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Review on natural plant fibres and their hybrid composites for structural applications: Recent trends and future perspectives

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A R T I C L E I N F O

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A B S T R A C T

Sustainability and environmental protection have given rise to the use of renewable and biobased materials in several application areas. Fibre reinforced composites are currently gaining a high market value in both structural and semi-structural applications. Making these materials environmentally friendly, renewable and lighter will protect the environment and increase resource use efficiency. Opposed to synthetic fibres such as carbon and glass, natural plant fibres are less expensive, lighter, degradable, easy to produce, non-toxic and environmentally friendly. However, natural plant fibres are inferior to their synthetic counterparts in both mechanical performance and tolerance to harsh environmental conditions. One method of compensating for these disadvantages is to combine natural and synthetic fibres in a single matrix forming a hybrid composite where the disadvantages of one are compensated by the other. In this way, sustainability and cost minimisation are achieved with acceptable mechanical and physical responses. However, successful implementation and advancement in the development of natural plant fibre reinforced polymer (FRP) hybrid composites require the development of workable conceptual design, suitable manufacturing techniques and understanding of the strengthening mechanisms. The main objectives of this review are to critically review the current state of knowledge in the development of natural FRP hybrid composites, outlining their properties and enhancing them while reducing environmental impact of the product through the hybridisation approach.

1. Introduction and background

Fibre reinforced polymer (FRP) composites are viable structural materials that have become the basis for many modern products, because they possess intrinsic properties and combination of properties which cannot be attained by conventional materials [1–4]. They are usually a combination of two or more constituents, one of which serving as the matrix and others as reinforcing phases. Thermoplastic and thermosetting polymers have been used as matrix phases. Fibres that have been used include glass, carbon, graphite, graphene, aramid, kevlar, natural and wood fibres. These fillers are used as short or long fibres (Fig. 1). The earlier can either be random or aligned, whereas the later can be unidirectional, woven, or non-woven. FRPs have been applied in areas such as aerospace (aeroplanes, helicopters, spacecrafts) [5,6], marine [7–9], automobile [10,11], sport [12], chemical equipment [13], civil infrastructure (including bridges) [14], building construction [15], biomedical and even household appliances [16]. These materials possess excellent specific strength and stiffness, durability, creep resistance, lightweight, heat, corrosion, and fatigue resistance [17]. They can also be tailored to satisfy specific performance requirements. However, FRPs are relatively cost intensive, poor damage tolerant, brittle, not easily adaptable, and some of them raise environmental concerns, including carbon and glass fibres from fossil sources. To overcome the disadvantages of traditional FRP, hybrid FRP composites are increasingly being studied and used in various engineering applications [18–22].

Hybrid composites are basically FRPs with two or more types of fibres combined systematically in a single matrix system to attain desired properties (Fig. 2). This kind of material benefits greatly from the synergistic effects of the various reinforcing phases. For instance, a more effective stress transfer can be obtained when fibres of differing diameters are used. This could result in improved fibre-matrix adhesion and consequently enhanced properties. Another example is realising a positive load bridging effect when fibres with comparatively high

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elongation capacity are combined with fibres of low elongation. In essence, hybrid composites could be regarded as the weighted sum of specific components, where a balance of advantages and disadvantages of these components are achieved. Hybridisation of FRPs can be achieved in different ways: (1) combination of two or more long fibres in the same matrix, (2) combination of long fibres and short fibres in the same matrix, (3) combination of two or more short fibres, (4) combination of short fibres with nanofillers and (5) combination of long fibres with nanofillers.

Although, fibre hybridisation has been used to solve several challenges in FRPs, realising cost effective and environmentally sustainable materials remain the primary challenge in the production of FRPs. The drive for environmental sustainability and cost effectiveness has necessitated the move from synthetic FRP composites to more environmentally friendly fibres. Natural plant fibres are proven suitable alternatives to synthetic fibres, because they are lightweight, renewable, sustainable, eco-friendly, carbon neutral, low cost, biodegradable and relatively available. They also possess good insulation properties, toughness, vibration damping, flexibility, and high specific strength and modulus when compared with their synthetic counterparts [23–35]. Biocomposites based on sisal, abaca, coir, cotton, flax, hemp, kenaf, ramie, jute and palm have been successfully applied as door panels, door linings, back seats, package trays, rear parcels, seat covers and door mats in automobiles [36–41]. However, natural plant fibres possess poor thermal and dimensional stability, high water adsorption capacity and poor adhesion to polymer matrix. These disadvantages can be overcome by hybridisation techniques. For example, hybrid glass-sisal fibre composites were observed to possess better water adsorption properties than sisal bio-composites coupled with improved elasticity [42]. In another study, hybrid kenaf-glass fibre composites resulted to 20 and 23% reduction in cost and weight respectively but maintained the mechanical resistance required for commercial pipes [43]. Natural - glass FRP hybrid composites aimed at replacing glass mat-thermoplastic (GMT) composites was reported to possess comparable and even better properties than currently used GMTs for car bumpers [44,45]. Hybridisation of treated kenaf and carbon fibre in epoxy matrix was observed to be cheaper and stronger than carbon FRP laminates [46]. Hybrid hemp (25 wt.%) - glass (15 wt.%) fibres in polypropylene was observed to be suitable for structural applications, where high stiffness and thermal resistances are required [47].

A successful advancement and implementation of natural FRP hybrid composites will involve: (1) development of workable conceptual design framework, (2) development of suitable manufacturing techniques and (3) improved understanding of the strengthening mechanisms, considering the basic structural components of natural plant fibres. Generally, the conceptual idea in the development of natural FRP hybrid composites is achieving sustainability and cost minimisation. A systematic design approach is needed in order to synergise these concepts with performance requirements (Fig. 3). Theoretically, three conceptual design frameworks can be identified in the development of natural FRP hybrid composites: (1) tailored property designs also called design for applications, (2) design for functionality/multi-functionality and (3) design for compensation. For instance, addition of aramid fibres to the outer layers of natural FRP composites should impart fire resistance function. Because aramid fibres normally do not melt, they will carbonise in fire to produce a protecting layer for the composites [48]. The most basic design in natural FRP hybrid composites is the design for compensation. It is directly related to the overall natural FRP hybrid composites design ideology, because it focuses on compensating deficiencies of natural FRP composites by looking for a suitable synthetic or natural counterpart. For example, carbon fibre reinforced composites used for bicycle parts possess very poor damping behaviour. To compensate for this poor vibration damping, flax fibres which are known for excellent vibration damping characteristics are systematically added to the composites [49]. However, there exist situations where synergistic effects are attained by combining two or more fibre types. These synergistic effects cause the resultant properties of the hybrid system to be either lower or higher than those of the individual components. In this case, the design of the hybrid composite has to be selected carefully to avoid negative hybrid effect. This requires a very good understanding of the development of hybrid effect in natural FRP hybrid composites.

A few review articles have been published in the area of natural and hybrid fibre reinforced polymer composites [18,21,50,51]. These articles were predominantly focused on natural FRP composites and synthetic-synthetic hybrid FRP composites. The present review goes beyond research in pristine natural FRP composites and synthetic FRP hybrid composites, focusing principally on natural FRP hybrid composites. To compensate the deficiency of previous reviews, this article critically discusses the current state-of-knowledge in the development of natural FRP hybrid composites with the aim of elucidating mechanisms, processes, materials in the production of natural FRP hybrid composites, and identify technical opportunities for further development of natural FRP hybrid composites. Firstly, the state-of-knowledge in natural FRP composites is highlighted, identifying important viable fibres for advanced applications, their properties and potentials. Then, hybridisation of natural FRP composites is discussed in details, elucidating concepts, techniques, properties and potentials of natural FRP hybrid

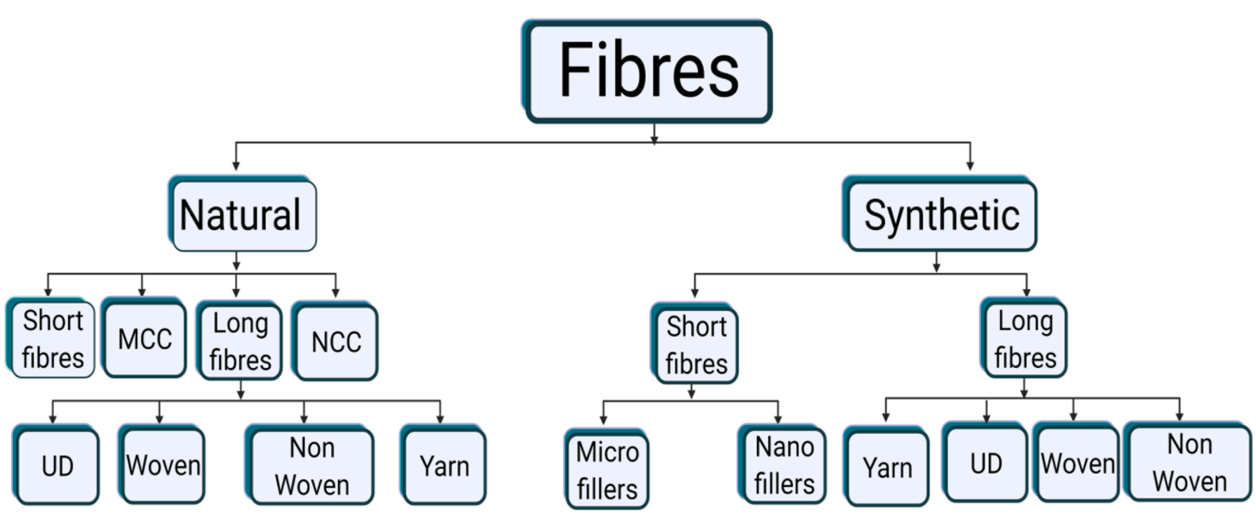

Fig. 1. Natural-synthetic fibres structural forms. Several combinations of natural/synthetic hybrids are possible depending on the hybridisation concept and application requirements. Concepts of hybridisation are presented in a subsequent section.

composites. A critical look at the challenges and prospects of hybridisation is presented in this section. Thereafter, prospective application areas are rigorously discussed, considering the properties of natural FRP hybrid composites. In this section, a critical consideration of the concept of bio-mimicking using hybridisation is proposed. Furthermore, the environmental aspect and acoustic behaviour of natural FRP hybrid composites are critically discussed, followed by prospects in improving thermal stability of structural members fabricated with natural FRP hybrid composites. The need for the application of modelling and simulation towards property enhancement is considered within the scope of this compendious review. Life cycle and cost analyses of natural and synthetic FRP composites are also juxtaposed. Finally, future prospects and research opportunities are presented.

2. Natural fibre-reinforced polymer composites

2.1. Natural plant fibres used in FRP composites

Natural FRP composites have gained popularity in recent years, due to their various attractive attributes. This is also necessitated by the ecological and environmental concerns arising from the use of non-renewable glass and carbon FRP composites. It is obvious that glass and carbon FRP composites possess high mechanical, thermal and environmental properties in comparison with natural FRP composites. But, it is noteworthy to highlight that the high energy consumption for the extraction, processing and disposal of conventional FRP composites are far higher than that of natural FRP composites. In this context, fully biobased composites where both reinforcements and matrices are from renewable sources provide significant environmental benefits [52]. Fibres such as flax, hemp, jute, kenaf, banana, pineapple and sisal are most commonly used natural plant fibres as reinforcements in composites. Moreover, these composites have lower density, biodegradability, abundance and non-toxic in nature [53,54].

Arising from the aforementioned benefits, research and development activities from both academic and industrial sectors are significantly increased in recent years. Moreover, consumer's behaviour and various government legislations have further forced the industrial communities to adopt materials that are sustainable and more environmentally friendly [55,56]. Despite many benefits, natural FRP composites are not without any challenges. Amongst other drawbacks, moisture absorption is one of the key challenges of natural FRP composites, because moisture absorption causes fibre swelling and debonding. These eventually lead to a weak fibre-matrix interface that ultimately affects the overall mechanical properties [57–59].

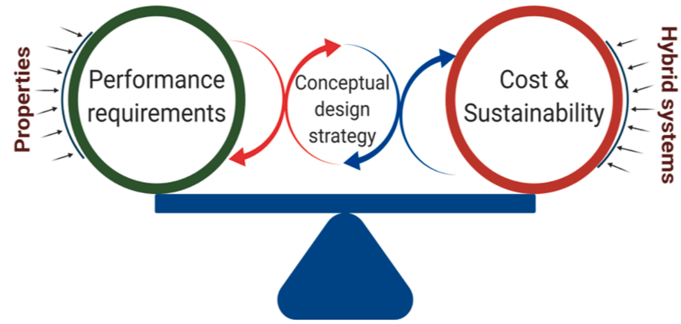

Fig. 3. Synergistic connection between natural FRP hybrid composites conceptual idea and overall material performance. Proper design strategies are needed to balance the two extremes.

