Chapter 6
Advanced Potential Hybrid Biocomposites in Aerospace Applications: A Comprehensive Review

Muhammad Farhan, M. T. Mastura, Shahid Pervez Ansari, Muhammed Muaz, Mohammad Azeem, and S. M. Sapuan

1 Introduction

1.1 Hybrid Biocomposites

There is a persistent demand for lightweight materials with superior strength and toughness for use in aerospace applications for several purposes. To meet this requirement, polymer matrix-based composite materials were created. Biocomposites are used in different applications including aircrafts, automobiles, biomedical industry, sporting equipment, helmets and household furnishings.

M. Farhan (✉)
Department of Mechanical Engineering, Faculty of Engineering and Technology, Integral University, Lucknow, India
e-mail: mufarhan@iul.ac.in

M. T. Mastura
Faculty of Mechanical and Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

S. P. Ansari
Z. H. College of Engineering and Technology, Department of Applied Chemistry, Faculty of Engineering and Technology, Aligarh Muslim University, Aligarh, India

M. Muaz
Z. H. College of Engineering and Technology, Department of Mechanical Engineering, Faculty of Engineering and Technology, Aligarh Muslim University, Aligarh, India

M. Azeem
Department of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Petronas, Seri Iskandar, Perak, Malaysia

N. Mazlan et al. (eds.), *Advanced Composites in Aerospace Engineering Applications*, https://doi.org/10.1007/978-3-030-88192-4_6

Hybrid biocomposites are a type of biocomposites in which the matrix or reinforcing phase is biodegradable (Idicula et al., 2005; Narnaware et al., 2015; Rajesh et al., 2018; Mohd Nurazzi et al., 2019; Aisyah et al., 2021; Alsubari et al., 2021; Nurazzi et al., 2021).

Green composites are biodegradable biocomposites in which both phases (reinforcing phase and matrix phase) are biodegradable. Generally, biodegradable components of biocomposites are often sourced from nature. Frequently mentioned natural fibres and fillers used as reinforcements are banana, sisal rice straw, coir, hemp, clays, wood flour, coir shell and natural biodegradable matrices such as starch, polylactic acid, soy, coir shell, etc. (Jacob et al., 2006; Ramesh et al., 2013; Silva et al., 2013; Sathishkumar et al., 2017; Saxena & Gupta, 2019; Ilyas et al., 2019a, 2020a, b, 2021; Syafiq et al., 2020; Jumaidin et al., 2021; Punia Bangar et al., 2021).

One of the several ways used to minimize the brittleness of carbon fibre composites and produce improved toughness qualities was to hybridize them with fibres of different nature (Swolfs et al., 2015). In hybrids, the reinforcement mix is chosen in such a way that each component's qualities are essentially distinct. Deviations may develop as a result of a synergistic impact, such as a positive or negative hybrid impact (less than the expected) (Nurazzi et al., 2020; Rozilah et al., 2020; Alsubari et al., 2021). Hybrid biocomposites are biocomposites with two or more reinforcing elements in a single matrix. The reinforcements might come in a variety of physical forms. Fibres with other fibres, fibres with particle fillers, two types of particle fillers, layered fibrous mats, and so on are some of the conceivable combinations. Figure 6.1 shows an overview of hybrid biocomposites, as well as other types of composites.

The hybrid biocomposites widely used in the phenomenon of hybridization for high-performance fibres such as carbon, Kevlar and basalt have been extensively examined, while biodegradable reinforcement-based hybrid biocomposites have received less attention. Natural fibres and fillers were combined with man-made reinforcements by researchers. Only a few research studies have been published in which both the reinforcing and reinforcing phases are made of biodegradable fibres. This study will look at hybrid biocomposites, which are composites with at least one biodegradable fibre or filler as a reinforcement (Singh & Mukhopadhyay, 2020).

S. M. Sapuan
Advanced Engineering Materials and Composites Research Centre (AEMC), Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia,
Serdang, Selangor, Malaysia

Laboratory of Biocomposite Institute of Tropical Forestry and Forest Products (INTROP),
Universiti Putra Malaysia, Serdang, Selangor, Malaysia

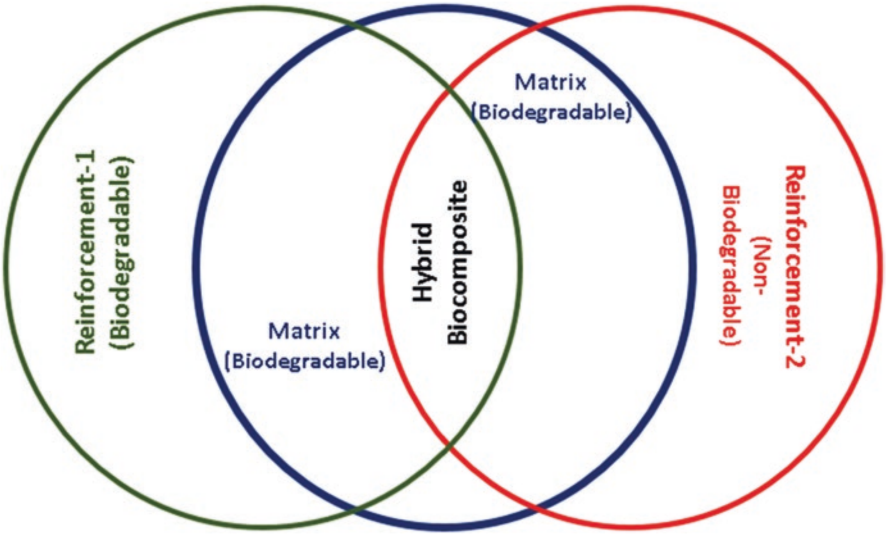

Fig. 6.1 Representation of hybrid biocomposites

2 Reinforcements and Matrices of Hybrid Biocomposites

2.1 Reinforcing Phases of Hybrid Biocomposites

Phases that reinforce each other the usage of several forms of biodegradable reinforcements in hybrid biocomposites have been described by researchers. Almost all of the documented reinforcements come from nature, and the majority of them contain cellulose as the primary component. Hybrid composites with two reinforcing phases were reported by the majority of researchers. There are a few publications till now that report more than two reinforcing phases. Some researchers (Otto et al., 2017; Pradhan & Acharya, 2021) have described studies with three reinforcing stages. The usage of particle fillers in hybrid biocomposites has also been reported to be restricted. Researchers have mostly utilized fibres in the form of fibrous webs, both woven and non-woven, as reinforcements.

Various types of natural fibres are investigated in conjunction with man-made or natural fibres, while research on hybrid biocomposites including both natural and man-made reinforcements is dominated by those containing one natural and one man-made fibre. Glass fibres in various physical forms make up a significant component of these man-made fibres, which are employed as one of the ingredients. There are additional studies on particle filler-based hybrid biocomposites. Coir and kenaf fibres were combined with wood flour (Yao et al., 2012; Yahaya et al., 2017). In epoxy resin, fly ash was used as a filler with jute fibres. Carbon black was mixed with pineapple leaf fibres in a natural rubber matrix. However, particulate-based

Table 6.1 Recent advances with different reinforcements used in hybrid biocomposites (Singh & Mukhopadhyay, 2020)

Reinforcements	References
Fibres	
Glass	Gangil et al. (2020), Ramesh et al. (2013), Birat et al. (2015), Rout et al. (2001), Petrucci et al. (2015), Leman et al. (2008), Sreekumar et al. (2012), Rout et al. (2001)
Bamboo	Cai et al. (2021), Samanta et al. (2015)
Flax	Petrucci et al. (2015), Santulli et al. (2005), Prabhakaran et al. (2014), Zhang et al. (2020), Ahmed et al. (2013), Živković et al. (2017), Ravandi et al. (2019), Papa et al. (2020), Fiore et al. (2017), Petrucci et al. (2015)
Hemp	Ridzuan et al. (2017), Halimatul et al. (2019)
Coir	Sathishkumar et al. (2017), Boujmal et al. (2018)
Silk	Jawaid et al. (2013), Faezipour et al. (2016)
OPEFB	Kadem et al. (2018)
Pineapple	Idicula et al. (2006)
Banana	Rajesh et al. (2018), Idicula et al. (2005), Silva et al. (2013), Boopalan et al. (2013), Idicula et al. (2005), Sanjay et al. (2017)
Sisal	Idicula et al. (2005), Gupta and Srivastava (2016), Sathishkumar et al. (2017), Ramesh et al. (2013), Silva et al. (2013), Jacob et al. (2006), Aslan et al. (2018), Idicula et al. (2005), Jacob et al. (2006)
Kenaf	Atiqah et al. (2017), Yahaya et al. (2017), Sivakumar et al. (2018), Sathishkumar et al. (2017)
Oil palm fibre	Jawaid et al. (2013), Sreekumar et al. (2012), Ishak et al. (1998), Jacob et al., 2006)
Cotton	Sathishkumar et al. (2017), Athijayamani et al. (2010), Alsina et al. (2005)
Lyocell	Idicula et al. (2006)
Seaweed	Sapuan and Ilyas (2018)
Palmyra	Nunna et al. (2012)
Baggase	Boujmal et al. (2018), Saw et al. (2011)
Particulate filler	
Clay	Qaiss et al. (2015), Essabir et al. (2017)
Wood flour	Jawaid et al. (2013), Faezipour et al. (2016)
Fly ash	Raghavendra et al. (2016)
Coconut shell	Dhakal et al. (2018)
Flour silica	Gonçalves et al. (2014)
Cornhusk	Kwon et al. (2014)

fillers are used in a smaller percentage of research. Table 6.1 summarizes the various types of fibres and fillers that were employed as reinforcements (Yantaboot & Amornsakchai, 2017).

