insulating properties, as evidenced by the burning effect. Moreover, the researchers also conducted another study analyzing the effect of moisture absorption on the flexural properties of kenaf/glass/UPE rods (Alaseel et al. 2022). The study highlighted that the flexural strength of pultruded hybrid composites was retained by the arrangement of kenaf fiber in a composite when the hydrophilic fiber was concentrated at the center of a cross-section of the composite rod.

Tribological properties of pultruded hybrid plant/glass fiber composites

Tribological properties are the wear and friction properties of a material. Researchers recorded that plant fibers demonstrated less abrasive damage to processing equipment due to the high cellulose content of the soft fibers. Nasir and Ghazali (2014). conducted a different approach to unidirectional glass-pultruded-kenaf (UGPK) composites by comparing their tribological properties with paddy straw-reinforced polypropylene, pure polypropylene, and pultruded glass fiber. The findings show that hybrid glass/kenaf pultruded composites scored the lowest wear rate and highest coefficient of

friction compared to other samples, including pure glass fiber pultruded composites. It validates the strong bonding between fiber and matrix in pultruded kenaf/glass hybrid composites, making them a suitable alternative to conventional fiberglass profiles. According to researchers, optimum fiber loading and fiber treatment of plant fibers could result in better wear and friction properties (Nirmal, Hashim, and Megat Ahmad 2015; Sumithra and Sidda Reddy 2018). Another study on the wear resistance of hybrid pultruded composites was conducted by (Kumar, Walia, and Angra 2021b), when tested with different loading parameters of hybrid fillers. From the experiments, 9 Wt.% loading of hybrid fillers recorded the highest wear resistance, scoring the lowest coefficient of friction (COF) in hybrid jute/glass pultruded composites. The low coefficient of friction improved the wear resistance in the composites.

In general, hybridization of composites is known to be a method for overcoming the limitations of both plant and synthetic materials by combining multiple materials to utilize and enhance the individual characteristics of each material (Naga Kumar, Prabhakar, and Il Song 2019). Applying the hybridization of plant and synthetic fibers into pultrusion will open opportunities in manufacturing high-performance structural profiles with advantages from both types of fibers. In most cases, the mechanical and physical properties of pultruded hybrid glass/plant fiber composites were not as high as pure fiberglass composites. However, they performed better than pure pultruded PFCs (Figure 6). However, pure plant fiber reinforced pultruded composites and hybrid glass/plant fiber hybrid composites demonstrate better properties than petroleum-based plastic materials. Pure pultruded PFCs are suitable for low load-bearing structural applications. In contrast, the hybrid composites could replace pure fiberglass composites in moderate load-bearing pultruded profiles in various industries such as aerospace, civil, marine, automotive and sporting goods. For instance, bicycle frames, seat frames, ladders, stairs, gratings, flooring beams and mezzanine floors are some examples of moderate load-bearing structural applications in which glass/plant hybrid pultruded profiles can be potentially applied. Overall, it can be concluded that hybridizing plant fibers with synthetic fibers via pultrusion has shown impressive, improved properties compared to pure plant fiber and reinforced pultruded composites. Hence, it is crucial to analyze the application suitability of pultruded plant fiber reinforced composite profiles to match the product design criteria in terms of mechanical and physical performance.

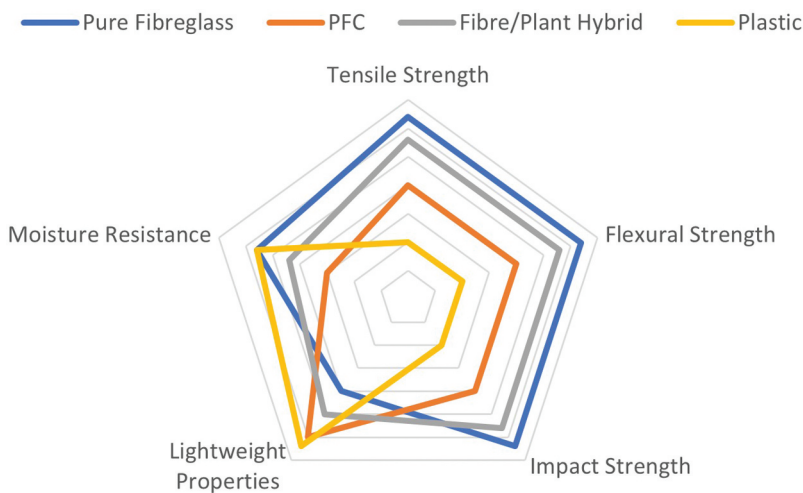


Figure 6. Graphical comparison of properties between synthetic materials and pultruded PFCs.

Future scope and research directions

Pultruded composites have gained significant traction across a multitude of industries and market sectors due to their exceptional versatility and performance capabilities (Pultruded Composites Market Growing, Says EPTA | Composites World 2022; Vedernikov et al. 2020). The Asia Pacific region is poised to emerge as a dominant player in the pultrusion market, primarily driven by its surging demand for pultruded products (Rasheed et al. 2023; Pultrusion Market Size, Share, Industry Forecast 2029 2022, Key Development Opportunities for the Pultrusion Market 2022, Pultrusion Products Market Size, Trends - Industry Outlook Report 2028 2022). These versatile pultruded profiles find extensive use in various sectors, including construction, automotive, aerospace, maritime, utilities, and energy. Their appeal lies in the ability to serve both straightforward and complex structural applications. Notably, pultruded profiles offer the advantage of uniform cross-sections and the flexibility to be manufactured in varying lengths, making them adaptable to diverse project requirements. Furthermore, the ease of working with pultruded profiles, whether cutting, painting, drilling, or attaching them to other materials using adhesives, rivets, screws, or bolts, enhances their practicality in diverse applications. As the utilization of pultruded profiles continues to expand across industries, the imperative for sustainable materials becomes increasingly apparent. This is where plant fibers come into the spotlight, serving as cost-effective, eco-friendly, and lightweight alternatives. They offer a promising solution for developing sustainable structural profiles, particularly in low to moderate load-bearing applications. Integrating plant fiber yarns and woven plant fiber mats into the conventional pultrusion process requires minimal modification to the existing setup (Figure 7), making it a feasible and eco-conscious transition (Baley et al. 2020). This innovation aligns with sustainability goals and capitalizes on the inherent benefits of plant fibers to create more environmentally responsible and efficient structural solutions for a wide range of applications.

While pultruded Plant Fibre Composites (PFCs) exhibit commendable mechanical properties well-suited for low to moderate-load applications, it is essential to acknowledge their inherent limitations.

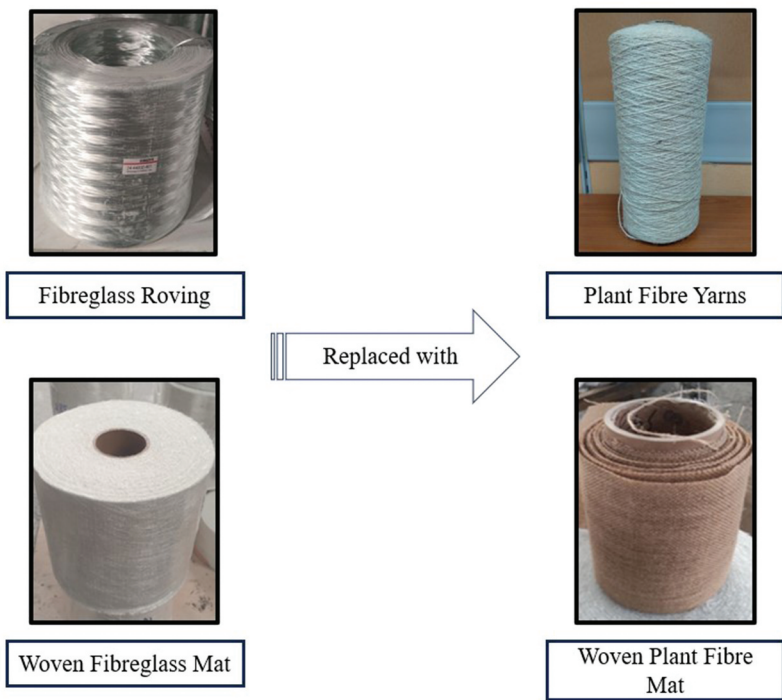


Figure 7. Plant fibres in yarn and woven form as sustainable alternatives in pultrusion.