2.2. Matrix system used in natural FRP composites

There are different matrices used for natural FRP composites. The overall properties of composites are significantly influenced by the matrix type used. Thermosets matrices provide higher mechanical properties than the thermoplastic matrices. The key benefits and limitations of thermoplastic and thermoset matrices are illustrated in the Table 1.

2.3. Processing and manufacturing of natural FRP composites

Processing methods significantly influence final properties of FRP composites. Hence, they should be carefully selected towards optimised performances of the composites. The manufacturing techniques are generally governed by parameters such as temperature, pressure and fibre parameters (aspect ratio and volume fraction). Optimization of fibre aspect ratio and volume fraction are key issues in the manufacturing of FRP composites. Manufacturing of FRP composites involves thermo-mechanical processes. Natural FRP composites have limitations as they have low processing temperatures.

2.3.1. Hand lay-up

Hand lay-up is one of the most commonly used fabrication processes for composite materials with benefits of simple, low cost, low skill requirements. It involves draping and impregnation of the fibres with resins. This technique can be used for both large and small parts. Therefore, there is no part size limit. This method suffers from poor physical appearance of the parts and high void contents. Improved techniques can be used to reduce these manufacturing induced defects.

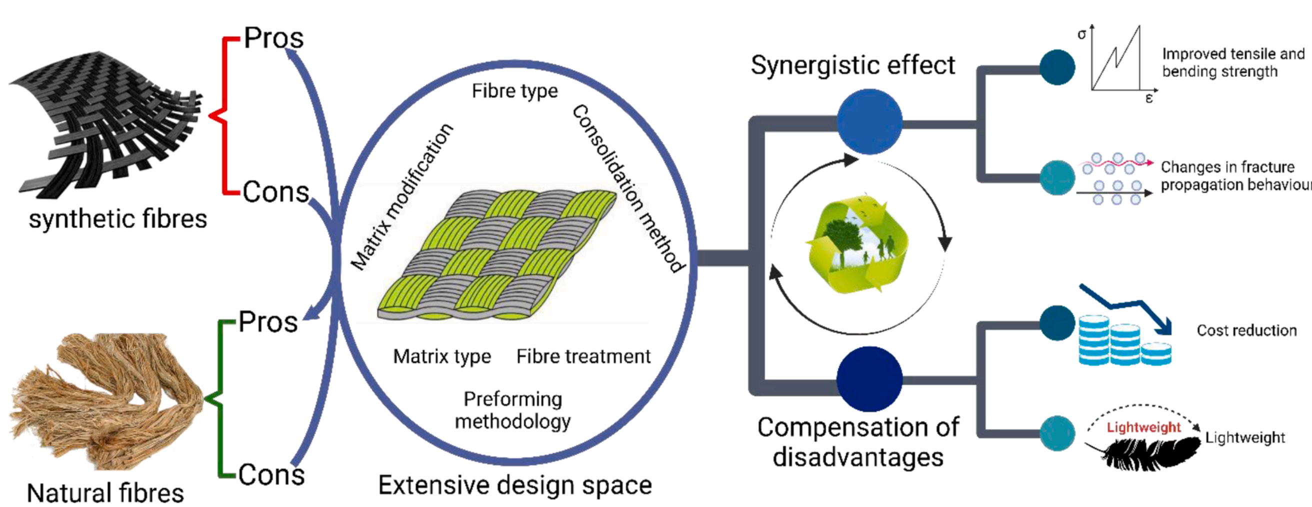

Fig. 2. The general concept of natural FRP hybrid composites.

Table 1
Advantages and limitations of different matrices [60,61].

Matrix types	Examples	Advantages	Drawbacks
Thermosets	Epoxy, polyimides, vinyl ester, polyester	Higher temperature resistance than thermoplastics counterparts, highly flexible design, excellent aesthetic appearance, better dimensional stability, cost-effective, high strength and stiffness, excellent wettability, high thermal stability.	Non-renewable sources, Mostly brittle in nature
Thermoplastics	Polypropylene, polystyrene, nylon and Teflon	Highly recyclable, aesthetically-superior finishes, high-impact resistance, remoulding/ reshaping capabilities, chemical resistant, hard crystalline or rubbery surface options, eco-friendly manufacturing, easy processing, good toughness properties	Low strength compared to thermosets, generally more expensive than thermoset
Bio-based		Sometimes Biodegradable, Good end-of life option	Low strength and stiffness Low processing temperatures

Hand lay-up method accommodates woven, non-woven mats as well as rovings. Very often, hand lay-up process is used in combination with compression moulding and autoclaving techniques [53].

2.3.2. Resin transfer moulding

Resin transfer moulding (RTM) has significantly gain popularity, due to its ability to produce parts with good surface finish and low void contents. It is a closed-mould technique and hardly releases volatile substances into the atmosphere during fabrication process. The resin is injected directly into the closed mould of two halves with no direct exposure of the resin to air. The reinforcements are pre-positioned in the closed mould and the resins are transported to impregnate the fibres via pressure or vacuum assisted method. These are used to fabricate high quality parts for high end applications, such as aerospace and automotive sectors. The high surface quality is achieved with relatively low mould temperatures of 60–90 °C and relatively low pressure which has a substantial impact on reducing the cost of tooling.

2.3.3. Pultrusion

Pultrusion is an advanced manufacturing process for producing unidirectional fibre composites. During the process, fibres released from rovings are pulled from a creel through a resin bath for impregnation via a heated die. The die completes the impregnation of the fibres and also controls the resin content. The parts are cured into its final shape as it passes through the die. This cured profile is then automatically cut to desired length. The matrices used in this process are common thermosets matrices such as epoxy, polyester, vinyl ester and phenolic resins. Pultrusion is an attractive and economical process, because it requires less time. Because of contact curing and controlled resin content, parts produced via this process are usually of good wettability and high surface quality. High fibre volume fraction can be achieved, which helps in achieving high mechanical properties. One of the drawbacks of this process is that the heated moulds are costly. Applications of this process include beams and girders.

2.3.4. Filament winding

Filament winding is peculiar to hollow, circular or oval sectioned components, such as pipes and tanks. Fibre tows are passed through a resin bath before being wound onto a mandrel in a variety of orientations, controlled by the fibre feeding mechanism, and rate of rotation of the mandrel. Factors such as winding angle and drag pressure determine the mechanical properties of the fabricated composite structures. Recent advances in filament winding is the use of robots (smart manufacturing).

2.3.5. Compression moulding

Compression moulding is a traditional technique used to fabricate both thermosets and thermoplastic composites. During this process, pressure and temperature are utilised while consolidation of composites is completed or fully cured. Depending on the required composite part, both temperature and pressure are varied or controlled. This technique is mainly used for fabricating large flat and curved parts. For large parts, controlling of uniform thickness can be challenging. In comparison with various fabrication processes, compression moulding is considered as the most economical process for high quality composite parts.

2.4. Factors affecting mechanical performance of natural FRP composites

The overall mechanical properties of FRP composites including natural FRP composites are determined by the properties of the fibre and matrix. In comparison to the matrix, fibre plays the major role in withstanding the load whereas the matrix protects the fibre. Although the matrix plays minor role in the overall mechanical properties, compressive and in-plane shear strengths are significantly influenced by the type of matrix used [62,63]. There are many factors that affect the mechanical properties of natural FRP composites, as subsequently discussed.

2.4.1. Fibre surface modification

Surface modification of fibres is normally used to improve matrix-fibre adhesion in FRP composites. For example, Pickering et al. [51] showed that 10 wt.% NaOH treatment of hemp fibres along with optimised processing temperature led to improvement in the mechanical properties of hemp fibre reinforced polypropylene (PP) composites. The overall performance improvement was attributed to the alkali treatment method, resulting to a higher fibre crystallinity index when compared with untreated fibre. Therefore, fibre surface modification plays an important role in fibre-matrix interfacial bonding.

2.4.2. Fibre types and manufacturing parameters

Fibre types also influence the overall mechanical performance of natural FRP composites. Fibre structure and morphology play an important role in the load bearing capability of composites. The investigation carried out by Pickering et al. [51] further demonstrated that at low fibre weight contents of 30 and 40 wt.%, better reinforcement effect was achieved with longer fibres. Conversely, higher fibre content of 50 wt.% brought about a reduction in mechanical properties. This was attributed to damage in fibres due to increased frictional contact during processing of the composites. It is well established that different fibre forms, such as random, non-woven, woven, short and unidirectional long fibres influence the final properties of resultant composites.

It is worth noting that there is an optimum fibre volume fraction where the improvement in mechanical properties start declining. In the case of natural FRP composites, influence of moisture absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites was reported by [53]. Investigating the effect of different volume fractions of hemp fibres in the composite system showed that 26 vol.% was the optimal, below and above which the mechanical properties such as tensile and flexural properties reduced. In addition, higher moisture absorption was recorded with higher fibre volume fraction. The effect on moisture absorption was more severe at higher temperature resulting from the swelling of fibres at fibre-matrix interface.

2.4.3. Fibre orientation/dimension

In FRP composite manufacturing, fibre orientation and dimension play important roles in determining the mechanical properties of the composites. Unidirectional reinforced composites are shown to always result to higher tensile properties when compared with short fibres. The length of the fibre significantly influences the overall mechanical properties. There are many reports, which suggest that best mechanical properties are achieved when fibre orientation is parallel to its loading direction [64].

2.5. Advantages and drawbacks of natural FRP composites

The advantages of using natural FRP composites are:

- Abundance,
- Higher specific strength and modulus compared to conventional glass fibres
- Light weight,
- Cost-effectiveness
- Reliability
- Biodegradability
- Non-toxicity
- Less energy required for manufacturing
- CO_2 absorption during their growth [53,56,64,65]

Some drawbacks of natural FRP composites:

- Hydrophilicity due to their structural morphologies and chemical compositions (cellulose, hemicellulose, lignin, pectin and waxy substances) Property variation (growing conditions and climate influencing the overall properties of fibres)
- Sensitivity to climatic conditions
- Low thermal stability
- Poor microbial resistance [54,65,66]

There are many improvement techniques already developed to reduce the aforementioned drawbacks, including surface modifications: chemical, plasma, thermal, biological, and enzymatic processes. Moreover, various additives suitable to improve the flammability, fire resistance and microbial attacks of FRP composites have been investigated. Current state of knowledge on flammability and fire resistance in natural FRP composites have been covered in previous literature [67,68]. The use of these additives has been reported to concurrently improve the moisture repelling behaviour, which leads to an improvement in compatibility between fibre and the matrix [69,70].

2.6. Applications of natural FRP composites

Natural FRP composites are currently applied in various industries, because of their many advantages including light weight, comparable specific strength and modulus to glass FRP counterparts. These sectors include transport (automobile, marine and aerospace), construction, sports and the packaging [71,72]. Natural FRP composites are useful in the automotive industries for lightweight structures, which leads to reduction in the overall CO_2 emission. This is very beneficial to the economy as the transport sector is known to contribute to a significant amount of greenhouse gases (GHGs). Natural FRP composites has been applied as semi-structural interior parts of automotive components. However, natural FRP composites are yet to be fully integrated in automotive structural components [71,73].

Conventional synthetic fibre composites including glass FRPs are extensively used in marine sector, due to their ease of fabrication, low cost and high mechanical performance. In recent years, there has been growing concerns about the pollution caused by the use of these synthetic fibres. This has led to a significant attraction towards the use of sustainable lightweight composites, such as natural FRP composites [65]. Glass and carbon FRP composites are being used in building and construction applications. The use of energy efficient materials have become an urgent issue in the building and construction industries [74]. There has been a significant effort in recent years to use sustainable materials in this sector. Hemp shiv combined with lime-based matrix, also known as 'hempcrete', have been used as natural insulation material it has good thermal and insulation properties. This material, in addition to flax, sisal and other natural plant fibres have been used in this sector, due to their excellent thermal and acoustic insulation properties [75]. The use of aforementioned materials in construction sector significantly reduces the overall cost coupled with their environmental benefits [65].