Another part of Table 6.1 shows that the bulk of literature on hybrid biocomposites contains fibres, with the majority of them containing one reinforcement in the form of glass in a fibrous form. In hybrid biocomposites, there have been just a few research on the use of particle fillers.

2.2 Matrix Phase of Hybrid Biocomposites

The bulk of the above-mentioned reinforcements have been reinforced with thermoset matrices. The use of polyester and epoxy-based resins in natural fibre-based hybrid composites is well documented in the literature (Nurazzi et al., 2019; Kumar et al., 2020; Suriani et al., 2021a, b, c, d). Other thermoset resins such as phenol formaldehyde and novolac, on the other hand, have been reported. Thermoset resin is thought to be able to efficiently saturate the fibres, resulting in improved penetration into the fibrous web and layers. It might be the reason why thermoset resins have been employed so extensively in natural fibre-based hybrid composites so far. There are also a few investigations using thermoplastic resins such polypropylene, polyethylene, thermoplastic natural rubber and soybean oil (Sanjay & Yogesha, 2016). Table 6.2 lists the many types of matrices utilized in hybrid biocomposites, as well as the research that have reported on them. In comparison to thermoplastic polymers, thermoset resins have been employed more frequently as a matrix in hybrid biocomposites, as shown in Table 6.2. The most common matrix phase is epoxy-based resins. Epoxy resins are a prominent kind of thermoset composite matrix. The resin, modifiers and cross-linking agent can be used to customize the properties of cured epoxy resin to obtain specific performance characteristics. There are various properties for which epoxies are favoured as a resin.

Epoxies have extremely good chemical resistance, particularly in alkaline conditions. It provides excellent adherence to a wide range of surfaces. In terms of mechanical qualities, they feature a mix of high tensile, compressive and flexural strengths. Shrinkage in thermoset resins is frequently a source of concern. On cure,

Table 6.2 Different matrices used in hybrid biocomposites (Singh & Mukhopadhyay, 2020)

Matrices	References
Thermoset	
Epoxy resin	Fiore et al. (2017), Sanjay and Yogesha (2018), Jawaid et al. (2013), Gupta and Srivastava (2016), Ramesh et al. (2013), Gonçalves et al. (2014)
Modified epoxy resin	Saw et al. (2011), Rozman et al. (2013), Vijaya Ramnath et al. (2015)
Polyester	Atiqah et al. (2019), Rout et al. (2001), Idicula et al. (2006)
Natural rubber	Jacob et al. (2006)
Phenolic resin	Bach et al. (2017), Raj et al. (2017)
Banana	Sathishkumar et al. (2017), Reddy (2019), Vijaya Ramnath et al. (2015)
Kenaf	Sathishkumar et al. (2017)
Soybean oil matrix	Santulli (2007)
Thermoplastic	
Polypropylene	Qaiss et al. (2015), Birat et al. (2015), Aslan et al. (2018), Rozman et al. (2013)
PLA	Battegazzore et al. (2019), Kwon et al. (2014)
Polyethylene	Boujmal et al. (2018), Essabir et al. (2017)

the epoxies showed very little shrinking. Epoxies are useful in areas where electrical insulation is required. They are also corrosion resistant. When compared to other thermoset materials, their fatigue strength is better.

3 Natural Fibre-Reinforced Polymer Composite

Natural fibre polymer composite consists of natural fibres as reinforced material and polymer as matrix (Ayu et al., 2020; Aiza Jaafar et al., 2021). These two materials are compounded together to obtain superior material properties and replace the traditional materials. Natural fibre in polymer composite can be classified into three main categories which are plant-based fibre, animal-based fibre and mineral-based fibre. As shown in Fig. 6.2, plant-based fibres are extracted from different parts of the plant such as bast, fruit, seed and leaf. Kenaf, hemp, jute, flax, ramie and roselle are the fibres that are collected from the outer layers of the plant stem. Coconut coir fibre is an example of the fibre is that collected from the fruit where it is extracted from the outer layers of the internal crust of the coconut. Kapok and cotton fibres are the examples of fibres that are collected from the seed of the plant. Banana and pineapple leaf fibres are the most found fibres that are extracted from the leaf of the plant. Generally, all the natural fibres that are plant-based type are known as cellulose fibres as they contain a high percentage of cellulose. Plant-based fibres also contain hemicellulose, lignin, pectin and wax as these chemical compositions exhibit the material properties of the fibres. Animal-based fibres are mostly found in the application of medical tools where this type of fibres can be degraded in the human body without adverse toxicity. Animal-based fibres also known as protein-based fibres primarily contained a series of amino acid and peptide chains. Similar with the plant-based fibres, animal-based fibres are collected from different parts of animal such as hair, feathers, cocoon and skin. Wool and keratin are the examples of the fibres that are collected from the hair or fur of the animals. Silk is one of the fibrous proteins that is produced by moth, spider and scorpion and consists of glycine, alanine and serine. With good mechanical properties and hydrophobic properties, silk is mostly found in tissue scaffold applications. Collagen is another type of protein-based fibres where it is collected from the skin, tendon, cartilage, bone and internal organs of animals containing repeating amino acid chain. Generally, these animal-based fibres are preferable in the selection of biomaterials due to its low cost

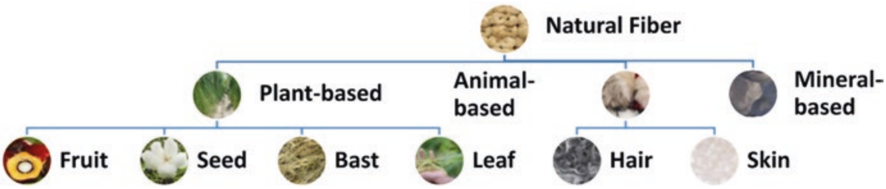

Fig. 6.2 Types of natural fibres

and biocompatibility in medical application. Mineral-based fibre is a solid substance that is not made by an organism, and it is naturally occurred with definite chemical composition and has a systematic and repeating pattern of internal structure. On earth, plenty of mineral resources varied based on their mineral formulae. Each mineral material is unique, and a complex method could classify the type of mineral materials. A mineral is a type of material that has a wide range of species that is modified based on the weathering process and geologic conditions. Consequently, the chemical and mineral content of the fibres are different from location to location. Mineral-based fibres are preferable in producing fibre-reinforced concrete composite because of their low cost of production, good deformation properties and improved crack resistance and concrete durability. Basalt fibre that contains SiO2, Al2O3, MgO, CaO, Fe2O3 and FeO is mostly found to be reinforced in a polymer composite material. Other mineral fibres that are used as reinforced materials in polymer composites are kaolinite, amosite, actinolite and tremolite.