These limitations, including high water absorption, limited flame retardancy, and low chemical and UV resistance properties, render them less suitable for deployment in harsh outdoor and aqueous environments (Bourmaud et al. 2020). To unlock the full potential of PFCs in such challenging settings, it is imperative to delve into further research focused on enhancing their performance. One promising improvement avenue lies in exploring advanced coatings and surface engineering techniques tailored explicitly for pultruded PFCs (Da Wu et al. 2023; Ding, Zhao, and Yu 2022; Pourhashem et al. 2020; Wang et al. 2019). These innovations aim to mitigate the limitations and bolster their applicability in extreme conditions. For instance, integrating surfacing veils represents a crucial area of investigation. These veils can enhance temperature stability, fire resistance, chemical resistance, abrasion resistance, and moisture resistance in pultruded profiles reinforced with plant fibers. PFCs can become more resilient and adaptable to demanding outdoor and aqueous environments by addressing these key attributes. An investigation by (Kandare, Luangtriratana, and Kandola 2014), demonstrated that the fire-retardant properties of balsa-flax/epoxy laminates significantly improved when a thin glass fiber veil impregnated with ammonium polyphosphate was used as a surfacing veil. The researchers mentioned that applying fire retardant surfacing veils in plant-fiber composites proves their potential in semi-structural engineering applications threatened by fire. Studies have also been carried out on fiber coatings for plant fibers in composites to enhance their compatibility with the surrounding matrix material, improving adhesion and overall composite performance (Arulvel et al. 2021; Mysamy and Krishnasamy 2022). These fiber surface coatings can mitigate moisture absorption and fiber-matrix bonding issues, leading to stronger and more durable PFCs for structural profile applications. According to (Page et al. 2021), linseed oil coating on flax fiber reinforcement improved the flexural strength of the composites.

In addition to examining fiber reinforcements, an equally crucial aspect deserving of attention lies in selecting matrix systems used in pultruded Plant Fiber Composites (PFCs). This facet has seen a notable shift in focus, driven by the emergence of bio-based resins and innovative thermoplastic pultrusion techniques. Bio-based resins have risen to prominence as they enhance the sustainability quotient of these profiles and seamlessly align with broader eco-friendly objectives. Researchers and industrialists have developed resins derived from plant oil and starches, a distinct departure from conventional petrochemical-based options (Cataño et al. 2023). Notably, this shift toward bio-based resins has encompassed various renewable alternatives, including olive oil, sunflower oil, soybean oil, corn oil, castor oil, rapeseed oil, and linseed oil (Bassett et al. 2016; Latif et al. 2020). The research landscape is ripe for exploring abundant renewable alternatives, such as cellulosic plant fibers and vegetable oil-based bio-resins, which promise to achieve 100% sustainable pultruded profiles.

Additionally, using thermoplastic pultrusion allows for more excellent recyclability of the composites, minimizing their environmental footprint (Awais et al. 2021; Chen et al. 2019; Lessard, Dubé, and Laberge Lebel 2022). This approach fosters a holistic approach to materials development, ensuring that PFCs meet performance demands and align with sustainability and environmental considerations. Several studies on thermoplastic pultrusion have been recorded by (Minchenkov et al. 2021, 2022). The researchers stated that replacing thermosets with thermoplastics in pultrusion benefits in improved impact strength, recyclable, and allows welded joints in pultruded profiles. However, thermoplastic resin has a significant problem for its application in pultrusion. Due to its high melt viscosity, which hinders fiber impregnation, prepregs such as tow pregs, commingled yarns, and preconsolidated tapes are used in thermoplastic pultrusion (Minchenkov et al. 2023; Vedernikov et al. 2022). To facilitate plant fiber reinforcement in thermoplastic pultrusion, plant fiber prepregs are another unexplored scope of research which needs significant attention. Parameters such as the resin flow, impregnation, crystallization, heat transfer, and pulling speed must be investigated when different resin systems are used (Alsinani and Laberge Lebel 2022; Alsinani, Ghaedsharaf, and Laberge Lebel 2021).

Expanding upon the review, it becomes evident that further investigation into various mechanical properties is imperative for harnessing the full potential of plant fibers in pultruded structural profiles. While the existing research has shed light on essential aspects, such as tensile strength and stiffness, it

is equally essential to explore properties like fatigue resistance, creep behavior, damping properties, and thermomechanical attributes (Rahman 2021; Yu et al. 2023). The determination of glass transition temperatures is of particular significance, which can provide valuable insights into the temperature ranges within which these profiles can perform optimally. In addition to the considerations mentioned earlier, it is crucial to emphasize the need to develop novel methodologies for determining the optimal parameters in the pultrusion process of Plant Fibre Composites (PFCs) through numerical modeling and machine learning (Safonov, Carlone, and Akhatov 2018; Safonov et al. 2020; Sandberg et al. 2021, 2020; Tucci et al. 2020). This entails leveraging computational tools and simulations to fine-tune various processing parameters, such as temperature profiles, pulling speeds, and resin formulations. By utilizing computer predictive methods, researchers and manufacturers can achieve greater precision and efficiency in the pultrusion of PFCs, ultimately leading to improved product quality, reduced material waste, and enhanced sustainability (Duchet-Rumeau et al. 2022).

Researchers are actively contributing their findings to address the inherent limitations of pultruded Plant Fibre Composites (PFCs), aiming to position them as a viable and eco-friendly choice for manufacturing profiles across diverse sectors. The trajectory for the adoption of both pure and hybrid pultruded composites derived from PFCs is expected to experience significant growth on a global scale (Johnson, Kang, and Akil 2016). As researchers and industrialists continue to refine the selection of reinforcements and optimize processing techniques, there is a tangible opportunity to design and develop structural materials that prioritize environmental sustainability and offer economic advantages (Balakrishnan et al. 2022; Kamarudin et al. 2022). Figure 8 and Table 3 illustrate a range of potential applications for pultruded PFCs across various industries, focusing on applications involving low to moderate loads.

Overall, implying plant fibers into pultruded composites represents a significant step in manufacturing high-performance and environmentally friendly materials for structural and non-structural applications that can potentially replace and reduce the use of synthetic fibers and plastic materials in numerous applications and industries. Pultruded PFCs could potentially reduce the carbon emissions from the petrochemical production plants of synthetic fibers and plastics, causing numerous negative environmental issues in the past few decades. Developing sustainable materials is related to the environment’s social and economic status,

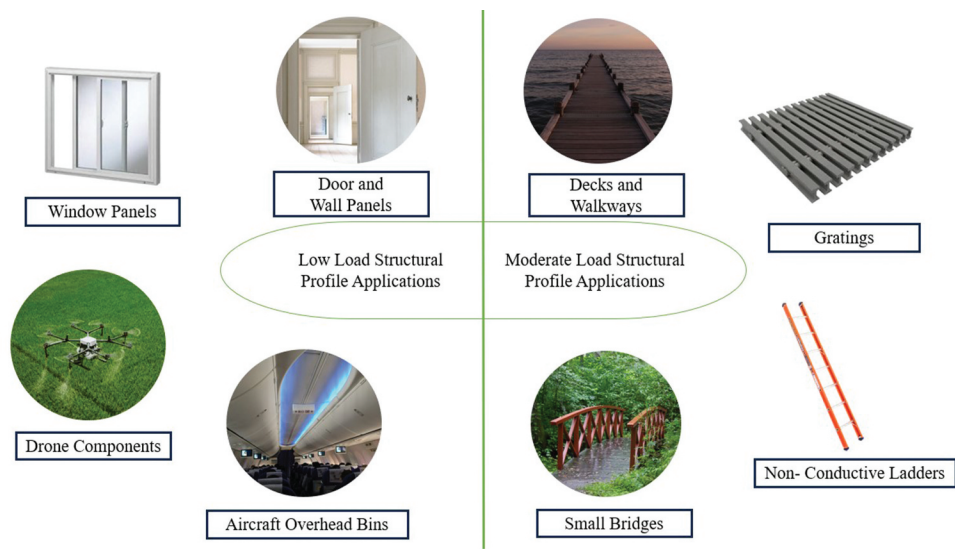


Figure 8. Moderate and low load application possibilities of pultruded PFCs.

Table 3. Potential industrial applications of pultruded PFCs (Ramasubbu and Madasamy 2020; Syduzzaman et al. 2020).

Industries	Applications
Aerospace	Maintenance platforms and ladders, aircraft interior profiles, satellite components, drone components, upper deck floor beams.
Construction	Residential and commercial windows, doors, frame profiles, electrical supports, roll-up door panels, construction board, insulation board.
Electrical and Electronics	Switch boxes, cored tubing, cable trays, static arrestors, trunking.
Transportation	Automotive components, fittings, enclosures, chassis rails, bumper beams, roof beams.
Utilities and other applications	Utility poles, tool handles, demisting blades, cross arms, line markers, non-conductive ladders and rails, fiber optic cabling, fishing rods, ski poles, tennis rackets.

which ensures a carbon-free environment while improving the standard of life (Agan and Balcilar 2022; Du, Li, and Yan 2019; Yi et al. 2019). Hence, the implication of plant fibers in uplifting green technology serves numerous advantages economically, socially, and environmentally. These efforts are believed to uplift the agricultural industry for composite manufacturing and create more job opportunities among the farmers and labors in the agricultural sectors. Besides, waste materials such as pineapple leaf fibers, coir, sugarcane, and oil palm fibers can be innovated efficiently into producing pultruded PFCs, which can be used in various applications. The innovations in eco-friendly materials do not significantly contribute to solving sustainability issues for the economies with low-income levels. At the same time, the mitigation effect becomes significant for those with developed economies. Therefore, the government and private agencies of the developed economies should encourage the R&D sectors and industry players to make green materials emerge in the near future.