2.7. Recent advances in processing of natural FRP composites

The demand for use of natural plant fibres as reinforcements in composite materials is continuously growing in various sectors such as transport, construction, aerospace and packaging industry due to their environmentally friendly and sustainability attributes. Due to new environmental legislations, it is expected that the use of natural FRP composites will increase significantly in the near future, considering their several benefits and the need for sustainability. Major challenges in the processing of natural FRP composites are compatibility of natural plant fibres with polymer matrices and understanding their behaviours when exposed to extreme environmental conditions [76]. These conditions affect the long-term durability and contribute to poor interfacial properties [77]. This leads to inferior mechanical properties and thus limits their usage in semi-structural and structural applications. These limitations could be overcome by various optimisation techniques including the use of hybridisation approach, fibre modifications and pre-processing amongst others. Hybridisation reduces the moisture absorption behaviour, helps in achieving balanced mechanical and thermal properties as well as increases the long-term durability of natural FRP composites. Thus, making natural FRP hybridised composites as potential replacement for glass and carbon fibre composites [65].

3. Hybridisation of natural FRP composites

3.1. Concept of natural FRP hybrid composites

Hybrid composites are a mixture of more than one type of fibre within a polymer matrix, where the disadvantage of one fibre is being compensated by the advantage of the second fibre. They are initially designed as structural composites of two or more fibres/reinforcements. Hybrid composites combine the outstanding qualities of both synthetic and natural plant fibres through a series of manufacturing processes. Application of hybrid composites has now extended towards enhanced functions, due to growth of advanced materials, such as carbon nanotubes and graphene [78,79]. Hybrid composites can be strengthened by incorporating nano particles.

Polymer matrices are used in natural FRP hybrid composites to provide bonding for fibres to enhance load-bearing capacity of the hybrid composites. They also promote improved surface quality. Polymer matrices are usually grouped into either thermosetting or thermoplastic resins. A comprehensive overview of polymers used in natural FRP composites can be found in Alagesan et al. [20]. Moving forward, natural FRP hybrid composites can also include fillers; micro and nanofillers, such as aluminium oxides, silicon nano/microparticles, carbon-nanotubes, graphite and fullerenes. Overview of widely used nanofillers can be found in Akpan et al. [80]. Addition of fillers within hybrid composites enhances mechanical properties by increasing interfacial bonding between matrix and fibres. Also, it leads to enhanced dispersion and interaction between fibre/reinforcement and matrix. Summarily, different categories of natural FRP hybrid composites are presented in Fig. 4, which mainly depend on their reinforcing elements and their orientations/arrangements. Fabrication procedure for natural

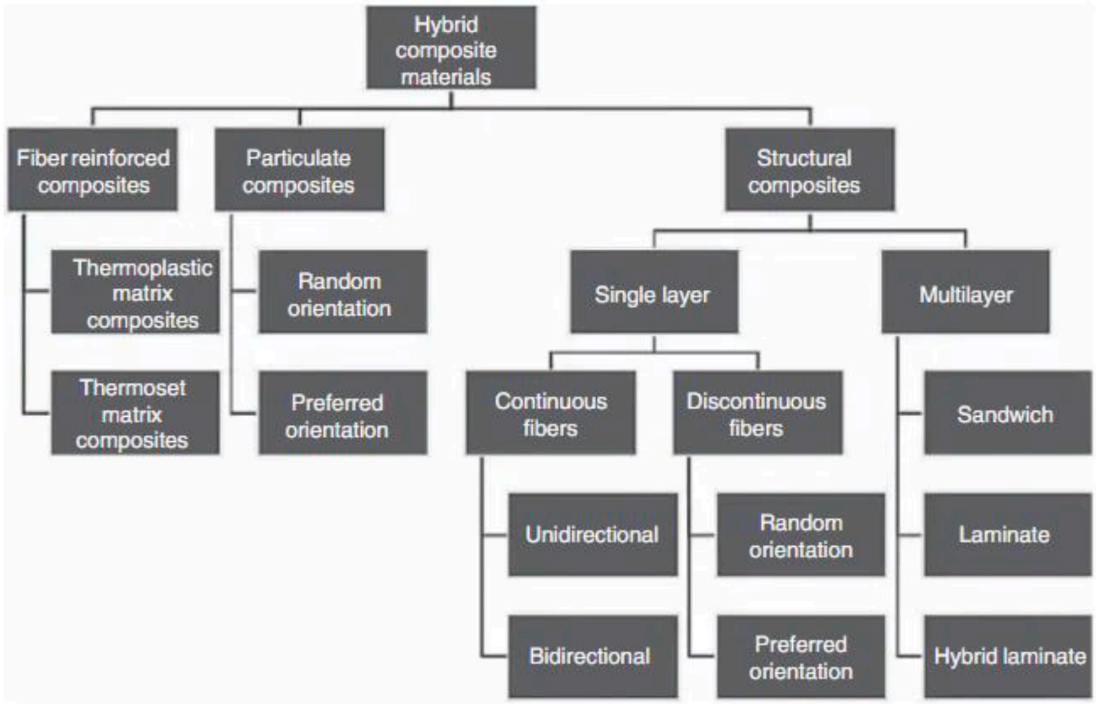

Fig. 4. Various categories of natural FRP hybrid composites [20] (Reprinted with permission from John Wiley and Sons, Permission Number: 5,415,541,191,029).

FRP hybrid composites involves preparation of preforms and incorporating them into the polymer matrix. There are several processing methods that can be applied to produce composite. These methods can be categorised based on the technique of applying combining the fibre and polymer matrix. They are divided into either open or closed moulding. Open moulding involves exposing resin to atmosphere during curing phase, while closed moulding occurs when resin is not exposed to atmosphere. Open moulding technique has been extensively applied, because it supports reduced processing requirements and suitability with different fibre options. Closed moulding technique is efficient for producing three-dimensional (3D) composite laminates with less material requirement.

The commonest types of open moulding methods include hand lay-up and spray up techniques. Hand lay-up method involves reinforcing matrix with fibres in an open mould layer-by-layer until a certain required thickness of composite laminates is achieved. Spray up techniques requires spraying fibres with matrix in an open mould until the required composite system is obtained. Closed moulding techniques include, but are not limited to, compression, extrusion, resin transfer moulding and injection moulding.

Extrusion processing involve the use of bead shaped thermoplastics, which are combined with fibres through rotating screws, compressed and then squeezed out through dies. Injection moulding uses either thermosetting or thermoplastic matrix. This process requires high viscosity and varying fibre arrangements along mould. Resin transfer moulding depends on thermosetting matrix and utilises pultruding method to produce composites. Dry fibre preforms are arranged within the mould space and then clamped during injection phase. This is followed by injecting molten plastic into the mould, using inlet spaces within the mould. Then, the composite product undergoes cooling stage and is removed for post curing. Compression moulding is based on thermoplastic or thermosetting matrix. Reinforcement materials are mixed with the matrix and processed under certain temperatures and pressures [23]. It can either be hot/cold compression and autoclave processes. Within the autoclave process, matrix preforms are placed within the mould at a predetermined arrangement. Then, the laminates are placed beneath vacuum inside an autoclave. Laminates undergo heating processes, followed by curing [81].

It is quite necessary to note that all the aforementioned manufacturing processes and techniques could be adopted to fabricate natural FRP hybrid composites of improved properties for several structural and semi-structural engineering applications.

3.2. Hybridisation techniques

Formation of natural FRP hybrid composites involves combination of different fibres/reinforcements within a polymer composite system. Natural FRP hybrid combinations can be categorised into three main types, based on distribution of reinforcements. These include interply, intraply and super hybridisation. Interply hybridisation is obtained when individual constituents are stacked in layers at laminate level, intraply hybridisation is formed from parallel combination of constituents within plies, whereas super hybridisation involves layers containing metal/composite and matrix arranged in a specific order, as illustrated in Fig. 5.

Another aspect of natural FRP hybrid composites is dispersion hybridisation. In this type of hybridisation, the hybrid fibres are dispersed within the original in certain patterns. Fig. 6 displays the major dispersion types; Fig. 6(a) depicts hybrid with small amount of spreading, where each of fibre classes are in separate layers, Fig. 6(b) shows an increase in number of layers, while Fig. 6(c) presents dispersion at fibre bundle level and Fig. 6(d) displays fibres in a random distribution [50].

Furthermore, design of natural FRP hybrid composites always follows the Puck's criteria, which indicates that fracture strength and rigidity of fibre types should be above those of polymer matrices. Also, polymer matrices are designed to have greater elongation at break than the fibres [83]. Hybridisation procedures derive enhanced properties from combination of constituents, based on rule of mixtures, according to Eqs. (1) and (2).

$$P_H = P_{c1}V_{c1} + P_{c2}V_{c2} \quad (1)$$

Where, P_H represents resultant properties of natural FRP hybrid

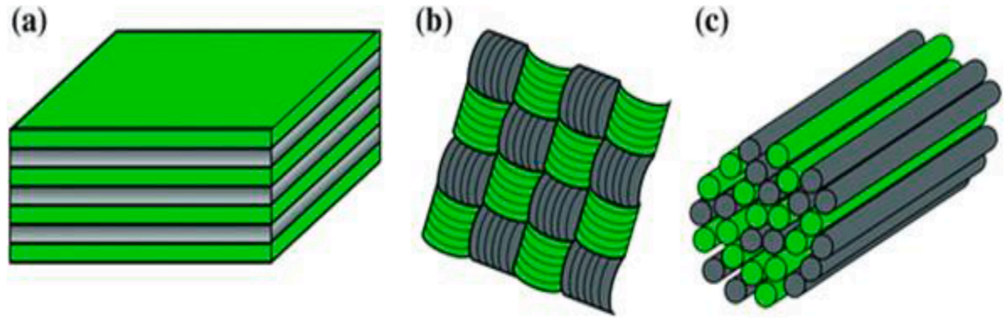

Fig. 5. Fibre arrangements within natural FRP hybrid composites, depicting: (a) interply, (b) intraply, and (c) intrayarn types [82,83] (Reprinted with permission from Elsevier, Permission Number: 5,415,570,626,045).

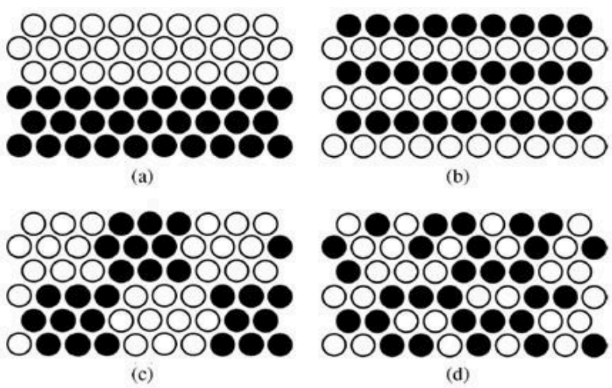

Fig. 6. Amount of fibre spreading in (a) two layers, (b) alternating layers, (c) bundle-bundle dispersion and (d) irregular dispersion [50,83] (Reprinted with permission from Elsevier, Permission Number: 5,415,570,626,045).

composites, P_{c1} and P_{C_2} stand for corresponding components C1 and C2 of natural FRP hybrid composites, while V_{C1} and V_{C2} denote volume fractions.

$$V_{C2} + V_{C2} = 1 \quad (2)$$

This law applies basically to static mechanical characteristics, including tensile and flexural features of natural FRP hybrid composites. Dynamic properties such as impact resistance exhibits more variable results, depending on geometric patterns applied during hybridisation [84].

3.3. Properties and potentials of natural FRP hybrid composites

Natural FRP hybrid composites are unique, as they offer some better advantages over monolithic composites, such as flexibility to obtain required properties and possibility of choosing cost-effective fibres. Some properties of natural FRP hybrid composites include enhanced comparative mechanical, thermal, chemical resistance and acoustic behaviour over monolithic composites [21]. They possess reduced cost, biodegradability, high strength, low weight and fatigue resistance. Both physical and mechanical behaviours of natural FRP hybrid composites depend on their individual fibre properties, fibres-matrix adhesion, fibre arrangement, volume, length and stacking sequence. According to Edoziuno et al. [85], key parameters which impact behaviour of resultant hybrid composites include type of reinforcing materials, manufacturing techniques, and interaction between filler and matrix. Hybridisation of natural with synthetic fibres, such as carbon or glass fibres improves strength and resistance of composites to moisture/water absorption. However, some hybridisation effect can be detrimental to overall properties of natural FRP biocomposites, depending on the difference in specific mechanical feature of the hybrid constituents [86]. The rule of mixture could be applied to determine elastic characteristics of natural and synthetic fibres-based hybrid composites. Mechanical properties, including tensile and flexural strengths are affected in randomly arranged natural FRP hybrid composites.