Numerous studies on natural fibre-reinforced polymer composites have been conducted by past researchers. These studies include the exploration of the benefits of natural fibre-reinforced polymer composites and the investigation on how to counteract the weakness of the composites. Generally, the applications of natural fibre-reinforced polymer composites are mostly due to the sustainable properties of the materials. The application of natural fibre-reinforced polymer composites could reduce plastic consumption, especially in product design parts. Having a substitute to traditional plastic applications with biodegradable materials like natural fibre-reinforced polymer composite is a best way to reduce the consumption of non-renewable materials and save the life of more creatures on earth, especially those that live in the ocean. In a life cycle analysis of the natural fibre-reinforced polymer composite, this type of materials exhibits lower toxicity and lower harmful emission for the whole of their life compared with synthetic fibre composites and neat polymer materials. Moreover, natural fibre-reinforced polymer composites may improve the properties of the traditional materials used in various types of applications such as automotive, defence technology and food packaging. In automotive applications, Yahaya et al. (2017) studied on non-woven kenaf and hybrid non-woven/woven kenaf fabric for application on PROTON Saga FL car door map pocket. The hybrid composite is found to be lighter and has better tensile and flexural strength compared with neat polypropylene, and the composite is suitable for automotive door map pocket. In another study, Sanjay and Yogesha (2016) reviewed the application of natural fibre composites by renowned automotive manufacturer such as Mercedes-Benz, Audi and Toyota. Mercedes-Benz used epoxy matrix with jute addition in its 1996 vehicles for door panel, Audi launched A2 midrange car which used polyurethane reinforced with flax/sisal material mixture for the door trim panels, and Toyota car interior is made by developed eco-plastic made from sugarcane. Fogorasi and Barbu (2017) found that natural fibre-reinforced polymer composites have low density with weight reduction up to 10–30% and also their possible application for new production technologies and materials, and their favourable processing properties for lower tool usage. Natural fibre-reinforced polymer composites also have good mechanical and acoustic properties. In safety aspect, the composites give huge benefits due to their high stability and less splintering, providing a high standard of passive safety during collision or burning. Meanwhile in health aspect, the composites produce less harmful emission compared to glass fibre during the production.

Natural fibre-reinforced polymer composites are more compatible in additive manufacturing process compared to subtractive manufacturing process. Compression moulding, hand lay-up, extrusion and hot press are the most found manufacturing processes used by the engineers in fabricating the composites. Gupta et al. (2019) suggested hot press method to make composite by mixing the hemp non-woven mats with polypropylene fibres for various fibre volume fractions. For specimen preparation, Atiqah et al. (2019) used hand lay-up method to fabricate kenaf fibre with thermoset and used pre-gel coat during moulding process to produce good surface finish. Ferdous and Sarwar Hossain (2017) stated that the techniques used to manufacture biocomposite based on existing composite material processing techniques are press moulding, hand lay-up, filament winding, extrusion, injection moulding and compression moulding, but the majority of current biocomposite materials are based on thermoplastics processed by compounding and extrusion. Dashtizadeh et al. (2017) reviewed that hand lay-up and compression moulding methods are used for coir pith, nylon fabric and epoxy hybrid composite development.

4 Hybridization of Fibre-Reinforced Composites

Polymer matrix composites are made from two components: (1) polymer matrix and (2) reinforcing materials. In general, the polymer matrix is mainly chosen from elastomer and thermoplastic and thermoset polymers. At the same time, the reinforcing materials are either natural fibres or synthetic fibres used in the polymer matrix composites (PMCs). During the synthesis of any desired PMC, selecting a reinforcing material with desired properties is a serious challenge for scientists, engineers and manufacturers in various industries. The critical attributes of reinforcing materials are their economic-ecological balance and performance. Being economical, eco-friendly (biodegradable) and lightweight are few benefits of natural fibres. Due to the rising demands and stringent regulatory limits to operate, the natural fibres are preferred over synthetic fibres. However, synthetic fibres can be used as when required due to their excellent performance and durability (Gangil et al., 2020) (Sapuan et al., 2019).

A new trend to utilize two types of fibres to prepare PMCs (hybrid composites) with desired properties has recently attracted interest in the field of materials science and engineering. The hybrid composites offer the benefits of both the fibres being used to reinforce the matrix. Therefore, the hybrid composites yield superior properties than PMCs based on a single type of fibre. In general, hybrid composites refer to composites wherein the matrix contains two or more reinforcing materials. All the components play an important role to yield the desired properties in the hybrid composites. Matrix is the founding component and plays an important role in corrosion, resistance for chemicals and temperature, damage tolerance, etc.; the fibres act as reinforcing materials and play an important role to provide strength, stiffness and impact behaviour of the hybrid composites. The type/form of the fibres also affects the composite properties (Sapuan et al., 2019).

It has been reported that for automotive parts, thermoplastic composites reinforced with continuous fibres are better suited because of their excellent mechanical properties. Unlike synthetic fibre-reinforced composites, natural fibre composites offer slightly inferior properties compared to the glass fibre-based polymer composites. Therefore, to bridge this gap, the concept of hybridization of fibres (natural and synthetic) opted for improved mechanical properties for structural and semi-structural applications. It also helped to the reduction of cost and weight of the hybrid composites. It was observed that the hybrid composites yielded a balance of desired mechanical properties, economy and environment. As the different components play their roles, it is said that the synergetic effect of two types of fibres (natural/synthetic) causes a balance of mechanical properties and economy.

Therefore, hybridization may be termed as the reinforcement of natural and synthetic fibres with the matrix. It helps to reduce the usage of synthetic fibres and improve the properties of composites. The following are few important situations and reasons for the enhancement of the mechanical properties of hybrid composites over single component composites (Gupta & Deep, 2019; Boopalan et al., 2013).

Condition 1. Fibres of different diameters but same length: Different diameters increase the effective area for fibre-matrix adhesion, which favours uniform stress transfer.

Condition 2. Fibres with different modulus: The properties like stiffness and load bearing capacity are enhanced due to the presence of fibres of high modulus, while on the other hand, the low modulus fibre offers better damage tolerance at low cost.

Condition 3. Fibres with different elongation at break: As suggested by the situation, if load is applied to the hybrid composite, the fibres of lower elongation will break first followed by the load transfer to the fibres of higher elongation without the failure of the matrix.

4.1 Cellulosic/Synthetic Fibre (Hybrid)-Reinforced Biocomposites

Biopolymer composites refer to all those composites which have at least one bio-based or biodegradable constituent. Biocomposites may be classified into two groups: (1) partial biodegradable and (2) complete biodegradable biocomposites, depending on their constituents (matrix and fibres). The partially biodegradable biocomposites are made of bio-based/biodegradable matrices and synthetic fibres/non-biodegradable fibres (e.g. epoxy, polyester polyethylene, polypropylene, etc.) as reinforcement materials. The completely biodegradable/biocomposites are made of bio-based/biodegradable components which are derived either from renewable

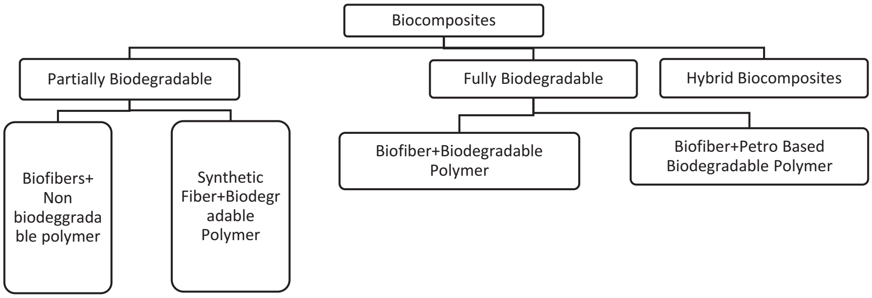

Fig. 6.3 Classification of biocomposites (Drzal et al., 2013)

biopolymer (cellulosic/starch-based plastics) or petroleum-based biodegradable polymers (e.g. polyester amides). In other terms, this classification suggests that the completely biodegradable composites (wherein the two components are completely biodegradable) will decompose and go back to the environment at the end of their life. The partially biodegradable composites (wherein one component is completely biodegradable and the other is non-biodegradable) do not exhibit 100% biodegradability. This classification does not suggest any idea of time, rate and amount of degradation. It only indicates that a biocomposite is fully/partially biodegradable at the end of its life. A schematic of the classification of biocomposites is presented in Fig. 6.3 (Rout et al., 2001; Manyatshe et al., 2020).

The main factors which play a significant role to yield the desired properties to the manufactured products from hybrid composite are as below:

1. Selection of materials (fibre and matrix): It depends primarily on the desired application.
2. The technique of preparation: It depends mainly on the type of fibre/matrix and working space (indoor/outdoor).
3. Fibre-matrix interaction: It is mainly controlled/manipulated by pre-treating the fibres or using coupling agents.

Cellulose is mainly found in the plant cell wall and the most abundant natural organic polymer on earth (Ilyas et al., 2018, 2019b; Ahmad Ilyas et al., 2019; Jumaidin et al., 2020; Omran et al., 2021). It offers good durability and strength. The structure of cellulose varies from highly ordered, microcrystalline region to less ordered, amorphous region. It gets hydrolyzed with acidic treatment and can also degrade on exposure to chemicals. On the other hand, hemicellulose, the second largest biomolecules, has much shorter chains and lower degree of polymerization than cellulose. As these are major components of many natural fibres, we will discuss some critical findings related to them (Bahrami et al., 2020).