Conclusion

From the review conducted, the following conclusions can be drawn. The implication of plant fibers such as kenaf and jute in pultruded plant fiber composites and pultruded hybrid glass/plant fiber composites show good properties, proving the capability as alternatives to conventional plastic and fiberglass materials in low load and moderate load-bearing structural and non-structural applications. Potential applications of plant fibers in pultruded FRP composites and their limitations are identified based on the mechanical and physical characterization of pure and hybrid pultruded PFCs. Applying plant fibers in developing pultruded profiles with their excellent low weight, low cost, good mechanical properties, and environmentally friendly properties will improve the sustainability and environmental issues in building materials. There is still a vast scope of work ranging from process parameters optimization and material characterization to product development for pultruded PFCs to make them competitive with synthetic fibers in commercial applications.

Highlights

- An overview of the optimum process parameters and characterization of pultruded PFCs from previous research work has been analyzed and highlighted.
- Implication of plant fibers such as kenaf and jute in pultruded plant fiber composites and pultruded hybrid glass/plant fiber composites show satisfactory properties and hence, proven the capability as alternatives to conventional pultruded fiberglass in low load and moderate load bearing structural applications respectively.
- Potential applications of plant fibers in pultruded FRP composites and their limitations were identified based on the mechanical and physical characterization of pure and hybrid pultruded PFCs.
- A huge scope of work and research gap ranging from process parameters optimization and material characterization to product development is discussed for pultruded PFCs to make it competitive to synthetic fibers in commercial applications.

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Disclosure statement

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Authors contributions

Conceptualization, TSB, MTHS, AUMS, and FSS; methodology, TSB, AUMS, and FSS; formal analysis, TSB; investigation, TSB; data curation, TSB; writing – original draft preparation, TSB; writing – review and editing, MTHS, TAS, FSS, SYN, and AAB; visualization, TSB; supervision, MTHS, AUMS, TAS, and AAB; project administration, MTHS, SYN, and TAS; funding acquisition, MTHS and SYN. All authors have read and agreed to the published version of the manuscript. All authors have accepted responsibility for the entire content of this manuscript and approved its submission. In contrast, the authors assisted in important tasks, such as manuscript preparation, clerical assistance, and technical assistance.

Data availability statement

All data generated or analyzed during this study are included in this published article.

References

- Agan, B. and M. Balcilar, "On the Determinants of Green Technology Diffusion: An Empirical Analysis of Economic, Social, Political, and Environmental Factors." *Sustainability* 14 (4): 2008, Feb. 2022, <https://doi.org/10.3390/SU14042008>.
- Ahmad, R., R. Hamid, and S. A. Osman. 2019. "Physical and Chemical Modifications of Plant Fibres for Reinforcement in Cementitious Composites." *Advances in Civil Engineering* 2019:1–18. <https://doi.org/10.1155/2019/5185806>.
- Akil, H. M., L. W. Cheng, Z. A. Mohd Ishak, A. Abu Bakar, and M. A. Abd Rahman. Sep 2009. "Water absorption study on pultruded jute fibre reinforced unsaturated polyester composites." *Composites Science and Technology* 69 (11–12): 1942–1948. <https://doi.org/10.1016/J.COMPOSITECH.2009.04.014>.
- Akil, H. M., I. M. De Rosa, C. Santulli, and F. Sarasini. May 2010. "Flexural Behaviour of Pultruded Jute/Glass and Kenaf/Glass Hybrid Composites Monitored Using Acoustic Emission." *Materials Science and Engineering: A* 527 (12): 2942–2950. <https://doi.org/10.1016/J.MSEA.2010.01.028>.
- Alaseel, B. H., M. A. Mohamed Nainar, N. A. Nordin, Z. Yahya, and M. N. Abdul Rahim. 2022. "Science & Technology Effect of Water Absorption on Flexural Properties of Kenaf/Glass Fibres Reinforced Unsaturated Polyester Hybrid Composites Rod." *Pertanika Journal of Science & Technology* 30 (1): 397–412. <https://doi.org/10.47836/pjst.30.1.22>.
- Alsinani, N., M. Ghaedsharaf, and L. Laberge Lebel. 2021. "Effect of Cooling Temperature on Deconsolidation and Pulling Forces in a Thermoplastic Pultrusion Process." *Composites Part B Engineering* 219 (Aug): 108889. <https://doi.org/10.1016/J.COMPOSITESB.2021.108889>.

- Alsinani, N., and L. Laberge Lebel. Oct 2022. "Effect of High Pulling Speeds on the Morphologies of Pultrudates in a Thermoplastic Pultrusion Process." *Journal of Thermoplastic Composite Materials* 36 (9): 3566–3584. <https://doi.org/10.1177/08927057221129991>.
- Angelov, I., S. Wiedmer, M. Evstatiev, K. Friedrich, and G. Mennig. May 2007. "Pultrusion of a Flax/Polypropylene Yarn." *Composites Part A, Applied Science and Manufacturing* 38 (5): 1431–1438. <https://doi.org/10.1016/J.COMPOSITESA.2006.01.024>.
- Aranberri, I., M. Landa, E. Elorza, A. M. Salaberria, and A. Rekondo. 2021. "Thermoformable and recyclable CFRP pultruded profile manufactured from an epoxy vitrimer." *Polymer Testing* 93:106931. <https://doi.org/10.1016/J.POLYMERTESTING.2020.106931>. Jan.
- Arulvel, S., D. Mallikarjuna Reddy, D. Dsilva Winfred Rufuss, and T. Akinaga. 2021. "A Comprehensive Review on Mechanical and Surface Characteristics of Composites Reinforced with Coated Fibres." *Surfaces and Interfaces* 27:101449. <https://doi.org/10.1016/J.SURFIN.2021.101449>. Dec.
- Asyraf, M. R. M., M. Y. Yahya, S. A. Hassan, R. A. Ilyas, D. D. C. V. Sheng, N. N. Mas'ood, W. A. A. Saad, A. H. M. Yusop, and M. Rafidah. 2023. Hybrid Synthetic and Natural Fibres in Honeycomb Sandwich Composite Structures for Structural Applications: A Brief Review Thermoplastic View Project Antibacterial Bionanocomposites Film View Project Hybrid Synthetic and Natural Fibres in Honeycomb Sandwich Composite Structures for Structural Applications: A Brief Review. *Journal of Natural Fibre Polymer Composites (JNEPC)* 2 (1): 2821–3289. [Online]. Accessed September 18, 2023 <https://www.researchgate.net/publication/372134074>.
- Awais, H., Y. Nawab, A. Amjad, A. Anjang, H. Md Akil, and M. S. Zainol Abidin. 2021. "Environmental Benign Natural Fibre Reinforced Thermoplastic Composites: A Review." *Composites Part C: Open Access* 4 (Mar): 100082. <https://doi.org/10.1016/J.JCOMC.2020.100082>.
- Balakrishnan, T. S., M. T. H. Sultan, J. Naveen, F. S. Shahar, M. I. Najeeb, A. U. M. Shah, T. Khan, and T. A. Sebaey. Aug 2022. "Selection of Natural Fibre for Pultruded Hybrid Synthetic/Natural Fibre Reinforced Polymer Composites Using Analytical Hierarchy Process for Structural Applications." *Polymers (Basel)* 14 (15): 3178. <https://doi.org/10.3390/POLYM14153178>.
- Balasubramanian, K., M. T. H. Sultan, and N. Rajeswari. Jan 2018 . "Manufacturing techniques of composites for aerospace applications." *Sustainable Composites for Aerospace Applications*, 55–67. <https://doi.org/10.1016/B978-0-08-102131-6.00004-9>.
- Baley, C., M. Gomina, J. Breard, A. Bourmaud, and P. Davies. 2020. "Variability of Mechanical Properties of Flax Fibres for Composite Reinforcement. A Review." *Industrial Crops & Products* 145:111984. <https://doi.org/10.1016/J.INDCROP.2019.111984>. Mar.
- Barkanov, E., P. Akishin, E. Namsone, J. Auzins, and A. Morozovs. Jan 2021. "Optimization of Pultrusion Processes for an Industrial Application." *Mechanics of Composite Materials* 56 (6): 697–712. <https://doi.org/10.1007/s11029-021-09916-7>.
- Bassam, A. M. N. M. Ansari, A. R. M. Nazim, S. Thilageshwaran, K. S. Vinoth, F. Abdullah, and N. A. Nordin "Dielectric Strength of Kenaf/Glass Fiber Reinforced Up Hybrid Composites Used as Insulator." *Proceedings of the 2020 International Conference and Utility Exhibition on Energy, Environment and Climate Change, ICUE 2020*, Oct. 2020, <https://doi.org/10.1109/ICUE49301.2020.9307148>.
- Bassett, A. W., S. Kumar Yadav, G. R. Palmese, and J. F. Stanzione. Dec 2016. "Recent Advances in Bio-Based Epoxy Resins and Bio-Based Epoxy Curing Agents." *Journal of Applied Polymer Science* 133 (45). <https://doi.org/10.1002/APP.44103>.
- Bechtold, G., S. Wiedmer, and K. Friedrich. Aug 2016. "Pultrusion of Thermoplastic Composites - New Developments and Modelling Studies." *Journal of Thermoplastic Composite Materials* 15 (5): 443–465. <https://doi.org/10.1177/0892705702015005202>.
- Bourmaud, A., D. U. Shah, J. Beaugrand, and H. N. Dhakal. 2020. "Property Changes in Plant Fibres During the Processing of Bio-Based Composites." *Industrial Crops & Products* 154:112705. <https://doi.org/10.1016/J.INDCROP.2020.112705>. Oct.
- Cataño, F. A., V. Moreno-Serna, A. Cament, C. Loyo, M. Yáñez-S, J. A. Ortiz, P. A. Zapata. et al. Sep 2023. "Green Composites Based on Thermoplastic Starch Reinforced with Micro- and Nano-Cellulose by Melt Blending - a Review." *International Journal of Biological Macromolecules* 248:125939. <https://doi.org/10.1016/J.IJBIOMAC.2023.125939>.
- Chang, B. P., W. H. Chan, M. H. Zamri, H. Md Akil, and H. G. Chuah. Jul 2019. "Investigating the Effects of Operational Factors on Wear Properties of Heat-Treated Pultruded Kenaf Fiber-Reinforced Polyester Composites Using Taguchi Method." *Journal of Natural Fibers* 16 (5): 702–717. <https://doi.org/10.1080/15440478.2018.1432001>.
- Chen, K., M. Jia, S. Hua, and P. Xue. Feb 2019. "Optimization of initiator and activator for reactive thermoplastic pultrusion." *Journal of Polymer Research* 26 (2): 1–10. <https://doi.org/10.1007/s10965-019-1708-6>.
- Chokshi, S., V. Parmar, P. Gohil, and V. Chaudhary. Oct 2022. "Chemical Composition and Mechanical Properties of Natural Fibers." *Journal of Natural Fibers* 19 (10): 3942–3953. <https://doi.org/10.1080/15440478.2020.1848738>.
- Correia, J. R. Jan 2023 . "Pultrusion of Advanced Composites." *Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications*, 137–177. <https://doi.org/10.1016/B978-0-12-820346-0.00007-1>.