Natural FRP composites are used in several components/sectors, such as automobile body designs, aeroplane interior, electrical appliances, building and construction, medical and electronic industries. Within automotive industry, natural FRP hybrid composites are used in internal parts of cars such as seat backs, drawers, door linens and door-trim panels. German automobile companies, including Volkswagen and Mercedes use cellulosic natural FRP composites in different automobiles. For example, coconut fibres latex composites have been used by Mercedes for seats and sisal fibre reinforced epoxy composites are used as door panels in their car models [87]. Ford also uses kenaf fibres reinforced poly propylene (PP) composites in Mondeo model for door panels. Other companies, such as Toyota and Volvo also use cellulose fibres to make car parts. Additionally, bamboo fibres have been used with concrete elements as reinforcement and sisal composites are used as roofing components [87]. Within aerospace industry, there is a shift towards application of natural FRP hybrid composites to address high energy and safety requirements. Furthermore, automobile door liners have been produced with hemp fibre and cabin doors of aeroplanes are fabricated with fibre based composites. Glass and carbon fibres are extensively used as reinforcing materials within aircraft components [20]. Also, modified twisted natural FRP hybrid composites of Indian mallow/Roselle fibre double layer longitudinal yarn mat and wood sawdust filler are used to fabricate tri-wheel auto-wheel hub to support transportation industry, ceiling fan blade as home appliance and wheeler side mirror casing, as shown in Fig. 7(a), (b) and (c), respectively. Additionally, glass/jute fibres reinforced epoxy hybrid composites fabricated by Bajpai et al. [88], is found to be a suitable alternative to existing industrial safety helmets.

3.4. Challenges of natural FRP hybrid composites

Mechanical performance of natural FRP hybrid composites, such as basalt fibre (BF)/poly lactic acid (PLA) composites are relatively low, approximately 60 – 120 MPa. This is attributed to low interfacial bonding within PLA/BF composite. Also, natural plant fibres with cellulose are hydrophilic, as they contain hydroxyl groups. This causes high moisture absorption within fibres and leads to swelling of natural FRP hybrid composites. However, the aforementioned challenges can be mitigated by chemical, biological and/or physical surface modifications, such as acid or alkali etching, coupling (using silane and maleated propylene), enzymatic hydrolysis, plasma discharge and spray coating, amongst others. These processes enhance adhesion between the polymer matrix and fibre surfaces, thereby reducing water absorption potential [90,91].

Also, chemical characterisation of newly researched natural reinforcements and matrices is required to improve on fibre-matrix

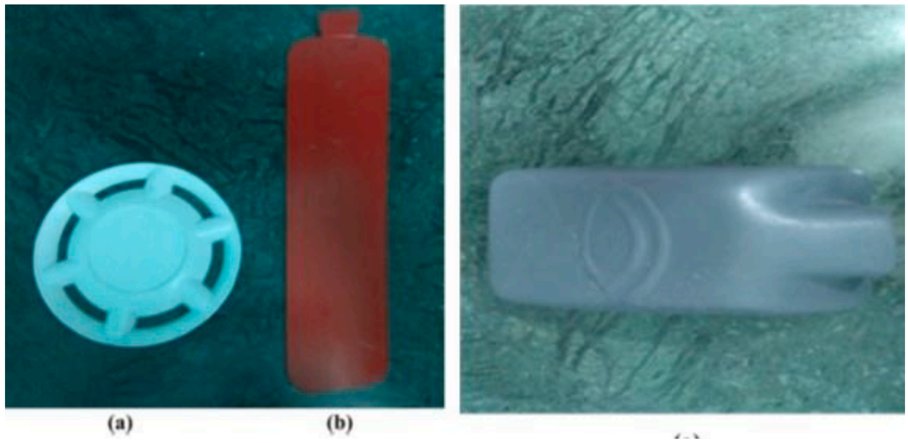

Fig. 7. (a) Tri-wheel auto-wheel hub, (b) ceiling fan blade and (c) wheeler side mirror casing made from twisted natural FRP hybrid composites [89] (Reprinted with permission from Elsevier, Permission Number: 5,415,571,506,733).

adhesion and compatibility of natural FRP hybrid composite laminates, and consequently their applications.

Besides, low thermal stability of natural plant fibres creates challenges when processing natural FRP hybrid composites. This is due to degradation of natural plant fibres with an increase in temperature, which influences the mechanical behaviours of natural FRP hybrid composites. This challenge increases when the amount of natural plant fibres in the hybrid composite increases. Care must be taken to determine suitable curing process parameters (pressure and temperature), considering the thermal properties of the constituting reinforcements. Another concern is fibre breakage during the compounding process, due to collision between fibres and tool/mould [91]. Fibre resistance to friction should be taken into consideration when designing the processing of the hybrid system. Ligno-cellulosic fibres readily undergo biological, chemical, thermal changes under photochemical process [86]. Although, this is an advantage when considering environmental concerns, but the tendency for easy degradation limits adaptability of natural FRP hybrid composites for long-term use [86]. Similarly, natural fibres tend to undergo degradation when they are in contact with the soil.

Another potential drawback associated with natural FRP hybrid composites is the presence of voids, which have significant impacts on their mechanical characteristics, amongst other properties. This could be due to trapping of air and other particles within spaces in composites during fabrication of the natural FRP hybrid composites. This can be controlled to an extent by ensuring uniform resin spread and removing air gaps [92]. Natural FRP hybrid composites accompanied with appropriate fibre surface modifications or treatments often exhibit enhanced mechanical characteristics over untreated counterparts, due to improved fibre-matrix adhesion [93]. Thus, natural FRP hybrid composites can be used for multiple applications, including functional and structural.

Moreover, there are limited robust predictive analytical models and/or standard design of experiments to effectively guide selection of reinforcements (fillers and/or fibres) and matrix for predetermined properties of the designed natural FRP hybrid composites. Predictive analytical modelling is required because it will lead to cost reduction, water adsorption reduction, strengthening, toughening, environmental sustainability, abrasive resistance, to mention but a few. Importantly, all the aforementioned challenges are potential research interests in the field of composite technology, which require extensive studies.

4. Properties of natural FRP hybrid composites

4.1. Mechanical properties of natural FRP hybrid composites

4.1.1. Tensile properties

Tensile properties are one of the most targeted properties in the hybridisation of natural FRP hybrid composites. This is generally because tensile properties of natural FRP composites are sure to increase when hybridized with synthetic fibres. Natural plant fibres generally possess lower tensile strength when compared with synthetic fibres such as carbon and glass fibres. This implies that addition of a certain amount of high performing synthetic fibres to natural plant fibres in a composite system will improve the tensile properties of the natural FRP composite. This is advantageous as there is improved tensile properties in a more sustainable composite. Past studies on hybridisation of natural and synthetic fibres focused mainly on the improvement in properties of the natural fibre composites by addition of a certain proportion of the synthetic part. A summary of tensile strength versus modulus of natural FRP hybrid composites from past studies are presented in Fig. 8. However, in some cases, the tensile properties can be lower or higher than expected. This is because of the occurrence of a synergistic effect in the hybrid system. Understanding the concept behind such effect is important for further development of natural FRP composites for advanced applications. For example, hybridisation of banana and coir fibres in polyethylene resulted in hybridisation effect in the tensile strength and modulus. Equal volume fraction of both fibres resulted in tensile strength and modulus higher than composites with individual fibres. This synergistic effect is attributed to the combination of low and high elongation fibres in the composites. Coir fibres possess a tensile elongation of 30%, whereas banana fibres possess tensile elongation of 10%. During the tensile test, the low elongation banana fibres bear the load until it fails, thereafter transferring the load to the high elongation coir fibres, which effectively transfers the stresses leading to increased tensile strength [94]. A similar but lesser effect was recorded when jute and banana fibres were hybridized at equal weight fractions in epoxy resin [95]. In this case, jute (2.5% tensile elongation) [96] serves as the low elongation fibres whereas banana (10% tensile elongation) serves as the high elongation fibres. The small difference in the elongation of the fibres may be the reason for the less increment noticed in the jute-banana hybrid composites. The mechanisms leading to this effect are not yet fully understood coupled with the complex interaction between varying fibre fractions, process parameters, and layup strategies, which are not simple to determine experimentally [18,97]. Moreover, the large design freedom triggers a complexity in the selection process and design of the desired hybrid system.

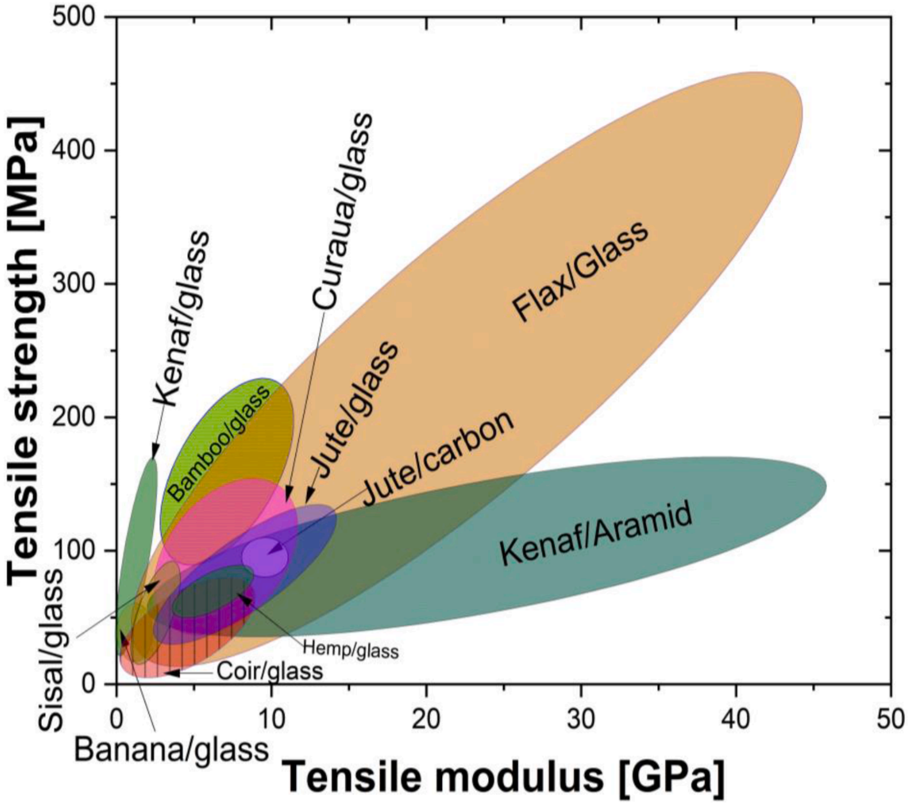

Fig. 8. Evaluation of tensile characteristics of selected natural/synthetic FRP hybrid composite. Data for the plot are from various publications cited in this article.

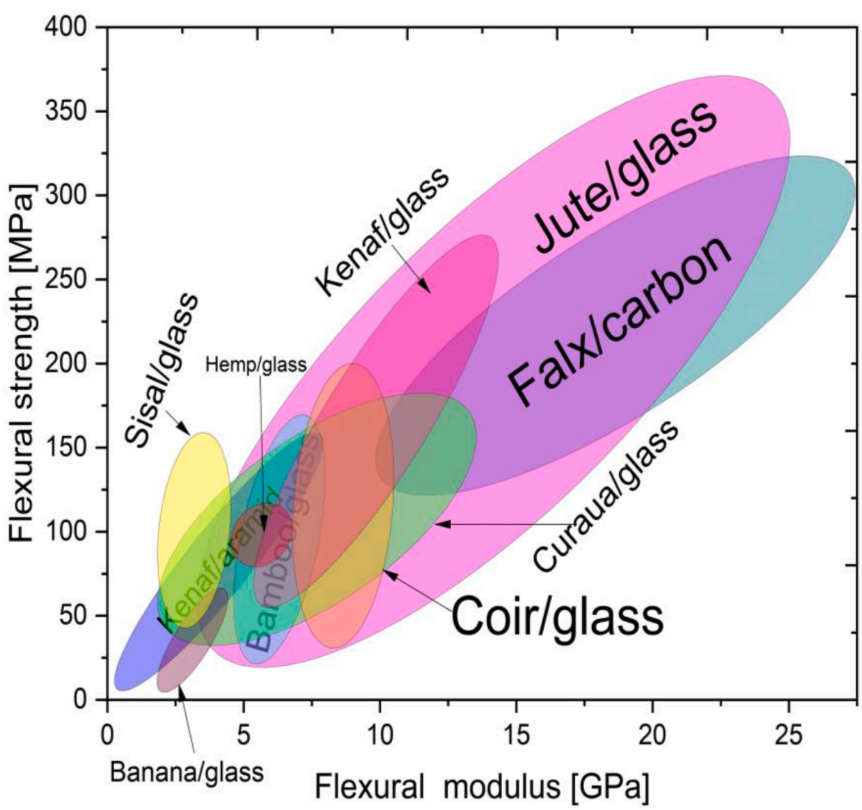

Fig. 9. Evaluation of flexural responses of selected natural/synthetic FRP hybrid composites. Data for the plot are from various publications cited in this article.