In cellulosic fibre-based hybrid biocomposites, hybrid arrangement inhibits moisture absorption into the biocomposites as the voids are filled up due to the packed arrangement of fibres during the formation of hybrid biocomposites. The hydrophilic nature of cellulosic fibres and the capillary action cause increased intake of water when these materials are soaked into the water, which results in the swelling of fibres. As a result, dimensional variation can occur in the composites, which finally affects their mechanical properties. Lignocellulosic fibres are also hydrophilic and incompatible to hydrophobic polymeric matrices and this causes poor adhesion between fibres and matrices; it makes the dispersion of fibres in the polymeric matrices difficult. Researchers studied composites of cellulosic fibres with polypropylene, polyethylene and polystyrene and found that the inadequate distribution of fibres results in their aggregation into knotted masses, leading to composites with poor final properties. Several methods have been reported to improve filler dispersion and interfacial interaction between filler and matrix. Cellulosic fibres exhibit low thermal stability which limits its processing to some techniques and its applications at lower temperatures. The low thermal stability increases the possibility of cellulosic degradation and the possibility of emissions of volatile materials that could adversely affect the composite properties. Processing temperatures are thus limited to about 200 °C, although it is possible to use a higher temperature for short periods (Nisini et al., 2017; Ishak et al., 1998; Jawaid & Abdul Khalil, 2011).

In cellulosic hybrid biocomposites, the properties (physical and mechanical) of the biocomposites are governed by the size of fibres, amount of fibres, orientation of fibres, extent of intermingling of the two fibres and the interfacial interaction between the fibres and matrix.

Most of the studies on cellulosic fibre hybrid composites are mainly related to their mechanical properties, effects of coupling agents, chemical treatments, etc. (Gao et al., 2003). Recently, Shahzad and Nasir (2017) have reported hybrid laminated biocomposites with enhanced mechanical properties. Figure 6.4 shows the bridging structure formed between cellulose nanocrystal (CNC) and cellulose nanofibre (CNF) arranged alternately. This configuration is advantageous; both the ductile and the brittle phases are present in the composite. The CNF, due to its high ductility, offers mechanical buffering in an alternating pattern and prevents the formation and propagation of cracks in the brittle layer of CNC. Additionally, the CNF layer establishes a strong network of hydrogen bonds with CNC layer which

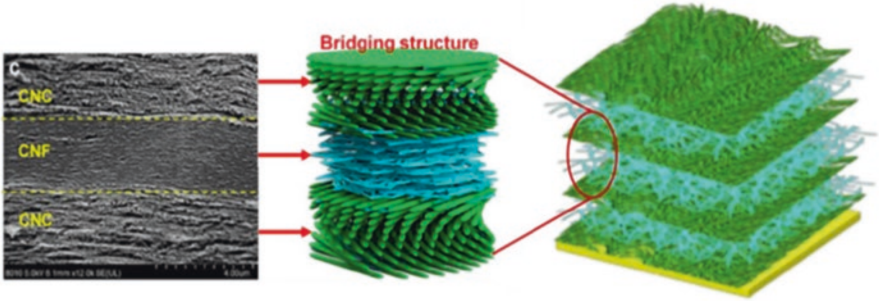

Fig. 6.4 Schematic of chiral nematic cellulose nanofibre/random cellulose nanofibre (CNC-CNF) biocomposite with an alternating sequence of layers and corresponding SEM image of layer. Adapted from (Shahzad & Nasir, 2017)

subsequently optimizes the load transfer property and enhances the strength and toughness of the biocomposites. Such biocomposites may find their application in soft robotics and calorimetric sensors.

5 Natural Fibre/Synthetic Fibre (Hybrid)-Reinforced Polymer Composites

We have discussed in our previous section that the mechanical properties of most of the natural fibres or their composites are inferior compared to that of synthetic fibres/composites. Also reported are some inherent challenges like poor dimensional stability, moisture absorption capacity, low thermal resistance and most importantly, adhesion of the natural fibres with the polymer matrix. Hybridization of natural fibres with synthetic fibres in the polymer matrix is considered as a promising option to overcome the disadvantages of natural fibres. The incorporation of synthetic fibres would improve the overall mechanical properties due to their poor water absorption capacity, dimensional stability, good interaction with polymer matrix, etc., owing to their relatively superior mechanical properties, negligible moisture absorption and compatibility with polymer. A comparative list of the mechanical properties of some natural fibres and synthetic fibres is given in Table 6.3. Glass fibres, carbon fibres and aramid fibres are the most important and widely used synthetic fibres for the manufacture of natural fibre/synthetic fibre hybrid composites. Though the hybrid composites exhibit superior mechanical properties compared to natural fibre-polymer composite, they are traded with biodegradability (Eichhorn et al., 2010).

The industrial applications of hybrid composites have slowly but steadily taken a good pace. The commonly used natural fibres for the purpose are bamboo fibres, coir fibre and jute fibre. Structural materials like wall (interior/exterior) of buildings, emergency shelters, deck, offshore deck platforms, insulated panels, roofing panels, etc. are generally made from hybrid composites. In 2010, Bachtiar et al. studied kenaf-glass hybrid epoxy composites and suggested their applications in car bumper beam materials. Tensile strength and modulus of hybrid composites were found to be higher than the typical car bumper beam material. Likewise, in 2015, Birat et al. (2015) reported a balance of properties (impact, strength, flow and heat deflection) desired for various automotive components. These reports are quite favourable and suggest the considerable potential of these materials in various industrial applications.

However, hybridization of natural fibres with synthetic fibres has some associated issues which need to be considered before the hybridization process. These are reinforcing efficiency of the two fibres (the hybrid effect discussed earlier), moisture content of natural fibres, dispersion of natural fibres in the matrix, fibre/matrix interface, thermal stability of natural fibres and biodegradability of the composites (Zhang et al., 2020).

Table 6.3 Mechanical and physical properties of natural fibres and synthetic fibres

Fibre	Coir	Cotton	E-glass	Flax	Hemp	Jute	Kenaf	Kevlar	Nettle	Ramie	Sisal	Wool	Alfa	Carbon	Harakeke	Silk	Feather	Wool
Density (g cm^{-3})	1.15–1.46	1.5–1.6	2.55	1.5	1.5	1.3–1.49	–	1.44	–	1.55	1.45	1.3	1.4	1.78	1.3	1.3	0.9–3.3	1.3
Diameter (μm)	100–460	12–38	<17	40–600	25–500	25–200	–	–	–	–	50–200	–	1.5–2.4	5–7	4.2–5.8	–	–	–
Length (mm)	1.2	10–60	Continuous	5–900	5–55	1.5–120	–		–	900–1200	–	38–152	350	–	4–5	Continuous	10–30	38–152
Tensile strength (MPa)	131–220	287–800	2000–3400	345–1500	690	393–800	930	3000	650	400–938	468–1627	50–315	188–308	3400–4800	440–990	100–1500	100–203	50–315
Stiffness/ Young’s modulus (GPa)	4–6	5.5–12.6	70–73	27.6	70	13–26.5	53	60	38	61.4–128	34.5–82.5	2.3–5	18–25	240–425	14–23	5–25	3–10	2.3–5
Specific tensile strength	110–180	190–530	800–1400	230–1220	1.47	300–610	–	–	–	270–620	362–610	38–242	134–220	–	338–761	100–1500	112–226	38–242
Specific Young’s modulus (GPa/g cm^{-3})	3.3–5	3.7–8.4	29	18–53	370–740	7.1–39	–	–	–	29–85	6.7–20	1.8–3.8	13–18	–	11–25	4–20	3.3–11	1.8–3.8
Failure strain (%)	15–30	3.0–10	2.5	1.2–3.2	39–47	1.5–1.8	–	–	–	2.0–3.8	2.0–2.5	13.2–35	1.5–2.4	–	4.2–5.8	15–60	6.9	13.2–35
Elongation at break (%)	15–40	7–8	2.5	2.7–3.2	1.6	1.16–1.5	1.6	2.5–3.7	1.7	1.2–3.8	1.6	–	–	1.4–1.8	–	–	–	–

The effects of hybridization have been elaborated on in previous sections. It can be said that the natural fibre-synthetic fibre hybrid composites exhibit hybrid impact in terms of their improved mechanical properties. The natural fibres absorb moisture from their surroundings due to their hydrophilic nature, but synthetic fibres exhibit inhibition of moisture absorption. The hydrophilic nature of natural fibres does not favour proper adhesion with polymer matrix. It can be overcome by hybridization of the natural fibres and synthetic fibres as the synthetic fibres are more compatible with polymer matrix and resistant to absorption of moisture. Natural fibres also exhibit lower thermal stability, which can be overcome by hybridization with synthetic fibres, which are thermally more stable. In terms of biodegradability, due to the presence of synthetic fibres, the biodegradability of the hybrid composites is reduced (Jawaid & Thariq, 2018).