- Da Wu, S., W. T. Chuang, J. C. Ho, H. C. Wu, and S. H. Hsu. Apr 2023. "Self-Healing of Recombinant Spider Silk Gel and Coating." *Polymers* 15 (8): 1855. <https://doi.org/10.3390/POLYM15081855>.
- Ding, J., H. Zhao, and H. Yu. 2022. "Bioinspired Strategies for Making Superior Graphene Composite Coatings." *Chemical Engineering Journal* 435:134808. <https://doi.org/10.1016/J.CEJ.2022.134808>. May.
- Duchet-Rumeau, J., J.-F. Gérard, E. Barkanov, P. Akishin, and E. Namsone-Sile. Feb 2022. "Effectiveness and Productivity Improvement of Conventional Pultrusion Processes." *Polymers* 14 (4): 841. <https://doi.org/10.3390/POLYM14040841>.
- Du, K., P. Li, and Z. Yan. 2019. "Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data." *Technological Forecasting & Social Change* 146 (Sep): 297–303. <https://doi.org/10.1016/J.TECHFORE.2019.06.010>.
- Edeerozey, A. M. M., H. M. Akil, A. B. Azhar, and M. I. Z. Ariffin. Apr 2007. "Chemical Modification of Kenaf Fibers." *Materials Letters* 61 (10): 2023–2025. <https://doi.org/10.1016/J.MATLET.2006.08.006>.
- El-Abbassi, F. E., M. Assarar, R. Ayad, A. Bourmaud, and C. Baley. 2020. "A Review on Alfa Fibre (Stipa Tenacissima L.): From the Plant Architecture to the Reinforcement of Polymer Composites." *Composites Part A, Applied Science and Manufacturing* 128:105677. <https://doi.org/10.1016/J.COMPOSITESA.2019.105677>. Jan.
- Esfandiari, P., J. F. Silva, P. J. Novo, J. P. Nunes, and A. T. Marques. Jun 2022. "Production and Processing of Pre-Impregnated Thermoplastic Tapes by Pultrusion and Compression Moulding." *Journal of Composite Materials* 56 (11): 1667–1676. <https://doi.org/10.1177/00219983221083841>.
- Fairuz, A. M., S. M. Sapuan, E. S. Zainudin, and C. N. A. Jaafar. 2015a. "Optimization of Pultrusion Process for Kenaf Fibre Reinforced Vinyl Ester Composites." *Applied Mechanics and Materials* 761 (May): 499–503. <https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMM.761.499>.
- Fairuz, A. M., S. M. Sapuan, E. S. Zainudin, and C. N. A. Jaafar. Sep 2015b. "Pultrusion Process of Natural Fibre-Reinforced Polymer Composites." *Manufacturing of Natural Fibre Reinforced Polymer Composites*, 217–231. https://doi.org/10.1007/978-3-319-07944-8_11.
- Fairuz, A. M., S. M. Sapuan, E. S. Zainudin, and C. N. A. Jaafar. 2016. "Effect of Filler Loading on Mechanical Properties of Pultruded Kenaf Fibre Reinforced Vinyl Ester Composites." *Journal of Mechanical Engineering and Sciences (JMES)* ISSN 10 (1): 1931–1942. <https://doi.org/10.15282/jmes.10.1.2016.16.0184>.
- Fornari, A., M. Rossi, D. Rocco, and L. Mattiello. Dec 2022. "A Review of Applications of Nanocellulose to Preserve and Protect Cultural Heritage Wood, Paintings, and Historical Papers." *Applied Sciences* 12 (24): 12846. <https://doi.org/10.3390/APP122412846>.
- Furtos, G., L. Molnar, L. Silaghi-Dumitrescu, P. Pascuta, and K. Korniejenko. Dec 2022. "Mechanical and Thermal Properties of Wood Fiber Reinforced Geopolymer Composites." *Journal of Natural Fibers* 19 (13): 6676–6691. <https://doi.org/10.1080/15440478.2021.1929655>.
- Furtos, G., L. Silaghi-Dumitrescu, P. Pascuta, C. Sarosi, and K. Korniejenko. Feb 2021. "Mechanical Properties of Wood Fiber Reinforced Geopolymer Composites with Sand Addition." *Journal of Natural Fibers* 18 (2): 285–296. <https://doi.org/10.1080/15440478.2019.1621792>.
- Gupta, A., R. Vaishya, K. L. A. Khan, R. S. Walia, and H. Singh. Oct 2019. "Multi-Response Optimization of Hybrid Filler Composition for Pultruded Jute Fiber Reinforced Polymer Composite." *Materials Research Express* 6 (11): 115324. <https://doi.org/10.1088/2053-1591/AB4945>.
- Haag, K., J. Padovani, S. Fita, J.-P. Trouvé, C. Pineau, S. Hawkins, H. De Jong, et al. Apr 2017. "Influence of Flax Fibre Variety and Year-To-Year Variability on Composite Properties." *Industrial Crops & Products* 98:1–9. <https://doi.org/10.1016/J.INDCROP.2016.12.028>.
- Hashemi, F., P. M. Tahir, B. Madsen, M. Jawaid, D. L. Majid, L. Brancheriau, A. H. Juliana, et al. Sep 2015. "Volumetric Composition and Shear Strength Evaluation of Pultruded Hybrid Kenaf/Glass Fiber Composites." *Journal of Composite Materials* 50 (17): 2291–2303. <https://doi.org/10.1177/0021998315602948>.
- Hedayati Velis, H., M. Golzar, and O. Yousefzade. Dec 2018. "Composites Based on HDPE, Jute Fiber, Wood, and Thermoplastic Starch in Tubular Pultrusion Die: The Correlation Between Mechanical Performance and Microstructure." *Advances in Polymer Technology* 37 (8): 3483–3491. <https://doi.org/10.1002/ADV.22132>.
- Hofmann, M., M. Machado, A. Shahid, F. Dourado, M. Garrido, J. C. Bordado, J. R. Correia, et al. Mar 2023. "Pultruded Carbon Fibre Reinforced Polymer Strips Produced with a Novel Bio-Based Thermoset Polyester for Structural Strengthening." *Composites Science and Technology* 234:109936. <https://doi.org/10.1016/J.COMPSCITECH.2023.109936>.
- Johnson, S., L. Kang, and H. M. Akil. 2016. "Mechanical Behavior of Jute Hybrid Bio-Composites." *Composites Part B Engineering* 91 (Apr): 83–93. <https://doi.org/10.1016/J.COMPOSITESB.2015.12.052>.
- Joshi, S. C., Y. C. Lam, and U. Win Tun. Dec 2003. "Improved Cure Optimization in Pultrusion with Pre-Heating and Die-Cooler Temperature." *Composites Part A, Applied Science and Manufacturing* 34 (12): 1151–1159. <https://doi.org/10.1016/J.COMPOSITESA.2003.08.003>.
- Juliana, A. H., H. A. Aisyah, M. T. Paridah, C. C. Y. Adrian, and S. H. Lee. Jun 2018. "Kenaf Fiber : Structure and Properties." *Kenaf Fibers and Composites*, 23–36. <https://doi.org/10.1201/9781351050944-2>.
- Kamarudin, S. H., M. S. Mohd Basri, M. Rayung, F. Abu, S. Ahmad, M. N. Norizan, S. Osman, et al. Sep 2022. "A Review on Natural Fiber Reinforced Polymer Composites (NFRPC) for Sustainable Industrial Applications." *Polymers* 14 (17): 3698. <https://doi.org/10.3390/POLYM14173698>.