4.1.2. Flexural properties

Flexural strength refers to maximum bending stress on composites when subjected to bending loads [98,99]. This depends on various factors, such as fibre materials, particle size, percentage of filler and fibre orientations. A summary of flexural properties of natural FRP hybrid composites are shown in Fig. 9. A careful comparison of the articles studying the effect of hybridisation on the flexural properties of natural FRP hybrid composites show that the outcome is strongly dependant on the type of fibre, modification and layup strategy, matrix type and modification, processing parameters and fibre-matrix adhesion [83,87, 100-110]. Although synergistic effects have been noticed in synthetic FRP hybrid composites, there are currently no reports on the existence of this mechanism in natural FRP hybrid composites.

4.1.3. Compressive properties

Compressive strength of a composite material shows its ability to withstand induced compressive force [112]. Compressive strength can also be affected by matrix friction angle and interfacial fracture energy. From results of study on compressive strength and strain of woven kenaf/glass FRP hybrid composites, it is observed that addition of kenaf ply show minimal impacts on their compressive strengths, during compressive loading conditions. However, their compressive moduli increase as more kenaf fibres are added. This is caused by ductility characteristics of kenaf fibres [113]. Incorporating hydrophobic silica nanoparticles is observed to increase the porosity of Kenaf/glass FRP hybrid composites and consequently, it reduces their compressive strengths and moduli. This decrease is attributed to the inefficient stress transfer as a result of presence of pores [101].

Furthermore, Sapiai et al. [114] analyse the impact of treatment of carbon nanotubes (CNT) on compressive behaviours of kenaf/glass FRP hybrid composites, using concentrated acid and silane treatment. It is observed that compressive response of CNT-modified kenaf/glass composites improve. This is due to improved wettability and adhesion of epoxy matrix [114]. The effect of surface microfibrillation of sisal pulps on the compressive properties of sisal pulp/Aramid FRP hybrid composites has been examined [115]. It is shown that increased degree of microfibrillation of the sisal fibres led to increasing compressive strength of the hybrid composites.

4.1.4. Fatigue resistance

Fatigue properties of natural FRP hybrid composites are linked to fibre/matrix type and fibre volume content [116]. Natural FRP hybrid composites exhibit better fatigue properties than single natural FRP composites in situations where high elongation fibres are combined with low elongation fibres. The high elongation fibres act as crack arrestors for broken low elongation fibres. Analysis of fatigue properties of flax, carbon fibre and their hybrid laminates of equivalent applied load shows that flax fibre and hybrid laminates possess better fatigue life than carbon fibre laminates [117]. Additionally, stiffness degradation of flax FRP hybrid composite laminates is better than carbon laminate counterparts. Tensile fatigue resistance can be enhanced through improved fibre spreading and fibre-matrix bonding [50,116]. Also, symmetric lay-up in interply natural FRP hybrid composites show enhanced fatigue resistance over asymmetric lay-up, because of reduced interlaminar shear stresses observe within symmetric lay-up configurations [82].

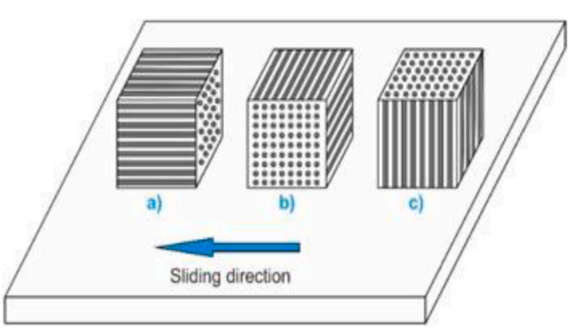

Fig. 10. (a) Parallel, (b) anti-parallel and (c) normal fibre orientations versus sliding direction [111], Source: https://www.mdpi.com/openaccess.

4.1.5. Impact resistance

Impact resistance of a composite can be explained as energy required by it to fracture under applied load. It sometimes reflect damaged section, following non-penetrative impact and residual characteristics [50]. Natural FRP hybrid composites are usually exposed to a variety of impacts through their life cycles. Hence, these characteristics are tested to determine their impact qualities [118]. Natural FRP hybrid composites often experience internal damage during transient impact loading, hence their energy absorbing capacity needs to be optimised [119]. Impact strength is determined by capacity of matrix to transfer load homogeneously to supporting fibres. It is also dependant on fibre length, fibre loading, yarn geometry, fibre orientation and arrangement within matrix material [98,120].

Addition of synthetic fibres such as carbon and glass to single natural FRP hybrid composite provides improved impact strength, due to an improved interfacial adhesion between synthetic fibres and polymer matrix and hence effective energy absorption. Also, natural plant fibres hybrids including jute/sisal and jute/curaua FRP hybrid composites are found to produce similar energy absorption when compared with jute/glass composites. This indicates that sisal and curaua are potential replacements to glass fibres in hybrid composites [121]. Impact strengths of natural FRP hybrid composites can be improved by chemical treatments of the fibres. For example, untreated kenaf FRP hybrid composites exhibit lower impact strengths when compared with treated counterparts [122]. Conversely, impact strength can be reduced due to presence of micro-spaces around fibre and matrix, thereby leading to cracks upon impact. These cracks readily propagate within natural FRP hybrid composites.

Moreso, impact behaviour of epoxy composites is investigated by adding flax to E-glass fibres. It is observed that E-glass fibres/flax-epoxy hybrid composites possess considerable better impact results with significant weight reduction over E-glass/epoxy composites [123]. Impact response of oil palm/glass fibre hybrid composites is investigated and their impact strengths improve with addition of glass fibres, greater impact strength is observed when the samples are impacted on the glass fibre layer [124]. A negative hybrid effect is observed in impact response of oil palm/jute fibre-based epoxy hybrid composites of different stacking arrangements [125]. Impact properties of non-hybridized composites are higher than those of the hybrid composites. Impact behaviours of surface treated sisal fibres-based vinyl ester composites is studied, considering fracture resistance property. Results show that silane treatment enhanced their fracture resistance when compared with untreated composites [126]. Experiment on impact characteristics of glass/kenaf FRP hybrid composites with natural rubber is carried out. Tests are conducted, involving treatment of kenaf and glass fibres with sodium hydroxide and silane, respectively. It is discovered that treatments improve their impact strengths. This is attributed to their improved fibres-matrix interfacial bonding. Treated fibres record better surface characteristics, by removing wax layer along with impurities in comparison with untreated counterparts [127]. Srinivasan et al. [128] investigate into impact characteristics of banana/flax/glass hybrid composites. The tri-hybrid composites possess best impact response when compared with banana/glass and flax/glass FRP composites. Enhancement of impact properties of hybrid composites has been linked to addition of nano and microfiller particles, which improve surface interaction between fibres and matrix [118,129].

4.1.6. Post-impact properties

Low velocity impact on natural FRP hybrid composites can lead to damage reactions, such as matrix cracking, delamination, rebounding, penetration and perforation [122]. Matrix cracking is an initial response to low velocity damage, which leads to delamination as a larger load is applied. This is followed by transverse shear stresses around the impacted matrix surface, which progresses into debonding. This then leads to fibre pull-out [122]. Furthermore, pine tree damage is another reaction that occurs during shear and bending cracking [122]. Formation of these damage-induced responses reduce the strength of natural FRP composite materials. Residual strength is also reduced, due to fibre cracks in impacted zone [130]. Impact response can also be microscopic in form of delamination, which reduces residual compressive strengths of natural FRP hybrid composites [131].

Factors which influence impact properties of natural and synthetic FRP hybrid composites include, but are not limited to, stacking sequence, fibre content and arrangement. Furthermore, placing natural fibre layers in external portion (skins) exhibits greater deformation than when placed in internal section, acting as a core [132]. Temperature change has a significant effect on residual strength. Propagation of impact generated delamination is reduced at higher temperatures than at lower temperatures [133].

Impact strength tests are conducted on kenaf modified hybrid composites. Impact behaviour of modified hybrid composites is better than that of unmodified kenaf fibres with similar mass ratios. Also, it is observed that modified composites undergo no slipping after impact tests. This is attributed to mercerisation treatments of kenaf fibres, which produces an improved adhesion between kenaf fibres and matrix. Also, arrangement of fibres supports an increase in their impact resistance [134].

4.1.7. Tribological properties

Wear and friction are commonly observed phenomena in natural FRP hybrid composite materials, depending on their applications. Therefore, analysis is required to achieve an improved performance of natural FRP hybrid composites. Tribological behaviours of natural FRP hybrid composites are based on factors such as, operating conditions (Fig. 10), matrix type and fibre orientation [111]. Effect of hybridisation on the wear properties of jute/sisal polypropylene hybrid composites is investigated. Hybrid effect is noticed in the specific wear rate of the hybrid composites. Results were consistent over a wide range of sliding speeds and distances. The best specific wear rate is noticed when the fibres were treated in an alkaline medium. Similar results are noted with coefficient of friction of the hybrid composites [135]. The reason for this hybrid effect was not experimented in the study. Effect of addition of nanoclay on the tribological properties of natural FRP composites is reported [136]. Varying conditions including, silane and alkaline treatments, mass fractions of nanoclay, applied strains, sliding distances and velocities are investigated. Results show that addition of nanoclay led to a decrease in the specific wear rate of the composites. However, a threshold is reached at 2 wt.% of nanoclay, depending on the fibre treatment applied. According to microscopic analysis, it is evident that silane treated composites possess maximum interfacial bonding, as shown by smoother surfaces when compared with untreated specimens. In another study, Hemp, flax and jute fibres hybridised in epoxy resin to investigate their effect on tribological properties of the hybrid composites. Results show that the coefficient of friction and specific wear rate of the hybrid composites (hemp/flax, hemp/jute and flax/jute) lie between those of their single fibre composites [137].

4.1.8. Scratch resistance (surface hardness and nano-indentation hardness)

Scratch resistance is related to the capacity of a material to withstand mechanically generated surface indentation [138], as illustrated in Fig. 11. Scratch resistance properties of natural FRP hybrid composites are key parameters that are often considered within composite development. Polymers are generally softer when compared with other materials, such as metals and thus, they are more susceptible to scrapes by particles, including grits and chips [138]. Furthermore, surface scratches can act as crack initiators and can potentially propagate leading fracture within natural FRP hybrid composites. Surface scratching is a complex dynamic process, which is affected by penetration depth, speed, load, indentation area and properties of the indenter and material [138]. Natural FRP composites possess poor scratch resistance in the presence of alkaline solutions, because it reduces hemicellulose content within the fibres. Unfortunately, the mechanism of scratch resistance of hybrid FRP composites have not been given much attention in the past decade.