6 Application of Hybrid Biocomposites in Aerospace Sector

Recent couple of decades have witnessed a steep growth in the aerospace sector which can easily be gauged from the exponential rise in air travellers and the number of satellites launched in space in the same period. This calls for better technological advancements in every aspect ranging from material procurement to manufacturing capabilities. The responsibility rests on the shoulders of engineers and researchers working on the frontline. The success of an air-/spacecraft relies to a much extent on the materials used for its manufacturing. A material is deemed good for aerospace industry if it is light and strong at the least. However, in recent times there are concerns which have gained importance and should be addressed on a priority basis. One is the noise generated from the aerospace vehicles and the other is the environmental degradation due to material manufacturing, and the disposal in the later stage (Scheff et al., 2020). The use of lightweight materials gained much popularity due to aerospace applications. It is known that majority of the aerospace industries relies on metals such as aluminium due to its high strength-to-weight characteristics. However, the use of metals is discouraged due first to the environmental factors and second to the high cost associated with them. There is an urge to explore alternatives that are cheaper, stronger, environmentally friendly and widely available in abundance. To this end hybrid biocomposites are being looked upon as a material of great potential for aerospace applications. A significant amount of research in recent years has shown that a large amount of aerospace structures can be made with materials derived from sources of biological origin. Many of the lightweight modern aircrafts have been made possible just because of the developments in composite materials. Hybrid biocomposites can be used inside the fuselage of the passenger aeroplanes that will not only reduce the acoustic signature from the engine and from the surrounding airflow but will also be cheap and eco-friendly (Winter et al., 2020).

Hybrid biocomposites have found application in the development of sound-absorbing materials which can potentially be used in the construction of anechoic chambers. Anechoic chambers are widely used in aerospace industry for free field testing of noise generated by aircrafts and rocket nozzles. Some of the earlier studies have shown that natural materials such as wood and coconut coir have good sound-absorbing characteristics and are suitable for making anechoic chambers (Ward et al., 2021) (Bhatnagar, 2006).

7 Direction and Future Applications of Hybrid Biocomposites for Advanced Applications

It is a well-established finding that several limitations are associated with biocomposites composed of a single natural fibre in a matrix. Many such problems can be addressed by the method of hybridization. A hybrid biocomposite, which consists of more than one biodegradable reinforcement material, exhibits extraordinary favourable properties. The most important aspect is that their properties can be tailored according to the requirement. Various such properties which cannot be imparted in a simple biocomposites can be imparted by developing hybrid biocomposites. Therefore, hybrid biocomposites have great scope in various crucial applications in future. Although such applications include aerospace sector, automobiles, sports accessories, furniture, civil structural components, etc., the most attracting and demanding applications are in the field of aerospace. Several applications in the aerospace industry need highly specific requirements which can be fulfilled by the hybrid biocomposites. The most important property of an aerial vehicle is that it should be as lighter in weight as possible. However, the reduction in weight cannot be made responsible for reduction in other crucial properties. For instance, the strength of such structures cannot be sacrificed at any cost. Lightweight unmanned aerial vehicle is one of the application areas where the hybrid biocomposites are attracting the researchers. The lightweight structure of the vehicle must have the desired strength compatible with unfavourable conditions. These criteria can be easily fulfilled while selecting proper reinforcement materials and arranging them in a proper fashion. There are several biodegradable materials which serve the purpose satisfactorily as described in the previous sections. Another application associated with the aerospace industry is the development of soundproof structures for passenger aircrafts. For unmanned vehicles, soundproofing is not essential. The concept of air taxi is also coming to be in effect in the very near future. Significant investments and research are being conducted in the area of urban air mobilities (Ward et al., 2021; Winter et al., 2020). Safe, quiet and efficient aircrafts will make the dream true (Scheff et al., 2020). Hybrid biocomposites are exhibiting the features favourable for such applications.

8 Conclusion

Hybrid biocomposites have shown great potential in aerospace applications. Conventional materials which are being used in such applications must be replaced necessarily with the hybrid biocomposites as far as environmental issues are concerned. It requires the research to be shifted towards the development of such hybrid biocomposites having required properties. Such combination of the properties, which cannot be achieved in a single conventional material, can be achieved in a properly designed hybrid biocomposites. The addition of more solid fibre or composite filler typically increases the mechanical overall characteristics, which is evident. The effect is sometimes referred to as a positive hybrid effect for hybrid biocomposites. Likewise, a degrading impact is referred to as the negative hybrid effect for a certain characteristic since it is added to weak fibre or filler. On the other hand, the synthetic fibres are non-biologically degradable, offer certain dangers to health and are more expensive, heavier and non-recycling. The path forward will be the hybridization of polymer composites with natural or synthetic matrix strengthened by natural or synthetic reinforcements.

In the near future, great scope exists for the research and development in this direction. Biodegradable matrix, two or more reinforcement materials, their orientation and stacking sequence, etc. are important parameters and must be taken into consideration judiciously. Their proper selection tailors the characteristics of the composites making them suitable for aerospace application. The research described in this chapter demonstrates that hybrid biocomposites are very promising as alternative materials for developing environmentally friendly materials.

Acknowledgement The authors thank Aligarh Muslim University, India, and Universiti Putra Malaysia for providing the facilities to carry out this research with technical support in writing this chapter. They are grateful to Dr. R.A. Ilyas of UTM, Malaysia, for his guidance throughout the chapter. The authors also thank Dr. Mohd Shadab Khan of Integral University, India, for his advice and fruitful discussions.

References

Ahmad Ilyas, R., Mohd Sapuan, S., Ibrahim, R., et al. (2019). Sugar palm (Arenga pinnata (Wurmb.) Merr) cellulosic fibre hierarchy: A comprehensive approach from macro to nano scale. *Journal of Materials Research and Technology, 8*, 2753–2766. https://doi.org/10.1016/j.jmrt.2019.04.011

Ahmed, E. M., Aggor, F. S., Awad, A. M., & El-Aref, A. T. (2013). An innovative method for preparation of nanometal hydroxide superabsorbent hydrogel. *Carbohydrate Polymers, 91*, 693–698. https://doi.org/10.1016/j.carbpol.2012.08.056

Aisyah, H. A., Paridah, M. T., Sapuan, S. M., et al. (2021). A comprehensive review on advanced sustainable woven natural fibre polymer composites. *Polymers (Basel), 13*, 471. https://doi.org/10.3390/polym13030471

Aiza Jaafar, C. N., Zainol, I., Ishak, N. S., et al. (2021). Effects of the liquid natural rubber (LNR) on mechanical properties and microstructure of epoxy/silica/kenaf hybrid composite for potential automotive applications. *Journal of Materials Research and Technology, 12*, 1026–1038. https://doi.org/10.1016/j.jmrt.2021.03.020

Alsina, O. L. S., de Carvalho, L. H., Ramos Filho, F. G., & D'Almeida, J. R. M. (2005). Thermal properties of hybrid lignocellulosic fabric-reinforced polyester matrix composites. *Polymer Testing, 24*, 81–85. https://doi.org/10.1016/j.polymertesting.2004.07.005

Alsubari, S., Zuhri, M. Y. M., Sapuan, S. M., et al. (2021). Potential of natural fiber reinforced polymer composites in sandwich structures: A review on its mechanical properties. *Polymers (Basel), 13*, 423. https://doi.org/10.3390/polym13030423

Aslan, M., Tufan, M., & Küçükömeroğlu, T. (2018). Tribological and mechanical performance of sisal-filled waste carbon and glass fibre hybrid composites. *Composites: Part B*. https://doi.org/10.1016/j.compositesb.2017.12.039

Athijayamani, A., Thiruchitrambalam, M., Manikandan, V., & Pazhanivel, B. (2010). Mechanical properties of natural fibers reinforced polyester hybrid composite. *International Journal of Plastics Technology, 14*, 104–116. https://doi.org/10.1007/s12588-009-0016-0

Atiqah, A., Jawaid, M., Ishak, M. R., & Sapuan, S. M. (2017). Moisture absorption and thickness swelling behaviour of sugar palm fibre reinforced thermoplastic polyurethane. *Procedia Engineering, 184*, 581–586. https://doi.org/10.1016/j.proeng.2017.04.142

Atiqah, A., Chandrasekar, M., Kumar, T. S. M., et al. (2019). *Characterization and interface of natural and synthetic hybrid composites characterization and interface of natural and synthetic hybrid composites*. Elsevier Ltd..