- Kandare, E., P. Luangtriratana, and B. K. Kandola. 2014. "Fire Reaction Properties of Flax/Epoxy Laminates and Their Balsa-Core Sandwich Composites with or without Fire Protection." *Composites Part B Engineering* 56 (Jan): 602–610. <https://doi.org/10.1016/J.COMPOSITESB.2013.08.090>.
- Karimah, A., M. R. Ridho, S. S. Munawar, D. S. Adi, R. Damayanti, B. Subiyanto, et al. Jul 2021. "A Review on Natural Fibers for Development of Eco-Friendly Bio-Composite: Characteristics, and Utilizations." *Journal of Materials Research and Technology* 13:2442–2458. <https://doi.org/10.1016/J.JMRT.2021.06.014>.
- Karthi, N., K. Kumaresan, S. Sathish, S. Gokulkumar, L. Prabhu, and N. Vigneshkumar. 2020. "An Overview: Natural Fiber Reinforced Hybrid Composites, Chemical Treatments and Application Areas." *Materials Today: Proceedings* 27 (Jan): 2828–2834. <https://doi.org/10.1016/J.MATPR.2020.01.011>.
- Keya, K. N., N. A. Kona, F. A. Koly, K. M. Maraz, M. N. Islam, and R. A. Khan. 2019. "Natural Fiber Reinforced Polymer Composites: History, Types, Advantages, and Applications." *Materials Engineering Research* 1 (2): 69–87. <https://doi.org/10.25082/MER.2019.02.006>.
- Key Development Opportunities for the Pultrusion Market. Mar 25, 2022. [Online]. <https://www.tencom.com/blog/opportunities-for-the-pultrusion-market>.
- Khoo, P. S., S. A. Hassan, R. A. Ilyas, T. G. Loganathan, R. T. Adhiguna, K. E. Reby Roy, M. Mubarak Ali, et al. 2023. "Tensile Properties of Ramie Fibre: Effect of Harvesting Day and Extraction Method." *Materials Today: Proceedings*. <https://doi.org/10.1016/J.MATPR.2023.04.247>.
- Koohestani, B., A. K. Darban, P. Mokhtari, E. Yilmaz, and E. Darezereshki. Jan 2019. "Comparison of Different Natural Fiber Treatments: A Literature Review." *International Journal of Environmental Science and Technology* 16 (1): 629–642. <https://doi.org/10.1007/S13762-018-1890-9>.
- Kumar, S., A. Manna, and R. Dang. 2022. "A Review on Applications of Natural Fiber-Reinforced Composites (NFRCS)." *Materials Today: Proceedings* 50:1632–1636. <https://doi.org/10.1016/J.MATPR.2021.09.131>. Jan.
- Kumar, N., R. S. Walia, and S. Angra. 2021a. "Study of Mechanical Properties of Pultruded Jute-Glass Reinforced Unsaturated Polyester Bio-Composites with Hybrid Filler Loading." *World Journal of Engineering* 18 (5): 660–674. <https://doi.org/10.1108/WJE-04-2020-0127>.
- Kumar, N., R. S. Walia, and S. Angra. Dec 2021b. "Tribological Characterization of Pultruded Hybrid Glass-Jute Fibre Reinforced Plastic Composites from Room Temperature to 75°C." *World Journal of Engineering* 19 (6): 871–887. <https://doi.org/10.1108/WJE-03-2021-0147/FULL/XML>.
- Lackey, E., J. G. Vaughan, K. Inamdar, and B. Hancock. 2007. "Statistical Characterization of Pultruded Composites with Natural Fiber Reinforcements - Part A: Fabrication." *Journal of Natural Fibers* 4 (4): 73–87. <https://doi.org/10.1080/15440470801894057>.
- Landesmann, A., C. A. Seruti, and E. D. M. Batista. Nov 2015. "Mechanical Properties of Glass Fiber Reinforced Polymers Members for Structural Applications." *Materials Research* 18 (6): 1372–1383. <https://doi.org/10.1590/1516-1439.044615>.
- Latif, R. F. E. A., Z. Zainal Abidin, F. Cardona, D. R. Awang Biak, K. Abdan, P. Mohd Tahir, and L. Kan Ern. Jan 2020. "Bio-Resin Production Through Ethylene Unsaturated Carbon Using Vegetable Oils." *Processes* 8 (1): 48. <https://doi.org/10.3390/PR8010048>.
- Lessard, F., M. Dubé, and L. Laberge Lebel. 2022. "A Model of Multi-Die Thermoplastic Pultrusion." *Composites Part B Engineering* 247 (Dec): 110319. <https://doi.org/10.1016/J.COMPOSITESB.2022.110319>.
- Li, J., S. C. Joshi, and Y. C. Lam. Feb 2002. "Curing optimization for pultruded composite sections." *Composites Science and Technology* 62 (3): 457–467. [https://doi.org/10.1016/S0266-3538\(02\)00018-0](https://doi.org/10.1016/S0266-3538(02)00018-0).
- Li, P., J. Ma, L. He, S. Wu, P. Yang, L. Zhao, Y. Zhang, et al. Sep 2023. "Pultrusion Preparation and Properties of Continuous Glass Fiber Reinforced Polylactic Acid Thermoplastic Composites." *Journal of Applied Polymer Science* 140 (33): e54292. <https://doi.org/10.1002/APP.54292>.
- Linganiso, L. Z., R. Bezerra, S. Bhat, M. John, R. Braeuning, and R. D. Anandjiwala. May 2013. "Pultrusion of Flax/Poly (lactic Acid) Commingled Yarns and Nonwoven Fabrics." *Journal of Thermoplastic Composite Materials* 27 (11): 1553–1572. <https://doi.org/10.1177/0892705713486137>.
- Liu, T. Q., P. Feng, Y. Wu, S. Liao, and X. Meng. 2021. "Developing an Innovative Curved-Pultruded Large-Scale GFRP Arch Beam." *Composite Structures* 256 (Jan): 113111. <https://doi.org/10.1016/J.COMPSTRUCT.2020.113111>.
- Madhu, P., M. R. Sanjay, P. Senthamaikannan, S. Pradeep, S. S. Saravanakumar, and B. Yogesha. Nov 2019. "A Review on Synthesis and Characterization of Commercially Available Natural Fibers: Part-I." *Journal of Natural Fibers* 16 (8): 1132–1144. <https://doi.org/10.1080/15440478.2018.1453433>.
- Madsen, B., F. Hashemi, and P. Tahir. Control and Design of Volumetric Composition in Pultruded Hybrid Fibre Composites. <https://doi.org/10.1088/1757-899X/139/1/012033>.
- Mahesh, V., and V. Mahesh. Apr 2023. "Harnessing of Waste Rubber Crumb and Development of Sustainable Hybrid Composite Using Kenaf (*Hibiscus Cannabinus*) for Structural Applications." *Journal of Natural Fibers* 20 (1): 45–55. <https://doi.org/10.1080/15440478.2022.2126423>.
- Malek, F. H. A., E. S. Zainudin, P. M. Tahir, and M. Jawaid. 2014. "The Effect of Additives on Bending Strenght of Pultruded Hybrid Reinforced Resol Type Phenolic Composite." *Applied Mechanics and Materials* 564:418–421. <https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMM.564.418>.