4.1.9. Creep

Creep is a very important service application characteristics of natural FRP hybrid composites, which depends on fibre content, fillers, interfacial modification and manufacturing methods. Addition of fibre leads to an increase in creep resistance of composites. Creep strain and strain rate increase with an increase in stress level on composites, while it reduces with addition of fibre content [133]. Adding rigid fillers enhances creep resistance by reducing movement of polymer chains [139]. Militky and Jabbar [140] perform creep strain tests on treated and untreated woven jute composites at various temperatures. Modification methods include plasma, laser, ozone and enzyme treatments. Laser treated composites record greatest elastic deformation at high temperatures within 70–100. However, a lower viscous deformation is observed over time when compared with other treated composites, leading to a reduced creep deformation. Laser treated composites perform better with strain tests, due to an improved fibre-matrix adhesion. This consequently produce an improved elastic behaviour of composite materials [132]. Also, creep behaviour is observed in carbon, glass and hybrid (interleaved and block) composites under various temperatures. Carbon shows a better creep resistance than glass and hybrid composites, while interleaved hybrid composites demonstrate similar characteristics to glass composites and, block hybrid composites

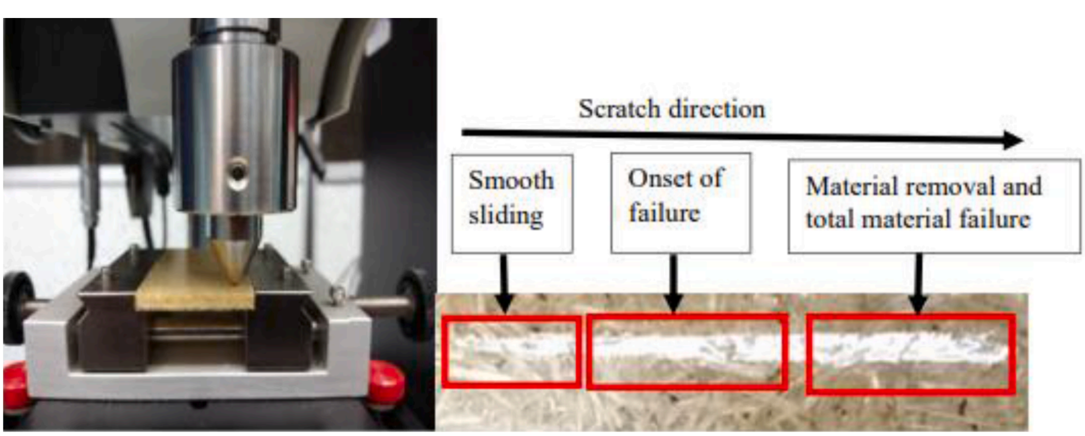

Fig. 11. Scratch experimentation [101] (Reprinted with permission from Elsevier, Permission Number: 5,415,600,054,988).

possess similar characteristics to carbon composites [141].

4.2. Fracture toughness of natural FRP hybrid composites

Materials in service are required to be able to absorb certain amount of energy under load before final failure. Failure in fibre reinforced composites occur by propagation of cracks (defects) through the material. These cracks are generated during production, processing (surface finishing, drilling etc.) and to a less extent when structurally loaded [25,126,142]. Fracture toughness is the ability of a material to store energy prior to fracture. It is directly related to the capacity of the material to resist crack propagation. Fracture toughness is measured by the critical intensity factor (K_c), whereas the resistance of materials against crack growth is measured by critical energy release rate (G_c) [143,144]. These parameters can be determined in several ways, depending on the mode of loading, type and composition of material, and stress conditions at the crack tip. Two fracture mechanics approaches are prominent in failure analysis of materials, including linear elastic fracture mechanics (LEFM) and elastic plastic fracture mechanics (EPFM). LEFM is the most commonly applied model for determination of fracture in metal and polymer composites. It assumes that the material behaves elastically in the vicinity of the crack tip. There are three modes of fracture by which crack can be propagated during loading, including: (1) Mode I, known as the opening mode, referring to applied tensile loading, (2) Mode II, known as the shear mode, referring to the applied shear stress in the in-plane direction and (3) Mode III, known as the tearing mode, referring to the applied shear stress out-of-plane. Mixed Mode (such as, mixture of Modes I and II) can also be applied [145]. The fracture mechanics concepts for these modes are basically the same irrespective of the methods applied. Natural FRP hybrid composites can be isotropic (such as short and non-woven fibre reinforced polymers) or laminated (such as unidirectional fibre reinforced laminates). Different methods are employed in the determination of fracture behaviour of these composites. To maximise performance for structural applications of natural FRP hybrid composites, unidirectional or optimally woven reinforcement systems are usually employed [146,147]. In the present review, attention is paid to laminated structures.

In laminated fibre reinforced composites, the most prevalent fracture behaviour is delamination at the laminar-laminar interface [148–151]. Generally, crack initiation, growth and propagation are usually accompanied by the release of strain energy. Therefore, the entire process of delamination can be described by measuring the strain energy released, considering the mode of loading on the material. Test methods that have been used to determine G_c of laminated composites include double cantilever beam (DCB) test for mode I, end notch flexure test for mode II and, end crack torsion test for mode III. Several studies have been published on the theories and mathematics governing these methods [151,152]. Despite advancement in the development of these methods, they are yet to be adapted for accurate measurement of natural FRP composites based on woven fibre mats. Natural FRP composites are gaining attention in structural and semi-structural applications. Hence, the need for in-service functionality assessment especially their resistance to crack propagation. Inter-laminar fracture toughness of natural FRP composites have been severally studied, mostly using the double cantilever beam methodology [150,153,154,154–159]. The fracture toughness of natural FRP composites were observed to be generally lower than synthetic fibre counterparts. However, they also reported the possibility of improving the fracture toughness of natural FRP composites by optimised fibre placement, fibre surface treatment, matrix toughening, through-thickness stitching and the use of hyper-branched polymers. A few studies on the effect of hybridisation on the fracture toughness of natural FRP hybrid composites have been reported. Hybridisation of glass fabric-phenolic resin composites with flax fabric resulted in improved fracture toughness [160]. Using DCB methodology, it was shown that the hybrid composite possess significantly higher fracture toughness than glass fibre reinforced composites. Inter-laminar shear stress (ILSS) of the hybrid composite was observed to be higher than those of flax and glass fibre composites. The improvement is attributed to the roughness of flax fibre surface, fibre bridging and entanglement at the flax-glass interface. Similar results were also reported for woven flax-glass fibres epoxy hybrid composites [161] using the same testing method. In this case, the fracture toughness of neat flax fibre composites was higher than that of the hybrid composite. Hybridisation of basalt and flax (stitched and unstitched) fibres in vinyl ester show no improvement in critical energy release rate when compared with flax fibre composites, tested in mode I using DCB [126]. It should be noted that only two layers of basalt fibres were used on reverse sides of the composites.

This means that the basalt fibres did not contribute to the inter-laminar crack propagation since it is not present in the central axis. Data for basalt FRP composites were not presented for comparison. Also, it is noted that the fibre volume fractions of the tested composites were slightly different for all the samples. It is also possible that the inter-spaced stitching was the cause of crack deviations from the primary crack direction to a secondary longitudinal crack. However, applying DCB to multi-directional woven fabric always result in crack deviation. In such cases, only values of (G_{IC}) at initiation are the valid [151,162]. Applying mode II using three-point-end-notched flexure tests to the same composites showed that the critical energy release rate of hybridised composite was 58 and 21% higher in the initiation and propagation stages respectively [142]. Applying the concept of intra-laminar hybridisation, Pereira et al. [163] reported that the critical energy release rate for woven jute-curaua fibre epoxy hybrid composites increased by 212% and sisal-curaua by 191% against pure jute and sisal reinforced composites. Samples were tested in mode I, using DCB methodology. Unfortunately, the crack propagation was quite unstable and limited by the formation of secondary cracks in the longitudinal direction. Poor fibre-matrix adhesion was also reported, giving rise to fibre pull-outs. The dominant failure mechanism was matrix cracking, because of poor transfer of stress at the fibre-matrix interface.

5. Effect of environmental conditions on structure and properties of natural FRP hybrid composites

Structural application of natural FRP composites is limited, because they are not very resilient in harsh environment by the virtue of being hydrophilic in nature resulting to poor mechanical properties [52,66]. This section discusses different issues arising from moisture absorption and exposure to different environmental conditions and their effects on the various properties.

5.1. Micro-macro structure of natural plant fibres as composite reinforcements

The properties of natural FRP composites is significantly influenced by the micro and macro structure and morphologies of the reinforcing fibres. Unlike conventional reinforcements such as glass and carbon fibres, natural plant fibres possess several unique characteristics, such as hierarchical cells structures, lumen and varying percentages of cellulose, hemicellulose, pectin, wax and lignin [164]. This hierarchical structure as depicted in Fig. 12 gives natural fibre a complex structure, which makes it difficult to fully understand the overall properties. The long-term durability and strength of the fibre depend on its structure including the microfibrillar angle (MFA), surface homogeneity, chemical compositions, length and diameter (aspect ratio).

5.2. Mechanisms of water absorption in natural fibre reinforced composites

Despite several benefits, natural fibre reinforced composites are prone to moisture absorption, due to their hydrophilic nature. This leads to poor mechanical and thermal properties. The water adsorption

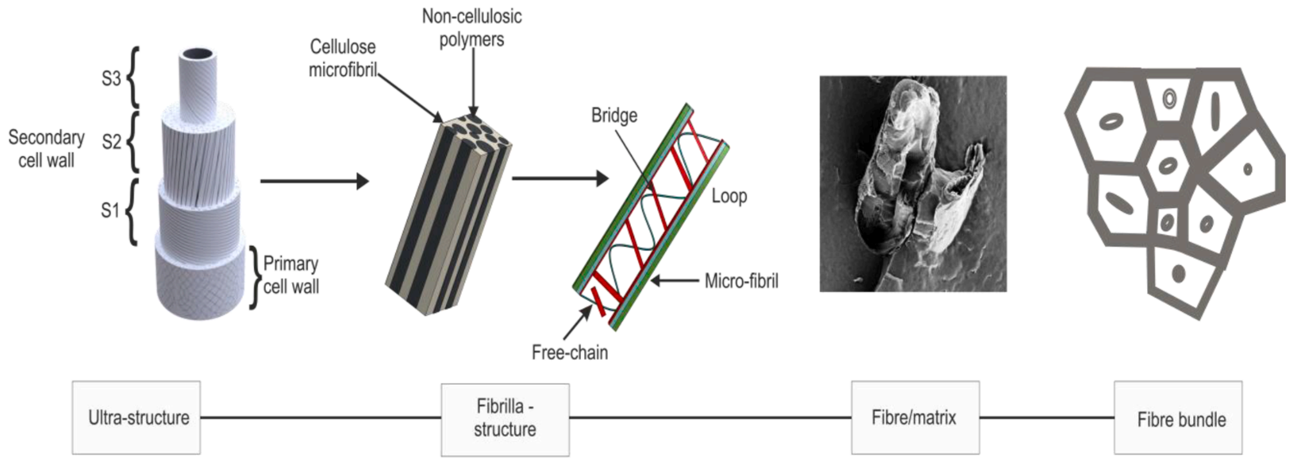

Fig. 12. Structure and various elements of natural fibre composites (a) fibre cell-wall structure and interface, (b) fibre- matrix interface, (c) fibre/fibre interface within the bundles.

behaviours of natural plant fibres are significantly influenced by environmental conditions such as temperature, humidity and ultraviolet (UV) exposures. Especially, at higher temperatures and humidity, the interface regions are severely damaged, leading to fibre-matrix debonding. This limits the stress transfer from matrix to fibres, affecting the thermomechanical properties [52]. At high temperatures, moisture ingress speeds up at the interfacial regions, leading to formation of voids, swelling of the fibres and generation of micro-cracks [53]. The micro and macro porosities in natural plant fibres create natural pathways for water molecule to travel to the fibre-matrix interfaces. In this condition, exposure to severe environmental conditions leads to increased material damage. Cellulose and hemicellulose are the key components of natural plant fibres (Fig. 13). Chemically, they possess very high amount of hydroxyl group, promoting moisture ingress.

Fig. 14 illustrates the water ingress mechanisms of natural FRP composites. It is widely accepted that, fibre-matrix interface plays key role in controlling the performance of composites exposed to water. The weak interface is the result of chemical reaction and the plasticization after the moisture ingresses into the interfacial regions. The water ingress causes the following outcomes:

- Weak fibre-matrix interface
- Swelling of the fibre-matrix interface
- Interface may dissolve and leach away (damaged microstructures)
- Lowering of overall mechanical properties

The rate of moisture ingress into natural FRP composites is dependant on environmental conditions, structure and composition of the natural FRP composites. This rate of ingress is quantified by coefficient of diffusion, which is described as rate of transport of liquid through a unit area of materials. There are several factors which contribute to diffusion rate, including porosity, void contents, degree of curing, materials homogeneity, manufacturing parameters, relative humidity, material thickness and fibre orientation, exposed surface areas and matrix types [56].