Ayu, R. S., Khalina, A., Harmaen, A. S., et al. (2020). Characterization study of empty fruit bunch (EFB) fibers reinforcement in poly(butylene) succinate (PBS)/starch/glycerol composite sheet. *Polymers (Basel), 12*, 1571. https://doi.org/10.3390/polym12071571

Bach, M. R., Chalivendra, V. B., Alves, C., & Depina, E. (2017). Mechanical characterization of natural biodegradable sandwich materials. *Journal of Sandwich Structures and Materials, 19*, 482–496. https://doi.org/10.1177/1099636215622143

Bahrami, M., Abenojar, J., & Martínez, M. Á. (2020). Recent progress in hybrid biocomposites: Mechanical properties, water absorption, and flame retardancy. *Materials (Basel), 13*, 5145. https://doi.org/10.3390/ma13225145

Battegazzore, D., Abt, T., Maspoch, M. L., & Frache, A. (2019). Multilayer cotton fabric bio-composites based on PLA and PHB copolymer for industrial load carrying applications. *Composites. Part B, Engineering, 163*, 761–768. https://doi.org/10.1016/j.compositesb.2019.01.057

Bhatnagar A (2006) Lightweight ballistic composites: Military and law-enforcement applications.

Birat, K., Panthapulakkal, S., Kronka, A., et al. (2015). Hybrid biocomposites with enhanced thermal and mechanical properties for structural applications. *Journal of Applied Polymer Science, 132*. https://doi.org/10.1002/app.42452

Boopalan, M., Niranjanaa, M., & Umapathy, M. J. (2013). Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. *Composites. Part B, Engineering, 51*, 54–57. https://doi.org/10.1016/j.compositesb.2013.02.033

Boujmal, R., Kakou, C. A., Nekhlaoui, S., et al. (2018). Alfa fibers/clay hybrid composites based on polypropylene. *Journal of Thermoplastic Composite Materials, 31*, 974–991. https://doi.org/10.1177/0892705717729197

Cai, S., Yang, K., Xu, Y., et al. (2021). Structure and moisture effect on the mechanical behavior of a natural biocomposite, buffalo horn sheath. *Composites Communications, 26*, 100748. https://doi.org/10.1016/j.coco.2021.100748

Dhakal, H. N., Ismail, S. O., Ojo, S. O., et al. (2018). Abrasive water jet drilling of advanced sustainable bio-fibre-reinforced polymer/hybrid composites: A comprehensive analysis of machining-induced damage responses. *International Journal of Advanced Manufacturing Technology, 99*, 2833–2847. https://doi.org/10.1007/s00170-018-2670-x

Drzal, L. T., Mohanty, A. K., & Misra, M. (2013). Bio-composite materials as alternatives to petroleum-based composites for automotive applications. *Magnesium, 40*, 1.3–1.2.

Eichhorn, S. J., Dufresne, A., Aranguren, M., et al. (2010). Review: Current international research into cellulose nanofibres and nanocomposites. *Journal of Materials Science, 45*, 1–33. https://doi.org/10.1007/s10853-009-3874-0

Essabir, H., Jawaid, M., Qaiss, A., & Bouhfid, R. (2017). Mechanical and thermal properties of polypropylene reinforced with doum fiber: Impact of fibrillization. In M. Jawaid, S. Sapuan, & O. Alothman (Eds.), *Green biocomposites. Green energy and technology* (pp. 255–270). Springer.

Faezipour, M., Shamsi, R., Ashori, A., et al. (2016). Hybrid composite using recycled polycarbonate/waste silk fibers and wood flour. *Polymer Composites, 37*, 1667–1673. https://doi.org/10.1002/pc.23339

Fiore, V., Scalici, T., Sarasini, F., et al. (2017). Salt-fog spray aging of jute-basalt reinforced hybrid structures: Flexural and low velocity impact response. *Composites. Part B, Engineering, 116*, 99–112. https://doi.org/10.1016/j.compositesb.2017.01.031

Gangil, B., Ranakoti, L., Verma, S., et al. (2020). Natural and synthetic fibers for hybrid composites. *Hybrid Fiber Compos Mater Manuf Process Eng*, 1–15.

Gao, P. X., Ding, Y., & Wang, Z. L. (2003). Crystallographic orientation-aligned ZnO nanorods grown by a tin catalyst. *Nano Letters, 3*, 1315–1320. https://doi.org/10.1021/nl034548q

Gonçalves, J. A. V., Campos, D. A. T., Oliveira, G., et al. (2014). Mechanical properties of epoxy resin based on granite stone powder from the Sergipe fold-and-thrust belt composites. *Materials Research, 17*, 878–887. https://doi.org/10.1590/S1516-14392014005000100

Gupta, M., & Deep, V. (2019). Effect of water absorption and stacking sequences on the properties of hybrid sisal/glass fibre reinforced polyester composite. *Proceedings of the Institution of Mechanical Engineers, Part L, 233*, 2045–2056. https://doi.org/10.1177/1464420718811867

Gupta, M. K., & Srivastava, R. K. (2016). A review on characterization of hybrid fibre reinforced polymer composite. *American Journal of Polymer Science & Engineering, 4*, 1–7.

Halimatul, M. J., Sapuan, S. M., Jawaid, M., et al. (2019). Effect of sago starch and plasticizer content on the properties of thermoplastic films: Mechanical testing and cyclic soaking-drying. *Polimery, 64*, 32–41. https://doi.org/10.14314/polimery.2019.6.5

Idicula, M., Malhotra, S. K., Joseph, K., & Thomas, S. (2005). Dynamic mechanical analysis of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites. *Composites Science and Technology, 65*, 1077–1087. https://doi.org/10.1016/j.compscitech.2004.10.023

Idicula, M., Boudenne, A., Umadevi, L., et al. (2006). Thermophysical properties of natural fibre reinforced polyester composites. *Composites Science and Technology, 66*, 2719–2725.

Ilyas, R. A., Sapuan, S. M., & Ishak, M. R. (2018). Isolation and characterization of nanocrystalline cellulose from sugar palm fibres (Arenga Pinnata). *Carbohydrate Polymers, 181*, 1038–1051. https://doi.org/10.1016/j.carbpol.2017.11.045

Ilyas, R. A., Sapuan, S. M., Ibrahim, R., et al. (2019a). Effect of sugar palm nanofibrillated cellulose concentrations on morphological, mechanical and physical properties of biodegradable films based on agro-waste sugar palm (Arenga pinnata(Wurmb.) Merr) starch. *Journal of Materials Research and Technology, 8*, 4819–4830. https://doi.org/10.1016/j.jmrt.2019.08.028

Ilyas, R. A., Sapuan, S. M., Ishak, M. R., & Zainudin, E. S. (2019b). Sugar palm nanofibrillated cellulose (Arenga pinnata (Wurmb.) Merr): Effect of cycles on their yield, physic-chemical, morphological and thermal behavior. *International Journal of Biological Macromolecules, 123*, 379–388. https://doi.org/10.1016/j.ijbiomac.2018.11.124

Ilyas, R. A., Sapuan, S. M., Atiqah, A., et al. (2020a). Sugar palm (Arenga pinnata [Wurmb.] Merr) starch films containing sugar palm nanofibrillated cellulose as reinforcement: Water barrier properties. *Polymer Composites, 41*, 459–467. https://doi.org/10.1002/pc.25379

Ilyas, R. A., Sapuan, S. M., Ibrahim, R., et al. (2020b). Thermal, biodegradability and water barrier properties of bio-nanocomposites based on plasticised sugar palm starch and nanofibrillated celluloses from sugar palm fibres. *Journal of Biobased Materials and Bioenergy, 14*, 234–248. https://doi.org/10.1166/jbmb.2020.1951

Ilyas, R. A., Sapuan, S. M., Harussani, M. M., et al. (2021). Polylactic acid (PLA) biocomposite: Processing, additive manufacturing and advanced applications. *Polymers (Basel), 13*, 1326. https://doi.org/10.3390/polym13081326

Ishak, Z. A. M., Aminullah, A., Ismail, H., & Rozman, H. D. (1998). Effect of silane-based coupling agents and acrylic acid based compatibilizers on mechanical properties of oil palm empty fruit bunch filled high-density polyethylene composites. *Journal of Applied Polymer Science, 68*, 2189–2203. https://doi.org/10.1002/(SICI)1097-4628(19980627)68:13<2189::AID-APP16>3.0.CO;2-V

Jacob, M., Varughese, K. T., & Thomas, S. (2006). Dielectric characteristics of sisal–oil palm hybrid biofibre reinforced natural rubber biocomposites. *Journal of Materials Science, 41*, 5538–5547. https://doi.org/10.1007/s10853-006-0298-y

Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers, 86*, 1–18. https://doi.org/10.1016/j.carbpol.2011.04.043

Jawaid, M., & Thariq, M. (2018). *Sustainable composites for aerospace applications*. Elsevier.