- Manivel, S., N. Pannirselvam, R. Gopinath, and T. P. Sathishkumar. Dec 2022. "Physico-Mechanical, Chemical Composition and Thermal Properties of Cellulose Fiber from Hibiscus Vitifolius Plant Stalk for Polymer Composites." *Journal of Natural Fibers* 19 (13): 6961–6976. <https://doi.org/10.1080/15440478.2021.1941484>.
- Memon, A., and A. Nakai. 2013a. "Mechanical Properties of Jute Spun Yarn/PLA Tubular Braided Composite by Pultrusion Molding." *Energy Procedia* 34:818–829. <https://doi.org/10.1016/J.EGYPRO.2013.06.818>. Jan.
- Memon, A., and A. Nakai. 2013b. "The Processing Design of Jute Spun Yarn/PLA Braided Composite by Pultrusion Molding." *Advances in Mechanical Engineering* 5 (Jan): 816513. <https://doi.org/10.1155/2013/816513>.
- Minchenkov, K., S. Gusev, A. Sulimov, A. Sergeichev, I. Safonov, and A. Safonov. 2023. "Experimental and Numerical Analyses of the Thermoplastic Pultrusion of Large Structural Profiles." *Materials & Design* 232 (Aug): 112149. <https://doi.org/10.1016/J.MATDES.2023.112149>.
- Minchenkov, K., A. Vedernikov, Y. Kuzminova, S. Gusev, A. Sulimov, A. Gulyaev, A. Kreslavskaya, et al. Nov 2022. "Effects of the Quality of Pre-Consolidated Materials on the Mechanical Properties and Morphology of Thermoplastic Pultruded Flat Laminates." *Composites Communications* 35:101281. <https://doi.org/10.1016/J.COCO.2022.101281>.
- Minchenkov, K., A. Vedernikov, A. Safonov, and I. Akhatov. Jan 2021. "Thermoplastic Pultrusion: A Review." *Polymers (Basel)* 13 (2): 1–36. <https://doi.org/10.3390/POLYM13020180>.
- Mochane, M. J., T. C. Mokhena, T. H. Mokhothu, A. Mtibe, E. R. Sadiku, S. S. Ray, I. D. Ibrahim, et al. Feb 2019. "Recent Progress on Natural Fiber Hybrid Composites for Advanced Applications: A Review." *Express Polymer Letters* 13 (2): 159–198. <https://doi.org/10.3144/EXPRESSPOLYMLETT.2019.15>
- Mylsamy, G., and P. Krishnasamy. 2022. "A Review on Natural Plant Fiber Epoxy and Polyester Composites – Coating and Performances." *Journal of Natural Fibers* 19 (16): 12772–12790. <https://doi.org/10.1080/15440478.2022.2075517>.
- Naga Kumar, C., M. N. Prabhakar, and J. Il Song. 2019. "Effect of Interface in Hybrid Reinforcement of Flax/Glass on Mechanical Properties of Vinyl Ester Composites." *Polymer Testing* 73:404–411. <https://doi.org/10.1016/J.POLYMERTESTING.2018.12.005>. Feb.
- Nasir, R. M., and N. A. Ghazali. Dec 2014. "Tribological Performance of Paddy Straw Reinforced Polypropylene (PSRP) and Unidirectional Glass-Pultruded-Kenaf (UGPK) Composites." *Jurnal Tribologi* 1:1–17. https://www.researchgate.net/publication/270572787_Tribological_performance_of_paddy_straw_reinforced_polypropylene_PSRP_and_unidirectional_glass-pultruded-kenaf_UGPK_composites.
- Neto, J. S. S., R. A. A. Lima, D. K. K. Cavalcanti, J. P. B. Souza, R. A. A. Aguiar, and M. D. Banea. Mar 2019. "Effect of Chemical Treatment on the Thermal Properties of Hybrid Natural Fiber-Reinforced Composites." *Journal of Applied Polymer Science* 136 (10). <https://doi.org/10.1002/APP.47154>.
- Neto, J., H. Queiroz, R. Aguiar, R. Lima, D. Cavalcanti, and M. D. Banea. 2022. "A Review of Recent Advances in Hybrid Natural Fiber Reinforced Polymer Composites." *Journal of Renewable Materials* 10 (3): 561–589. <https://doi.org/10.32604/JRM.2022.017434>.
- Nirmal, U., J. Hashim, and M. M. H. Megat Ahmad. Mar 2015. "A Review on Tribological Performance of Natural Fibre Polymeric Composites." *Tribology International* 83:77–104. <https://doi.org/10.1016/J.TRIBOINT.2014.11.003>.
- Nosbi, N., H. M. Akil, Z. A. Mohd Ishak, and A. Abu Bakar. Dec 2010. "Degradation of Compressive Properties of Pultruded Kenaf Fiber Reinforced Composites After Immersion in Various Solutions." *Materials & Design* 31 (10): 4960–4964. <https://doi.org/10.1016/J.MATDES.2010.04.037>.
- Nurazzi, N. M., M. R. M. Asyraf, S. Fatimah Athiyah, S. S. Shazleen, S. A. Rafiqah, M. M. Harussani, S. H. Kamarudin, et al. Jul 2021. "A Review on Mechanical Performance of Hybrid Natural Fiber Polymer Composites for Structural Applications." *Polymers (Basel)* 13 (13): 2170. <https://doi.org/10.3390/POLYM13132170>
- Omar, M. F., H. Md Akil, Z. A. Ahmad, A. A. M. Mazuki, and T. Yokoyama. Oct 2010. "Dynamic properties of pultruded natural fibre reinforced composites using Split Hopkinson Pressure Bar technique." *Materials & Design* 31 (9): 4209–4218. <https://doi.org/10.1016/J.MATDES.2010.04.036>.
- Osman, M. R., H. M. Akil, and Z. A. Mohd Ishak. Oct 2013. "Effect of Hybridization on the Water Absorption Behaviour of Pultruded Kenaf Fibre-Reinforced Polyester Composites." *Composite Interfaces* 20 (7): 517–528. <https://doi.org/10.1080/15685543.2013.811182>.
- Osman, M. R., A. A. M. Mazuki, H. M. Akil, Z. A. M. Ishak, and A. A. Bakar. 2014. "Effect of Chemical Treatment on the Mechanical Properties of Pultruded Kenaf Fibre Reinforced Polyester Composites." *Key Engineering Materials* 594–595:691–695. <https://doi.org/10.4028/WWW.SCIENTIFIC.NET/KEM.594-595.691>.
- Paciornik, S., F. M. Martinho, M. H. P. de Mauricio, and J. R. M. d'Almeida. Feb 2003. "Analysis of the Mechanical Behavior and Characterization of Pultruded Glass Fiber-Resin Matrix Composites." *Composites Science and Technology* 63 (2): 295–304. [https://doi.org/10.1016/S0266-3538\(02\)00249-X](https://doi.org/10.1016/S0266-3538(02)00249-X).
- Page, J., S. Amziane, M. Gomina, C. Djelal, and F. Audonnet. 2021. "Using Linseed Oil as Flax Fibre Coating for Fibre-Reinforced Cementitious Composite." *Industrial Crops & Products* 161:113168. <https://doi.org/10.1016/J.INDCROP.2020.113168>. Mar.
- Pannu, A. S., S. Singh, and V. Dhawan. Sep 2019. Composite Manufacturing Techniques – A Review On Injection, Compression, Pultrusion And Extrusion Process. *Journal of Advanced Scientific Research* 10 (3 Suppl 1): 146–151. [Online]. Accessed December 20, 2022 <https://www.sciensage.info/index.php/JASR/article/view/358>.