5.2.1. Effect of water absorption on performance of natural FRP composites

It has been shown that moisture absorption in natural FRP composites causes plasticisation leading to severe structural damage as a result of damaged fibre-matrix interface [53]. It has also been shown that humidity conditions during the composite fabrication plays a key role in deterioration of mechanical properties [59,167]. Moisture absorption causes hydrothermal expansion, matrix cracking or delamination which significantly reduces their mechanical and physical properties [53, 168–171]. Most studies on the water adsorption characteristics of natural FRP hybrid composites show that the water adsorption behaviour lies between those of the individual fibres. For example, hybrid composites with flax/hemp, jute/ramie, jute/roselle, ramie/roselle,

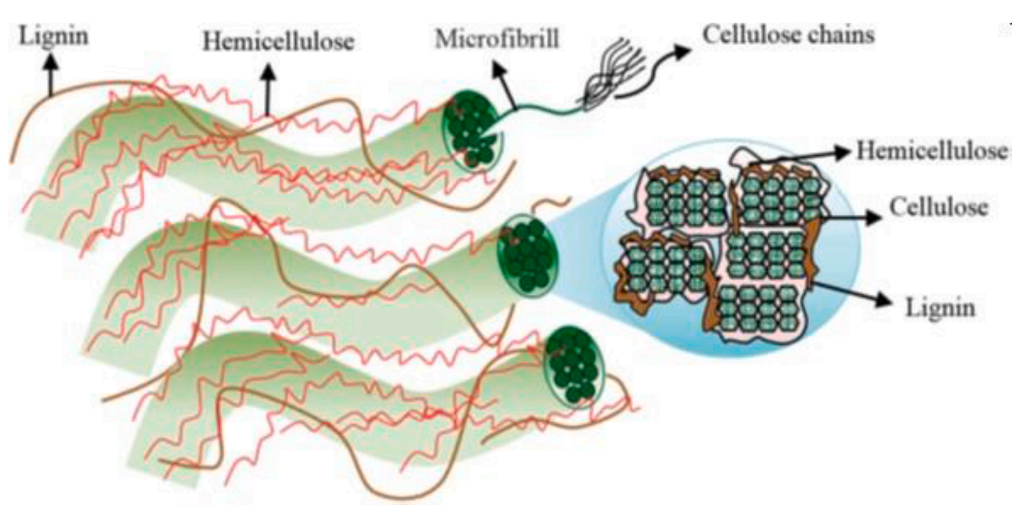

Fig. 13. Chemical composition and microfibrill of natural fibre cross-section [165] (Reprinted with permission from Taylor & Francis, Permission Number: 501, 768,787).

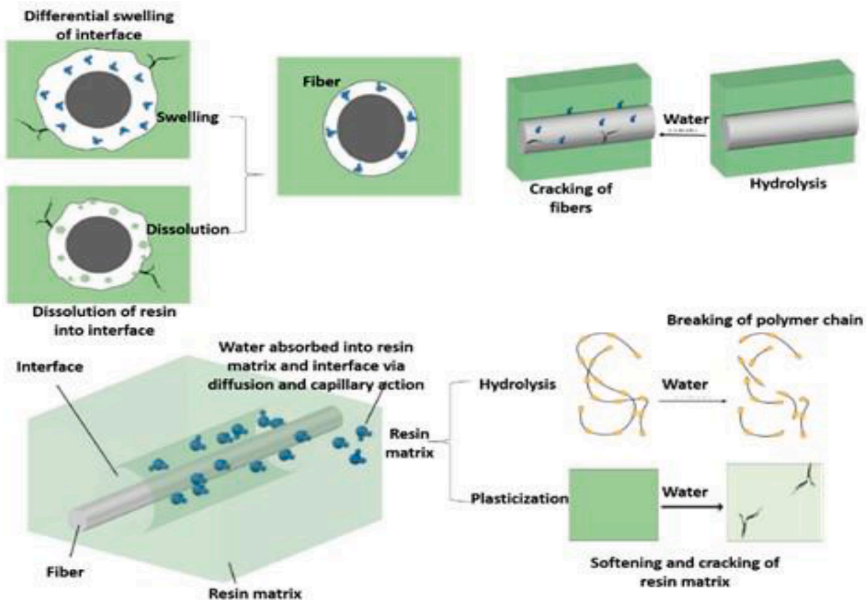

Fig. 14. Moisture absorption mechanisms of natural fibre composites [166] (Reprinted with permission from Elsevier, Permission Number: 5,415,611,269,586).

sisal/glass, empty palm bunch/jute, and kenaf/jute showed water adsorption between the individual fibres [172–178].

5.3. *Effect of cryogenic temperatures on natural FRP composites*

Cryogenic temperatures are amongst the various conditions that significantly influence the properties of fibre reinforced composites. Cryogenic temperatures are defined as below −150 °C [179]. FRP composites are extensively used in aerospace, space and marine industries. For these applications, understanding how these materials behave under low temperature is important. There are some reported works on cryogenic study for synthetic fibres [179]. But, very few studies are available on the performance of natural FRP composites under cryogenic conditions. For example, the work carried out by Vonod and Sudez [180] investigated the mechanical performance of hemp and jute reinforced composites using cryogenic liquids. All mechanical properties decreased with increase in cryogenic treatment time.

It is generally accepted that at sub-zero temperature, the strength, stiffness and the hardness of composites increase. However, it causes a decrease in ductility, causing lower strain, lower fracture and impact

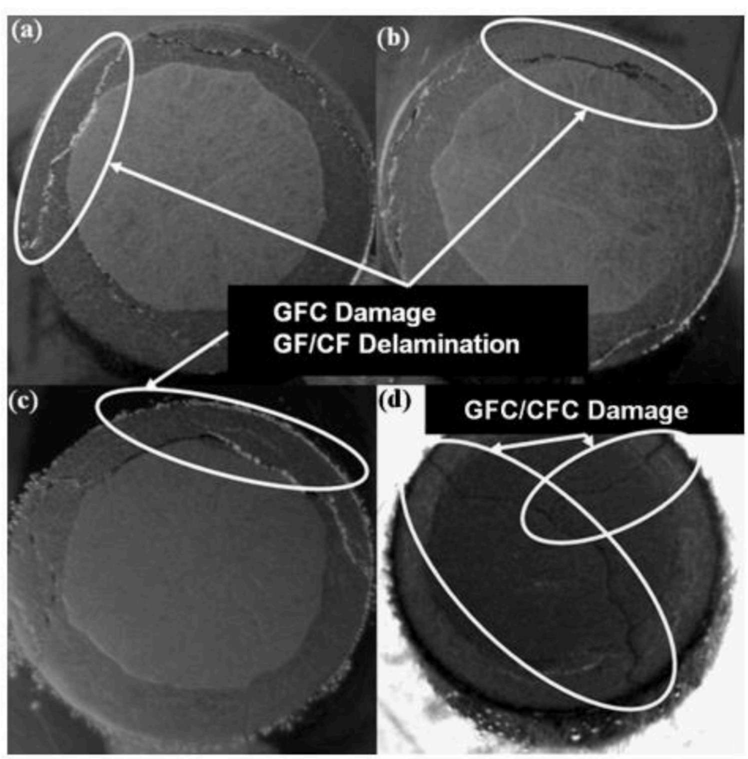

Fig. 15. Representative cross-sections of fatigue failed hybrid specimens undergone ageing tests for (a) 0, (b) 3, (c) 6 and (d) 12 months [183] (Reprinted with permission from Elsevier, Permission Number: 5,415,620,209,932).

toughness [114]. Whether it is natural FRP or conventional composites, in cryogenic temperatures, the composite materials face a significant reliability issues as in such harsh conditions, composites are vulnerable. The failure of composite components at the cryogenic temperature is attributed to high thermal stresses caused by the mismatch of coefficient of thermal expansion (CTE) of matrix and reinforcements [181].

Moreover, large micro cracks are induced which contributes to early failure of fibre and matrix. The overall failure mechanisms of the composites are significantly affected by the change in temperature. Furthermore, when composites are subjected to a combined thermal and mechanical loadings, micro-cracks are formed [182]. It can be suggested that cryogenic temperature contributes to increasing strength but significantly reduces the toughness and strain behaviours of the FRP composites. This is attributed to the formation of micro cracks and increased residual stresses. This behaviour can be more prevalent for impact properties because composites normally become harder and the elongation at break is reduced at these temperatures. Chen et al. [171] posited that reducing the CTE is one of the key aspects in the development of high-performance composites with acceptable mechanical properties. Fig. 15

There are reported works on how to improve the mechanical performance of composites under the cryogenic environments. It has been reported that the use of modifiers can improve the mechanical properties of FRP composites under cryogenic conditions [184].

5.4. Degradation in natural FRP composites under the influence of UV radiation

Exposure to ultraviolet (UV) radiation, moisture and high humidity have significant effects on the performance as well as on the degradation behaviour of natural FRP composite structures. Different materials respond to UV rays differently. UV rays are electromagnetic radiations generated naturally from the sun. The immediate effect of UV on composite materials is surface discolouration, due to photo-degradation reactions. This phenomenon does not only cause disassociation of chemical bonds of the polymers, but it also causes physical changes, such as micro-cracking. At elevated temperature, the degradation from UV can be further accelerated [185].

The exposure of natural FRP composites to UV environment is always a concern because their durability, mechanical performance and overall stability can be severely changed. This is one of the major issues facing outdoor applications of natural FRP composites. It has been observed that UV irradiation on natural FRP composites causes surface oxidation. This oxidation stimulates thermal and mechanical stresses on the surface and inner part of the composites, eventually resulting in stress concentration and shrinkage, thereby reducing the overall performance of the composites [186].

5.4.1. High temperature performance of natural FRP composites

Most plant fibres start degrading after 200 °C. This raises a serious concern for the processing of natural FRP composites as the fibres can degrade during processing. Especially when the processing is conducted at temperatures higher than the degradation temperature of the fibres. Polymers are not thermally stable near their glass transition temperatures. Similar trend is applicable to fibre reinforced composites. It is well accepted that biopolymers are more vulnerable at high temperatures when compared to their synthetic counterparts. The processing temperature of natural FRP composites largely depends on physical and chemical compositions of the fibres such as micro-fibril angle, fibre morphologies, cellulose, lignin and hemicellulose contents. This temperature is critical when natural plant fibres composites are manufactured using processes such as injection and extrusion moulding. The degradation temperatures of these components directly influence the processing temperatures. For example, hemicellulose in natural plant fibres degrades at temperatures well below 300 C, which means that processing natural FRP composites around this temperature will lead to degradation of the fibres. Dhakal et al. [69] highlighted that the degradation of hemp fibre starts around 240 °C with the degradation of hemicellulose. In addition to processing temperature, natural plant fibres also degrade during post-manufacturing processes such as drilling, turning, boring, to mention but a few.

6. Acoustic properties of natural FRP hybrid composites

6.1. Relevance of acoustic properties to natural FRP hybrid composites

Acoustic properties of materials are considered in structural engineering in order to optimise noise control and vibration damping [187]. Damping capacity of materials is a vital feature for materials that are used for structural purposes, especially where materials are exposed to various levels of vibrations throughout operations. Materials with low damping responses easily transmit vibration. Synthetic FRP composites possess lower damping properties when compared with natural FRP composites, thus hybridisation is used to improve damping quality of FRP hybrid composites [83].

6.2. Various techniques of analysing acoustic properties of natural FRP hybrid composites

Techniques for analysing acoustic properties of natural FRP hybrid composites include noise reduction coefficients, sound absorption coefficient (SAC), natural frequency and damping ratio measurements. SAC measurements are carried out using impedance tube and microphones. Incident and reflected wave are then separated to calculate absorption coefficient [187]. Flexural vibration testing is also commonly used to characterise natural FRP hybrids composites, such as carbon/flax FRP hybrid composites [83].

Also, impedance tube method is classified according to number of microphones used in testing procedure. Testing is done with two-microphone impedance, which involves generation of sound signals from speaker. The produced wave signals are propagated as plane waves within tubes to hit the sample surface. Reflected waves are then captured and compared to incident sound wave for further analysis [139].

6.3. Acoustic properties of natural FRP hybrid composites

Sound absorption coefficient of natural FRP hybrid composites is a function of frequency. Natural frequency of natural FRP hybrid composites depend on some factors, such as chemical composition, fibre loading, fibre volume fraction, fibre orientation, fibre and matrix interfacial adhesion [130]. Application of weaving architecture of fibres leads to increased natural frequencies and loss factors than knitted fibre patterns. Addition of fibre treatment leads to reduced natural frequency and damping factor [130]. Fibre volume fraction within the natural FRP hybrid composite directly correlates with their sound absorption coefficients. amongst natural plant fibres, flax fibres have comparatively higher sound absorption coefficient, due to higher porosity and air resistivity within flax fabrics [132]. Noise reduction coefficient of natural plant fibres, including ramie, jute and flax are observed to be approximately twice that of glass and carbon fibres [187]. For example, experiments performed with glass and flax fibre reinforced composites show that flax FRP composites is 51.03% higher in vibration damping than glass FRP composites [188]. In addition, damping coefficient of flax FRP composites is nearly four times higher than those reinforced with carbon fibre [83]. Stacking sequence of fibres also affects sound absorption characteristics of natural FRP hybrid composite laminates. It has been observed that composite samples with outer layers made of natural plant fibres possess greater noise reduction coefficient than those with glass fibres [132]. Assarar et al. [189] investigate into enhanced effects of stacking sequences on damping behaviours of flax/carbon epoxy hybrid composites. Due to effective damping properties of natural plant fibres, the study proposed their use for musical instruments.