Jawaid, M., Abdul Khalil, H. P. S., Hassan, A., et al. (2013). Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites. *Composites. Part B, Engineering, 45*, 619–624. https://doi.org/10.1016/j.compositesb.2012.04.068

Jumaidin, R., Khiruddin, M. A. A., Asyul Sutan Saidi, Z., et al. (2020). Effect of cogon grass fibre on the thermal, mechanical and biodegradation properties of thermoplastic cassava starch biocomposite. *International Journal of Biological Macromolecules, 146*, 746–755. https://doi.org/10.1016/j.ijbiomac.2019.11.011

Jumaidin, R., Diah, N. A., Ilyas, R. A., et al. (2021). Processing and characterisation of banana leaf fibre reinforced thermoplastic cassava starch composites. *Polymers (Basel), 13*, 1420. https://doi.org/10.3390/polym13091420

Kadem, S., Irinislimane, R., & Belhaneche-Bensemra, N. (2018). Novel biocomposites based on sunflower oil and alfa fibers as renewable resources. *Journal of Polymers and the Environment, 26*, 3086–3096. https://doi.org/10.1007/s10924-018-1196-5

Kumar, T. S. M., Chandrasekar, M., Senthilkumar, K., et al. (2020). Characterization, thermal and antimicrobial properties of hybrid cellulose nanocomposite films with in-situ generated copper nanoparticles in tamarindus indica nut powder. *Journal of Polymers and the Environment*, 1–10. https://doi.org/10.1007/s10924-020-01939-w

Kwon, H.-J., Sunthornvarabhas, J., Park, J.-W., et al. (2014). Tensile properties of kenaf fiber and corn husk flour reinforced poly(lactic acid) hybrid bio-composites: Role of aspect ratio of natural fibers. *Composites. Part B, Engineering, 56*, 232–237. https://doi.org/10.1016/j.compositesb.2013.08.003

Leman, Z., Sapuan, S. M., Azwan, M., et al. (2008). The effect of environmental treatments on fiber surface properties and tensile strength of sugar palm fiber-reinforced epoxy composites. *Polymer - Plastics Technology and Engineering, 47*, 606–612. https://doi.org/10.1080/03602550802059451

Manyatshe, A., Balogun, M. O., Nkambule, T. T. I., et al. (2020). Chemical modification of sugarcane bagasse with chitosan for the removal of phosphates in aqueous solution. *AIP Conference Proceedings, 2289*. https://doi.org/10.1063/5.0028378

Mohd Nurazzi, N., Khalina, A., Sapuan, S. M., & Ilyas, R. A. (2019). Mechanical properties of sugar palm yarn/woven glass fiber reinforced unsaturated polyester composites: Effect of fiber loadings and alkaline treatment. *Polimery/Polymers, 64*, 665. https://doi.org/10.14314/polimery.2019.10.3

Narnaware, P. H., Surose, R. G., & Gaikwad, S. V. (2015). Current status and the future potentials of renewable energy in India-A review. *International Journal on Advanced Science, Engineering and Information Technology*, 2321–9009.

Nisini, E., Santulli, C., & Liverani, A. (2017). Mechanical and impact characterization of hybrid composite laminates with carbon, basalt and flax fibres. *Composites. Part B, Engineering, 127*, 92–99. https://doi.org/10.1016/j.compositesb.2016.06.071

Nunna, S., Chandra, P. R., Shrivastava, S., & Jalan, A. K. (2012). A review on mechanical behavior of natural fiber based hybrid composites. *Journal of Reinforced Plastics and Composites, 31*, 759–769.

Nurazzi, N. M., Khalina, A., Sapuan, S. M., et al. (2019). Thermal properties of treated sugar palm yarn/glass fiber reinforced unsaturated polyester hybrid composites. *Journal of Materials Research and Technology*. https://doi.org/10.1016/j.jmrt.2019.11.086

Nurazzi, N. M., Khalina, A., Sapuan, S. M., et al. (2020). Thermal properties of treated sugar palm yarn/glass fiber reinforced unsaturated polyester hybrid composites. *Journal of Materials Research and Technology, 9*, 1606–1618. https://doi.org/10.1016/j.jmrt.2019.11.086

Nurazzi, N. M., Asyraf, M. R. M., Khalina, A., et al. (2021). A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications. *Polymers (Basel), 13*, 646. https://doi.org/10.3390/polym13040646

Omran, A. A. B., Mohammed, A. A. B. A., Sapuan, S. M., et al. (2021). Micro- and nanocellulose in polymer composite materials: A review. *Polymers (Basel), 13*, 231. https://doi.org/10.3390/polym13020231

Otto, G. P., Moisés, M. P., Carvalho, G., et al. (2017). Mechanical properties of a polyurethane hybrid composite with natural lignocellulosic fibers. *Composites. Part B, Engineering, 110*, 459–465. https://doi.org/10.1016/j.compositesb.2016.11.035

Papa, I., Ricciardi, M., Antonucci, V., et al. (2020). Comparison between different non-destructive techniques methods to detect and characterize impact damage on composite laminates. *Journal of Composite Materials, 54*, 617–631. https://doi.org/10.1177/0021998319864411

Petrucci, R., Santulli, C., Puglia, D., et al. (2015). Impact and post-impact damage characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion. *Composites. Part B, Engineering, 69*, 507–515. https://doi.org/10.1016/j.compositesb.2014.10.031

Prabhakaran, S., Krishnaraj, V., Kumar, M. S., & Zitoune, R. (2014). Sound and vibration damping properties of flax fiber reinforced composites. *Procedia Engineering, 97*, 573–581. https://doi.org/10.1016/j.proeng.2014.12.285

Pradhan, S., & Acharya, S. K. (2021). Solid particle erosive wear behaviour of Eulaliopsis binata fiber reinforced epoxy composite. *Proceedings of the Institution of Mechanical Engineers, Part J, 235*, 830–841. https://doi.org/10.1177/1350650120931645

Punia Bangar, S., Nehra, M., Siroha, A. K., et al. (2021). Development and characterization of physical modified pearl millet starch-based films. *Food, 10*, 1609. https://doi.org/10.3390/foods10071609

Qaiss, A., Bouhfid, R., & Essabir, H. (2015). Effect of processing conditions on the mechanical and morphological properties of composites reinforced by natural fibres. In *Manufacturing of natural fibre reinforced polymer composites* (pp. 177–197). Springer International Publishing.

Raghavendra, G., Ojha, S., Acharya, S. K., & Pal, S. K. (2016). A comparative analysis of woven jute/glass hybrid polymer composite with and without reinforcing of fly ash particles. *Polymer Composites, 37*, 658–665. https://doi.org/10.1002/pc.23222

Raj, F. M., Nagarajan, V. A., & Elsi, S. S. (2017). Mechanical, physical and dynamical properties of glass fiber and waste fishnet hybrid composites. *Polymer Bulletin, 74*, 1441–1460. https://doi.org/10.1007/s00289-016-1783-3

Rajesh, M., Singh, S. P., & Pitchaimani, J. (2018). Mechanical behavior of woven natural fiber fabric composites: Effect of weaving architecture, intra-ply hybridization and stacking sequence of fabrics. *Journal of Industrial Textiles, 47*, 938–959. https://doi.org/10.1177/1528083716679157

Ramesh, M., Palanikumar, K., & Reddy, K. H. (2013). Comparative evaluation on properties of hybrid glass fiber-sisal/jute reinforced epoxy composites. *Procedia Engeering, 51*, 745–750. https://doi.org/10.1016/j.proeng.2013.01.106

Ravandi, M., Kureemun, U., Banu, M., et al. (2019). Effect of interlayer carbon fiber dispersion on the low-velocity impact performance of woven flax-carbon hybrid composites. *Journal of Composite Materials, 53*, 1717–1734. https://doi.org/10.1177/0021998318808355

Reddy, N. (2019). Composites from coir fibers. In *Sustainable applications of coir and other coconut by-products* (pp. 141–185). Springer International Publishing.

Ridzuan, M. J. M., Majid, M. S. A., Afendi, M., et al. (2017). Effect of elevated temperature on the tensile strength of Napier/glass-epoxy hybrid reinforced composites. *AIP Conference Proceedings, 1902*, 020062.