- Parbin, S., N. K. Waghmare, S. K. Singh, and S. Khan. 2019. "Mechanical Properties of Natural Fiber Reinforced Epoxy Composites: A Review." *Procedia Computer Science* 152:375–379. <https://doi.org/10.1016/J.PROCS.2019.05.003>. Jan.
- Peng, X., M. Fan, J. Hartley, and M. Al-Zubaidy. Jan 2012. "Properties of Natural Fiber Composites Made by Pultrusion Process." *Journal of Composite Materials* 46 (2): 237–246. <https://doi.org/10.1177/0021998311410474>.
- Pirchio, D., J. A. Althouse, T. A. Madlem, M. D. Denavit, B. D. Weldon, and K. Q. Walsh. 2023. "Tensile Strength and Modulus of FRP Pultruded Composites at Varying Load Angles Relative to the Pultrusion Direction." *Construction and Building Materials* 385:131477. <https://doi.org/10.1016/J.CONBUILDMAT.2023.131477>. Jul.
- Pourhashem, S., F. Saba, J. Duan, A. Rashidi, F. Guan, E. G. Nezhad, B. Hou. et al. Aug 2020. "Polymer/Inorganic Nanocomposite Coatings with Superior Corrosion Protection Performance: A Review." *Journal of Industrial and Engineering Chemistry* 88:29–57. <https://doi.org/10.1016/J.JIEC.2020.04.029>.
- Prabhu, L., V. Krishnaraj, S. Sathish, S. Gokulkumar, N. Karthi, L. Rajeshkumar, D. Balaji. et al. Jan 2021. "A Review on Natural Fiber Reinforced Hybrid Composites: Chemical Treatments, Manufacturing Methods and Potential Applications." *Materials Today: Proceedings* 45:8080–8085. <https://doi.org/10.1016/J.MATPR.2021.01.280>.
- Pultruded Composites Market Growing, Says EPTA | CompositesWorld. Mar 25, 2022. [Online]. <https://www.compositesworld.com/articles/pultruded-composites-market-growing-says-epta>.
- Pultrusion Market Size, Share, Industry Forecast 2029. Mar 25, 2022. [Online]. <https://www.fortunebusinessinsights.com/pultrusion-market-104580>.
- Pultrusion Products Market Size, Trends - Industry Outlook Report 2028. Mar 25, 2022. [Online]. <https://www.gminsights.com/industry-analysis/pultrusion-products-market>.
- Qi, S., O. Alajarmeh, T. Shelley, P. Schubel, K. Rendle-Short, and X. Zeng. 2023. "Formation of Non-Uniform Fibre Distributions in Winding-Pultrusion Process and Its Effect on Axial Compressive Properties of Hollow GFRP Profiles." *Composites Part A, Applied Science and Manufacturing* 173:107659. <https://doi.org/10.1016/J.COMPOSITESA.2023.107659>. Oct.
- Rahman, M. Z. 2021. "Mechanical and Damping Performances of Flax Fibre Composites – a Review." *Composites Part C Open Access* 4:100081. <https://doi.org/10.1016/J.JCOMC.2020.100081>. Mar.
- Rajak, D. K., D. D. Pagar, R. Kumar, and C. I. Pruncu. Nov 2019. "Recent Progress of Reinforcement Materials: A Comprehensive Overview of Composite Materials." *Journal of Materials Research and Technology* 8 (6): 6354–6374. <https://doi.org/10.1016/J.JMRT.2019.09.068>.
- Rajesh, M., J. Kandasamy, D. Mallikarjuna Reddy, V. Mugeshkannan, and V. R. Kar. 2021. "Experimental Characterization for Natural Fiber and Hybrid Composites." *Structural Health Monitoring System for Synthetic, Hybrid and Natural Fiber Composites* 71–83. https://doi.org/10.1007/978-981-15-8840-2_6.
- Ramasubbu, R., and S. Madasamy. 2020. "Fabrication of Automobile Component Using Hybrid Natural Fiber Reinforced Polymer Composite." *Journal of Natural Fibers* 19 (2): 736–746. <https://doi.org/10.1080/15440478.2020.1761927>.
- Rasheed, R., I. Anwar, F. Tahir, A. Rizwan, H. Javed, and F. Sharif. Mar 2023. "Techno-Economic and Environmental Sustainability Analysis of Filament-Winding versus Pultrusion Based Glass-Fiber Composite Technologies." *Environmental Science and Pollution Research* 30 (13): 36276–36293. <https://doi.org/10.1007/s11356-022-24817-5>.
- Ravindran, L., M. S. Sreekala, and S. Thomas. 2019. "Novel Processing Parameters for the Extraction of Cellulose Nanofibres (CNF) from Environmentally Benign Pineapple Leaf Fibres (PALF): Structure-Property Relationships." *International Journal of Biological Macromolecules* 131 (Jun): 858–870. <https://doi.org/10.1016/J.IJBIOMAC.2019.03.134>.
- Roy, P., D. Tadele, F. Defersha, M. Misra, and A. K. Mohanty. Oct 2019. "Environmental and Economic Prospects of Biomaterials in the Automotive Industry." *Clean Technologies and Environmental Policy* 21 (8): 1535–1548. <https://doi.org/10.1007/s10098-019-01735-8>.
- Saba, N., M. T. Paridah, and M. Jawaid. Feb 2015. "Mechanical Properties of Kenaf Fibre Reinforced Polymer Composite: A Review." *Construction and Building Materials* 76:87–96. <https://doi.org/10.1016/J.CONBUILDMAT.2014.11.043>.
- Sadrmanesh, V., and Y. Chen. Oct 2018. "Bast Fibres: Structure, Processing, Properties, and Applications." *International Materials Reviews* 64 (7): 381–406. <https://doi.org/10.1080/09506608.2018.1501171>.
- Safiee, S., H. Md Akil, A. A. M. Mazuki, Z. A. M. Ishak, and A. A. Bakar. Mar 2011. "Properties of pultruded jute fiber reinforced unsaturated polyester composites." *Advanced Composite Materials* 20 (3): 231–244. <https://doi.org/10.1163/092430410X547047>.
- Safonov, A. A., P. Carlone, and I. Akhatov. Jan 2018. "Mathematical Simulation of Pultrusion Processes: A Review." *Composite Structures* 184:153–177. <https://doi.org/10.1016/J.COMPSTRUCT.2017.09.093>.
- Safonov, A., M. Gusev, A. Saratov, A. Konstantinov, I. Sergeichev, S. Konev, S. Gusev, et al. Mar 2020. "Modeling of Cracking During Pultrusion of Large-Size Profiles." *Composite Structures* 235:111801. <https://doi.org/10.1016/J.COMPSTRUCT.2019.111801>.
- Safri, S. N. A., M. T. H. Sultan, M. Jawaid, and K. Jayakrishna. Jan 2018. "Impact Behaviour of Hybrid Composites for Structural Applications: A Review." *Composites Part B Engineering* 133:112–121. <https://doi.org/10.1016/J.COMPOSITESB.2017.09.008>.

- Sahu, S., S. Nayak, S. B. B. P. J. Sahu, and M. K. Roul. Apr 2023. "Influence of Various Surface Treatments on Mechanical, Thermal, Morphological, and Water Absorption Properties of Rattan (*Calamus Beccarii*) Fiber." *Journal of Natural Fibers* 20 (1): 30–44. <https://doi.org/10.1080/15440478.2022.2125924>.
- Sandberg, M., O. Yuksel, I. Baran, J. H. Hattel, and J. Spangenberg. Apr 2021. "Numerical and Experimental Analysis of Resin-Flow, Heat-Transfer, and Cure in a Resin-Injection Pultrusion Process." *Composites Part A, Applied Science and Manufacturing* 143:106231. <https://doi.org/10.1016/J.COMPOSITESA.2020.106231>.
- Sandberg, M., O. Yuksel, I. Baran, J. Spangenberg, and J. H. Hattel. Jul 2021. "Steady-State Modelling and Analysis of Process-Induced Stress and Deformation in Thermoset Pultrusion Processes." *Composites Part B Engineering* 216:108812. <https://doi.org/10.1016/J.COMPOSITESB.2021.108812>.
- Sandberg, M., O. Yuksel, R. B. Comminal, M. R. Sonne, M. Jabbari, M. Larsen, F. B. Salling et al. Jan 2020. "Numerical Modeling of the Mechanics of Pultrusion." *Mechanics of Materials in Modern Manufacturing Methods and Processing Techniques* 173–195. <https://doi.org/10.1016/B978-0-12-818232-1.00006-0>.
- Sanjay, M. R., S. Siengchin, J. Parameswaranpillai, M. Jawaid, C. I. Pruncu, and A. Khan. Mar 2019. "A Comprehensive Review of Techniques for Natural Fibers as Reinforcement in Composites: Preparation, Processing and Characterization." *Carbohydrate Polymers* 207:108–121. <https://doi.org/10.1016/J.CARBPOL.2018.11.083>.
- Sanjay, M., and B. Yogesha. Jan 2017. "Studies on Natural/Glass Fiber Reinforced Polymer Hybrid Composites: An Evolution." *Materials Today: Proceedings* 4 (2): 2739–2747. <https://doi.org/10.1016/J.MATPR.2017.02.151>.
- Scheibe, M., M. Urbaniak, and A. Bledzki. Nov 2023. "Application of Natural (Plant) Fibers Particularly Hemp Fiber as Reinforcement in Hybrid Polymer Composites - Part II. Volume of Hemp Cultivation, Its Application and Sales Market." *Journal of Natural Fibers* 20 (2). <https://doi.org/10.1080/15440478.2023.2276715>.
- Setswalo, K., N. Molaletsa, O. P. Oladijo, E. T. Akinlabi, S. M. Rangappa, and S. Siengchin. 2021. "The Influence of Fiber Processing and Alkaline Treatment on the Properties of Natural Fiber-Reinforced Composites: A Review." *Applied Science and Engineering Progress* 14 (4): 632–650. <https://doi.org/10.14416/J.ASEP.2021.08.005>.
- Setswalo, K., O. P. Oladijo, M. Namoshe, E. T. Akinlabi, R. M. Sanjay, S. Siengchin, R. Srisuk, et al. Apr 2023. "The Water Absorption and Thermal Properties of Green *Pterocarpus Angolensis* (Mukwa)-Polylactide Composites." *Journal of Natural Fibers* 20 (1): 12–29. <https://doi.org/10.1080/15440478.2022.2124217>.
- Shalwan, A., and B. F. Yousif. Jun 2013. "In State of Art: Mechanical and Tribological Behaviour of Polymeric Composites Based on Natural Fibres." *Materials & Design* 48:14–24. <https://doi.org/10.1016/J.MATDES.2012.07.014>.
- Strauss, S., F. Wilhelm, A. Senz, H. Engelen, S. Boysen, N. Rilli, A. Celik, M. Ratka, and C. Bonten. Mar 2023. "Experimental and Simulative Analysis of the Pressure Development in a Closed Injection Pultrusion Process with Multiple Chamber Geometries." *Polymers* 15 (6): 1544. <https://doi.org/10.3390/POLYM15061544>.
- Struzziero, G., G. M. Maistros, J. Hartley, and A. A. Skordos. May 2021. "Materials Modelling and Process Simulation of the Pultrusion of Curved Parts." *Composites Part A, Applied Science and Manufacturing* 144:106328. <https://doi.org/10.1016/J.COMPOSITESA.2021.106328>.
- Sumithra, H., and B. Sidda Reddy. Mar 2018. "A Review on Tribological Behaviour of Natural Reinforced Composites." *Journal of Reinforced Plastics and Composites* 37 (5): 349–353. <https://doi.org/10.1177/0731684417747742>.
- Syduzzaman, M., M. A. A. Faruque, K. Bilisik, and M. Naebe. Oct 2020. "Plant-Based Natural Fibre Reinforced Composites: A Review on Fabrication, Properties and Applications." *Coatings* 10 (10): 973. <https://doi.org/10.3390/COATINGS10100973>.
- Tang, J., Z. Zhou, H. Chen, S. Wang, and A. Gutiérrez. Apr 2022. "Research on the Lightweight Design of GFRP Fabric Pultrusion Panels for Railway Vehicle." *Composite Structures* 286:115221. <https://doi.org/10.1016/J.COMPSTRUCT.2022.115221>.
- Tian, L., P. Zhang, and G. Xian. Aug 2023. "Continuous Fiber Reinforced Thermoplastic Composite Pultrusion with in situ Polymerizable Methyl Methacrylate: A Review." *Polymer Composites* 44 (8): 4345–4369. <https://doi.org/10.1002/PC.27427>.
- Tonatto, M. L. P., J. R. Tarpani, and S. C. Amico. 2021. "Short-Beam Shear Fatigue Behavior of Round Curved Pultruded Composite." *Materials and Manufacturing Processes* 29 (26): 5579–5587. <https://doi.org/10.1080/15376494.2021.1959968>.
- Top FRP Manufacturer and Supplier in Malaysia - Mui Fatt Marketing Sdn Bhd. Mar 26, 2022. [Online]. <https://www.muifatt.com.my/>.
- Tucci, F., R. Bezerra, F. Rubino, and P. Carlone. Jan 2020. "Multiphase Flow Simulation in Injection Pultrusion with Variable Properties." *Materials and Manufacturing Processes* 35 (2): 152–162. <https://doi.org/10.1080/10426914.2020.1711928>.
- van de Velde, K., and P. Kiekens. Nov 2001. "Thermoplastic Pultrusion of Natural Fibre Reinforced Composites." *Composite Structures* 54 (2–3): 355–360. [https://doi.org/10.1016/S0263-8223\(01\)00110-6](https://doi.org/10.1016/S0263-8223(01)00110-6).
- van de Velde, K., L. van Langenhove, and P. Kiekens. Research on the Use of Flax as Reinforcement for Thermoplastic Pultruded Composites. The 1st Nordic Conference on Flax and Hemp Processing, Institute of Fiber, Textile and Clothing, Tampere University of Technology, 1998, pp. 227–234., Accessed December 20, 2022. [Online]: <http://hdl.handle.net/1854/LU-282322>.