Rout, J., Misra, M., Tripathy, S. S., et al. (2001). The influence of fibre treatment on the performance of coir-polyester composites. *Composites Science and Technology, 61*, 1303–1310. https://doi.org/10.1016/S0266-3538(01)00021-5

Rozilah, A., Jaafar, C. N. A., Sapuan, S. M., et al. (2020). The effects of silver nanoparticles compositions on the mechanical, physiochemical, antibacterial, and morphology properties of sugar palm starch biocomposites for antibacterial coating. *Polymers (Basel), 12*, 2605. https://doi.org/10.3390/polym12112605

Rozman, H. D., Shannon-Ong, S. H., Azizah, A. B., & Tay, G. S. (2013). Preliminary study of non-woven composite: Effect of needle punching and kenaf fiber loadings on non-woven thermoplastic composites prepared from Kenaf and Polypropylene Fiber. *Journal of Polymers and the Environment, 21*, 1032–1039. https://doi.org/10.1007/s10924-013-0599-6

Samanta, S., Muralidhar, M., Singh, T. J., & Sarkar, S. (2015). Characterization of mechanical properties of hybrid Bamboo/GFRP and Jute/GFRP composites. *Materials Today: Proceedings, 2*, 1398–1405. https://doi.org/10.1016/j.matpr.2015.07.059

Sanjay, M. R., & Yogesha, B. (2016). Studies on mechanical properties of jute/E-glass fiber reinforced epoxy hybrid composites. *Journal of Minerals and Materials Characterization and Engineering, 04*, 15–25. https://doi.org/10.4236/jmmce.2016.41002

Sanjay, M., & Yogesha, B. (2018). Studies on hybridization effect of jute/kenaf/E-glass woven fabric epoxy composites for potential applications: Effect of laminate stacking sequences. *Journal of Industrial Textiles, 47*, 1830–1848. https://doi.org/10.1177/1528083717710713

Sanjay, M. R., Madhu, P., Jawaid, M., et al. (2017). Characterization and properties of natural fiber polymer composites: A comprehensive review. *Journal of Cleaner Production, 172*, 566–581. https://doi.org/10.1016/j.jclepro.2017.10.101

Santulli, C. (2007). Impact properties of glass/plant fibre hybrid laminates. *Journal of Materials Science, 42*, 3699–3707. https://doi.org/10.1007/s10853-006-0662-y

Santulli, C., Janssen, M., & Jeronimidis, G. (2005). Partial replacement of E-glass fibers with flax fibers in composites and effect on falling weight impact performance. *Journal of Materials Science, 40*, 3581–3585. https://doi.org/10.1007/s10853-005-2882-y

Sapuan, S. M., & Ilyas, R. A. (2018). Characterization of sugar palm nanocellulose and its potential for reinforcement with a starch-based composite. *Sugar Palm Biofibers, Biopolym Biocomposites*, 189–220. https://doi.org/10.1201/9780429443923-10

Sapuan, S. M., Sahari, J., Ishak, M. R., & Sanyang, M. L. (2019). *Sugar palm biofibers, biopolymers, and biocomposites, First*. CRC Press (Tailor & Francis Group)LLC.

Sathishkumar, T., Naveen, J., Navaneethakrishnan, P., et al. (2017). Characterization of sisal/cotton fibre woven mat reinforced polymer hybrid composites. *Journal of Industrial Textiles, 47*, 429–452. https://doi.org/10.1177/1528083716648764

Saw, S. K., Sarkhel, G., & Choudhury, A. (2011). Dynamic mechanical analysis of randomly oriented short bagasse/coir hybrid fibre-reinforced epoxy novolac composites. *Fibers and Polymers, 12*, 506–513. https://doi.org/10.1007/s12221-011-0506-5

Saxena, M., & Gupta, M. (2019). Mechanical, thermal, and water absorption properties of hybrid wood composites. *Proceedings of the Institution of Mechanical Engineers, Part L, 233*, 1914–1922. https://doi.org/10.1177/1464420718798661

Scheff, S., Friedman-Berg, F., Shively, J., & Carter, A. (2020). Human factors challenges in urban air mobility. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 64*, 179–182. https://doi.org/10.1177/1071181320641044

Shahzad, A., & Nasir, S. U. (2017). Mechanical properties of natural fiber/synthetic fiber reinforced polymer hybrid composites. In M. Jawaid, S. Sapuan, & O. Alothman (Eds.), *Green biocomposites. Green energy and technology* (pp. 355–396). Springer.

Silva, L., Panzera, T., Velloso, V., et al. (2013). Statistical design of polymeric composites reinforced with banana fibres and silica microparticles. *Journal of Composite Materials, 47*, 1199–1210. https://doi.org/10.1177/0021998312446499

Singh, V. K., & Mukhopadhyay, S. (2020). Hybrid biocomposites. *Indian Journal of Fibre & Textile Research, 45*, 224–246.

Sivakumar, D., Ng, L. F., Lau, S. M., & Lim, K. T. (2018). Fatigue life behaviour of Glass/Kenaf woven-ply polymer hybrid biocomposites. *Journal of Polymers and the Environment, 26*, 499–507. https://doi.org/10.1007/s10924-017-0970-0

Sreekumar, P. A., Agoudjil, B., Boudenne, A., et al. (2012). Transport properties of polyester composite reinforced with treated sisal fibers. *Journal of Reinforced Plastics and Composites, 31*, 117–127. https://doi.org/10.1177/0731684411431971

Suriani, M., Sapuan, S., Ruzaidi, C., et al. (2021a). Flammability, morphological and mechanical properties of sugar palm fiber/polyester yarn-reinforced epoxy hybrid biocomposites with magnesium hydroxide flame retardant filler. *Textile Research Journal*, 004051752110086. https://doi.org/10.1177/00405175211008615

Suriani, M. J., Radzi, F. S. M., Ilyas, R. A., et al. (2021b). Flammability, tensile, and morphological properties of oil palm empty fruit bunches fiber/pet yarn-reinforced epoxy fire retardant hybrid polymer composites. *Polymers (Basel), 13*, 1282. https://doi.org/10.3390/polym13081282

Suriani, M. J., Rapi, H. Z., Ilyas, R. A., et al. (2021c). Delamination and manufacturing defects in natural fiber-reinforced hybrid composite: A review. *Polymers (Basel), 13*, 1323. https://doi.org/10.3390/polym13081323

Suriani, M. J., Zainudin, H. A., Ilyas, R. A., et al. (2021d). Kenaf fiber/pet yarn reinforced epoxy hybrid polymer composites: Morphological, tensile, and flammability properties. *Polymers (Basel), 13*, 1532. https://doi.org/10.3390/polym13091532

Swolfs, Y., McMeeking, R. M., Verpoest, I., & Gorbatikh, L. (2015). The effect of fibre dispersion on initial failure strain and cluster development in unidirectional carbon/glass hybrid composites. *Composites. Part A, Applied Science and Manufacturing, 69*, 279–287. https://doi.org/10.1016/j.compositesa.2014.12.001

Syafiq, R., Sapuan, S. M., Zuhri, M. Y. M., et al. (2020). Antimicrobial activities of starch-based biopolymers and biocomposites incorporated with plant essential oils: A review. *Polymers (Basel), 12*, 2403. https://doi.org/10.3390/polym12102403

Vijaya Ramnath, B., Sharavanan, R., Chandrasekaran, M., et al. (2015). Experimental determination of mechanical properties of banana jute hybrid composite. *Fibers and Polymers, 16*, 164–172. https://doi.org/10.1007/s12221-015-0164-0

Ward, K. A., Winter, S. R., Cross, D. S., et al. (2021). Safety systems, culture, and willingness to fly in autonomous air taxis: A multi-study and mediation analysis. *Journal of Air Transport Management, 91*, 101975. https://doi.org/10.1016/j.jairtraman.2020.101975

Winter, S. R., Rice, S., & Lamb, T. L. (2020). A prediction model of Consumer's willingness to fly in autonomous air taxis. *Journal of Air Transport Management, 89*, 101926. https://doi.org/10.1016/j.jairtraman.2020.101926

Yahaya, R., Sapuan, S. M., Jawaid, M., et al. (2017). Review of kenaf reinforced hybrid biocomposites: Potential in defence applications. *Current Analytical Chemistry, 14*, 226–240. https://doi.org/10.2174/1573411013666171113150225

Yantaboot, K., & Amornsakchai, T. (2017). Effect of preparation methods and carbon black distribution on mechanical properties of short pineapple leaf fiber-carbon black reinforced natural rubber hybrid composites. *Polymer Testing, 61*, 223–228. https://doi.org/10.1016/j.polymertesting.2017.05.026

Yao, J., Hu, Y., & Lu, W. (2012). Performance research on coir fiber and wood debris hybrid boards. *BioResources, 7*, 4262–4272.

Zhang, X., Xiong, R., Kang, S., et al. (2020). Alternating stacking of nanocrystals and nanofibers into ultrastrong chiral biocomposite laminates. *ACS Nano, 14*, 14675–14685. https://doi.org/10.1021/acsnano.0c06192

Živković, I., Fragassa, C., Pavlović, A., & Brugo, T. (2017). Influence of moisture absorption on the impact properties of flax, basalt and hybrid flax/basalt fiber reinforced green composites. *Composites. Part B, Engineering, 111*, 148–164. https://doi.org/10.1016/j.compositesb.2016.12.018