- Vayabari, D. A. G., Z. Ilham, N. Md Saad, S. R. A. Usuldin, D. A. Norhisham, M. H. Abd Rahim, and W. A. A. Q. I. Wan-Mohtar. Aug 2023. "Cultivation Strategies of Kenaf (*Hibiscus Cannabinus* L.) as a Future Approach in Malaysian Agriculture Industry." *Horticulturae* 9 (8): 925. <https://doi.org/10.3390/HORTICULTURAE9080925>.
- Vedernikov, A., K. Minchenkov, S. Gusev, A. Sulimov, P. Zhou, C. Li, G. Xian, I. Akhatov, and A. Safonov. May 2022. "Effects of the Pre-Consolidated Materials Manufacturing Method on the Mechanical Properties of Pultruded Thermoplastic Composites." *Polymers* 14 (11): 2246. <https://doi.org/10.3390/POLYM14112246>.
- Vedernikov, A., Y. Nasonov, R. Korotkov, S. Gusev, I. Akhatov, and A. Safonov. Mar 2021. "Effects of Additives on the Cure Kinetics of Vinyl Ester Pultrusion Resins." *Journal of Composite Materials* 55 (21): 2921–2937. <https://doi.org/10.1177/00219983211001528>.
- Vedernikov, A., A. Safonov, F. Tucci, P. Carlone, and I. Akhatov. Nov 2020. "Pultruded materials and structures: A review." *Journal of Composite Materials* 54 (26): 4081–4117. <https://doi.org/10.1177/0021998320922894>.
- Vinod, A., M. R. Sanjay, and S. Siengchin. Feb 2023. "Recently Explored Natural Cellulosic Plant Fibers 2018–2022: A Potential Raw Material Resource for Lightweight Composites." *Industrial Crops & Products* 192:116099. <https://doi.org/10.1016/j.indcrop.2022.116099>.
- Volk, M., O. Yuksel, I. Baran, J. H. Hattel, J. Spangenberg, and M. Sandberg. Nov 2022. "Cost-Efficient, Automated, and Sustainable Composite Profile Manufacture: A Review of the State of the Art, Innovations, and Future of Pultrusion Technologies." *Composites Part B: Engineering* 246:110135. <https://doi.org/10.1016/J.COMPOSITESB.2022.110135>.
- Wang, Z., H.-C. Yang, F. He, S. Peng, Y. Li, L. Shao, S. B. Darling, et al. 2019. "Mussel-Inspired Surface Engineering for Water-Remediation Materials." *Matter* 1 (1): 115–155. <https://doi.org/10.1016/j.matt.2019.05.002>.
- Wilson, M. L., and J. D. Buckley. Aug 2016. "The Potential for Low Cost Thermoplastic Pultrusion." *Journal of Reinforced Plastics and Composites* 13 (10): 927–941. <https://doi.org/10.1177/073168449401301007>.
- Wu, Y., C. Xia, L. Cai, A. C. Garcia, and S. Q. Shi. May 2018. "Development of Natural Fiber-Reinforced Composite with Comparable Mechanical Properties and Reduced Energy Consumption and Environmental Impacts for Replacing Automotive Glass-Fiber Sheet Molding Compound." *Journal of Cleaner Production* 184:92–100. <https://doi.org/10.1016/J.CLEPRO.2018.02.257>.
- Yi, M., X. Fang, L. Wen, F. Guang, and Y. Zhang. Nov 2019. "The Heterogeneous Effects of Different Environmental Policy Instruments on Green Technology Innovation." *International Journal of Environmental Research and Public Health* 16 (23): 4660. <https://doi.org/10.3390/IJERPH16234660>.
- Yu, L., G. Liu, W. Wang, H. Hamada, and Y. Yang. Apr 2023. "Mechanical Failure Analysis of Pultrusion Glass Fiber Pipe Based on Acoustic Emission Technology." *Polymer Composites* 44 (4): 2196–2204. <https://doi.org/10.1002/PC.27236>.
- Zakaria, K. Z., H. M. Akil, M. S. M. Shamsuddin, and Z. A. M. Ishak. Sep 2020. "Mechanical Performance of Pultruded Kenaf/Glass Hybrid Fiber Reinforced Unsaturated Polyester Under Hygrothermal Conditions." *AIP Conference Proceedings* 2267 (1): 020045. <https://doi.org/10.1063/5.0016407>.
- Zakaria, N. A., M. R. Ishak, F. Mustapha, and N. Yidris. Jan 2023. "Tensile Properties of a Hybrid Kenaf-Glass Fibre Composite Shaft." *Materials Today: Proceedings* 74:492–498. <https://doi.org/10.1016/J.MATPR.2022.12.016>.
- Zakikhani, P., R. Zahari, M. T. H. Sultan, and D. L. Majid. Nov 2014. "Extraction and Preparation of Bamboo Fibre-Reinforced Composites." *Materials & Design* 63:820–828. <https://doi.org/10.1016/J.MATDES.2014.06.058>.
- Zamri, M. H., H. M. Akil, A. A. Bakar, Z. A. M. Ishak, and L. W. Cheng. Jan 2012. "Effect of Water Absorption on Pultruded Jute/Glass Fiber-Reinforced Unsaturated Polyester Hybrid Composites." *Journal of Composite Materials* 46 (1): 51–61. <https://doi.org/10.1177/0021998311410488>.
- Zamri, M. H., H. M. Akil, A. S. Helfy, Z. A. MohdIshak, and A. B. Azhar, "Pultruded Natural Fibre Reinforced Composites: Preparation, Properties And Applications." eprints@usm. Accessed February. https://www.researchgate.net/publication/283205781_PULTRUDED_NATURAL_FIBRE_REINFORCED_COMPOSITES_Preparation_Properties_and_Applications.
- Zamri, M. H., H. M. Akil, and Z. A. MohdIshak. Jan 2016. "Pultruded Kenaf Fibre Reinforced Composites: Effect of Different Kenaf Fibre Yarn Tex." *Procedia Chemistry* 19:577–585. <https://doi.org/10.1016/J.PROCHE.2016.03.056>.
- Zhang, P., F. Rubino, G. Pasquino, and P. Carlone. May 2023. "Thermoplastic Pultrusion Process of Polypropylene/Glass Tapes." *Polymers* 15 (10): 2374. <https://doi.org/10.3390/POLYM15102374>.
- Zhao, D., T. Q. Liu, X. Lu, and X. Meng. May 2022. "Experimental and Numerical Analysis of a Novel Curved Sandwich Panel with Pultruded GFRP Strip Core." *Composite Structures* 288:115404. <https://doi.org/10.1016/J.COMPSTRUCT.2022.115404>.