Ashworth et al. [190] investigate into damping effects of jute/carbon FRP hybrid composites. It is reported that they possess better damping response than single carbon FRP composites. Similarly, comprehensive review shows that hybridisation of hemp fibres with sisal fibres in poly lactic acid offers good damping properties [27]. Also, vibrational characteristics of banana fibres is studied and experimental results demonstrate that hydrophilic nature of natural plant fibres reduces bonding quality within fibre and matrix. When chemical treatments are introduced, their vibrational behaviours improve. Also, they exhibit significantly improved natural frequencies [27]. Zhang et al. [191] evaluate vibration damping characteristics of diverse samples at equivalent frequencies to natural modes. Resonant frequencies of cotton and poly lactic acid samples are lesser than frequencies obtained from other composite laminates, with a reduced flexural stiffness. These results indicate that natural FRP hybrid composites fabricated from natural plant fibres, such as bamboo/cotton/PLA are potential alternatives for engineering structural application, due to their best vibration damping and acoustic properties when compared with other composite counterparts.

6.4. Improving acoustic properties of natural FRP hybrid composites

Acoustic properties can be improved by considering layer/ply sequences of the natural FRP hybrid composite, increasing fibre weight fraction and filler reinforcement, amongst others [187]. Acoustic properties of kenaf and bamboo FRP hybrid composites was found to be lower than that of kenaf FRP composites. This is because hollow structure in kenaf FRP composites traps and absorbs sound, which is not applicable in the hybrid composites with less void content [130].

7. Thermal stability of natural FRP hybrid composites

Materials are made of chemical units. A change in surrounding temperature may cause alterations in the physical and chemical structures, depending on the temperature range. These changes are either reversible or irreversible. When the change is irreversible the material is said to have degraded during the cycle. Thermal stability is defined as the ability of a material to maintain its original physical and chemical structures when exposed to changes in temperature with no adverse effect on its properties, such as strength, toughness or elasticity. The absence of an irreversible reaction or decomposition is an indicator for thermal stability. Processing of FRP composites are usually performed at elevated temperatures. Raw materials for production of anticipated materials should not degrade within the processing temperature range. This underscores the importance of thermal stability of raw materials. Moreover, in heavily loaded material sections, heat is generated as a result of the mechanical work. These materials must be thermally stable within the loading range to avoid a reduction in mechanical ability. Furthermore, in certain applications, materials are subjected to constant changes in temperature with time. These materials should be thermally stable within the subjected temperature cycle to avoid reduction in properties and sudden failure. Thermal stability of composites is usually studied using thermogravimetric analysis (TGA). In TGA measurements, composite samples are subjected to a heating cycle under a predetermined atmosphere, temperature range and heating rate. The mass loss is recorded automatically relative to temperature. Thermal degradation parameters such as onset of degradation, maximum degradation temperature, residual mass amongst others are deduced from the plot of weight loss against temperature. A plot of the differential weight loss against temperature can also be used to explain the progress of degradation in relation to material composition. Natural FRP hybrid composites combine two or more fibres in a single matrix system. Their thermal stabilities are dependant on the chemical structures of both fibres and matrix. Synthetic fibres, such as carbon and glass fibres usually possess higher thermal stability than natural plant fibres. On the other hand, most thermoplastic polymers show lower thermal stability than thermosetting polymers. Thermal degradation of natural FRP reinforced composites depends to a large extent on the natural plant fibres in the hybrid system.

Cellulose, hemicellulose and lignin are the major components in natural plant fibres. They also contain some organics and extractives in minor quantities. The percentage composition of each component varies according to the type, origin, age and position in the natural fibre. Table 2 presents typical variation in composition of notable natural plant fibres.

Cellulose is a carbohydrate polymer composed of β-D-glucopyranose units connected together by $\beta-1$–4 glycosidic bonds (Fig. 16). The chains are completely linear with a tendency to form inter and intramolecular hydrogen bonds. These chains are randomly orientated in the unit cell so that a robust network of intra- and intermolecular hydrogen bonding arising from the abundant hydroxyl groups is formed. As the packing density increases, the hydrogen bonding strength increases, leading to the formation of highly ordered (crystalline) regions. However, in regions with low packing density, the hydrogen bonding strength is low, leading to the formation of less ordered (amorphous) regions. Thus, the microcrystalline cellulose is pictured as having crystalline regions interspaced by amorphous regions (Fig. 16b). The percentage of crystalline portions in relation to the amorphous portion is referred to as cellulose crystallinity (CrI). Some natural plant fibres have as high as 65% CrI in their native form. Most physical, chemical and mechanical properties of natural plant fibres are governed by the crystalline packing. Cellulose has six interconvertible polymorphs [213] including: cellulose I, II, III_I, III_{II}, IV_I and IV_{II}. Cellulose I is the native form and can be subdivided into I_α and I_β [214–217]. These differences arise from the dissimilarity in packing density and pattern. The crystallinity of cellulose plays a major role in the thermal degradation of natural plant fibres. In principle, heat diffusion in cellulose microfibrils will be harder when the chains are well packed and arranged (high crystallinity), resulting in increased thermal stability [218–221]. Treatments that change the crystalline behaviour of fibres always result in improved thermal stability [211,221–227]. Crystalline cellulose normally starts decomposing in the range of 315 - 320 °C [228,229]. Decomposition of cellulose at lower temperatures takes place mainly in the amorphous regions [230].

Hemicellulose is the second polysaccharide in natural plant fibres. It usually exists as a mixture of several polysaccharide monomers such as glucose, xylose, mannose, galacturonic acid, galactose, arabinose, 4-O-methylglucuronic acid and rhamnose. Hemicellulose in natural plant fibres usually contain two or more of the monomeric units in its backbone, for example, the predominant polysaccharides in jute has β-D-xylopyranose units as the backbone with a terminal 4-O-methyl-α-D-

Table 2
Approximate composition of some notable natural plant fibres. Data are collated from various publications [23,28,52,56,81,86,192–212].

Natural fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Wax (%)
Kenaf	44 - 57	21	15 - 19	2	–
Sisal	43 - 78	10 - 13	4 - 12	0.8 - 2	–
Coir	46	0.3	45	4	–
Hemp	70 - 92	18 - 22	3 - 5	0.9	0.8
Flax	60 - 81	14 - 19	2 - 3	0.9	–
Jute	51 - 84	12 - 20	5 - 13	0.2	0.5
Ramie	68 - 76	13 - 15	0.6 – 1.0	1.9 – 2.0	–
Cotton	82 - 96	2 - 6	0.5 – 1.0	5 - 7	0.6
Nettle	86	10	–	–	4
Pineapple	80 - 81	16 - 19	4.6 - 12	2 - 3	–
Oil palm	65	10.12	17.5	–	–
Curaua	73.6	9.9	7.5	–	–
Bamboo	26 - 43	30	21 - 31	–	–
Baggase	55.2	18.8	25.3	–	–

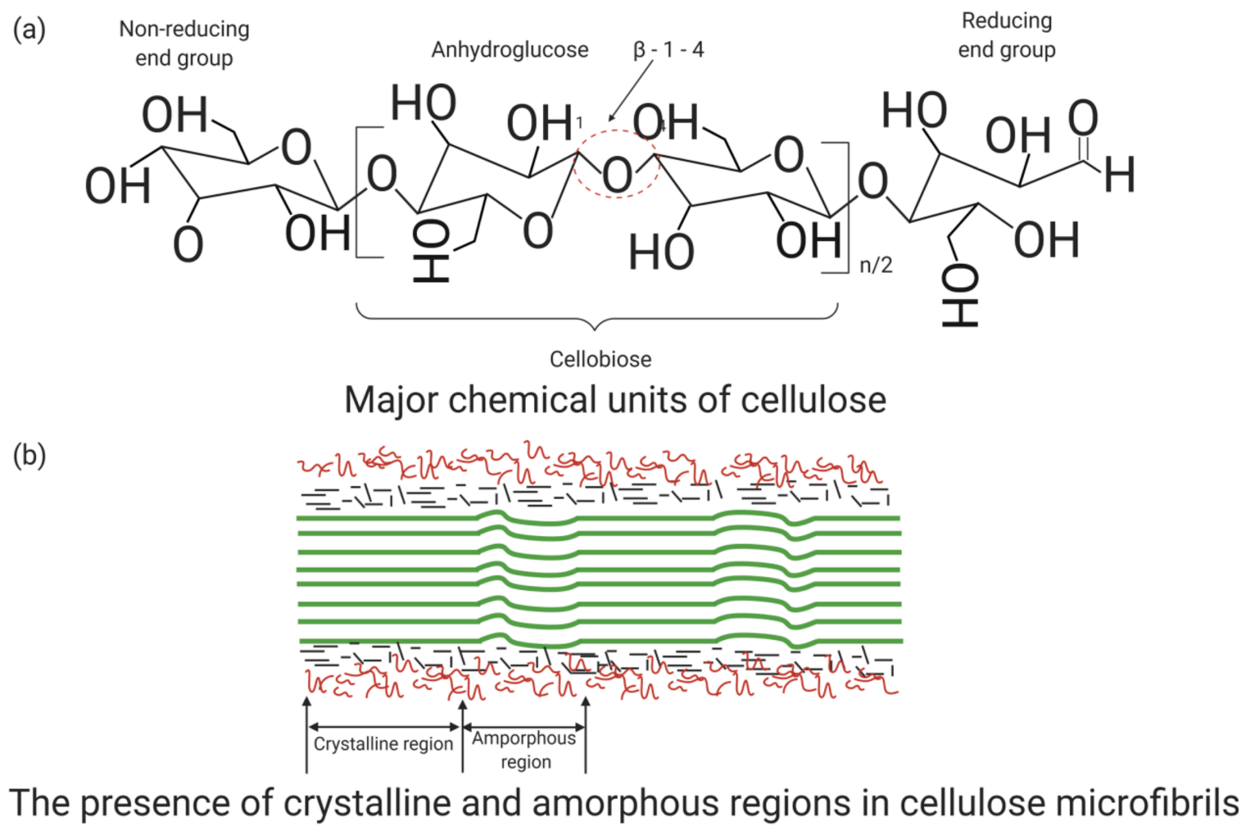

Fig. 16. Major structural units of cellulose in natural plant fibres.

glucouronic acid residue at every seventh xylose unit [231]. Their names are usually derived from prevalent monomeric unit in the backbone.

In some cases, the OH groups in the pyranose chains are partially substituted by O-acetyl or methyl groups (Fig. 17). They also contain branched units giving rise to non-crystalline nature. Hemicellulose contains abundant accessible OH groups (not involved in hydrogen bonding), which are responsible for most of the physical properties of hemicellulose. Hemicellulose is the least thermally stable polymer in natural plant fibres [232,233]. The branched structures in hemicellulose are easily degraded at low temperatures resulting in the production of volatiles. On the other hand, the substituted methyl and acetyl groups also degrade easily at low temperatures. Hemicellulose degrades completely over a narrow temperature range from 200 to 350 °C [234].

Lignin is a complex 3-dimensional amorphous and heterogeneous polymer of phenylpropane units. They are basically built up from three monomeric units to form the macromolecule. These monolignols (p-coumaryl, coniferyl, and sinapyl alcohols), which gives rise to the p-hydroxyphenyl (H), guaiacyl (G) and syringyl (S) units are connected through a series of linkages namely, $\beta - O - 4$, $\alpha - O - 4$, $\beta - 5$, $\beta - 1$, $\beta - \beta$, $4 - O - 5$, and $5 - 5$ (Fig. 18).

Lignin contain unsaturated functional groups, such as conjugated carbonyl groups, aromatic rings and carbon–carbon double bonds. Lignin is relatively thermally stable compared to hemicellulose. However, because of the presence of unsaturated units, lignin starts to

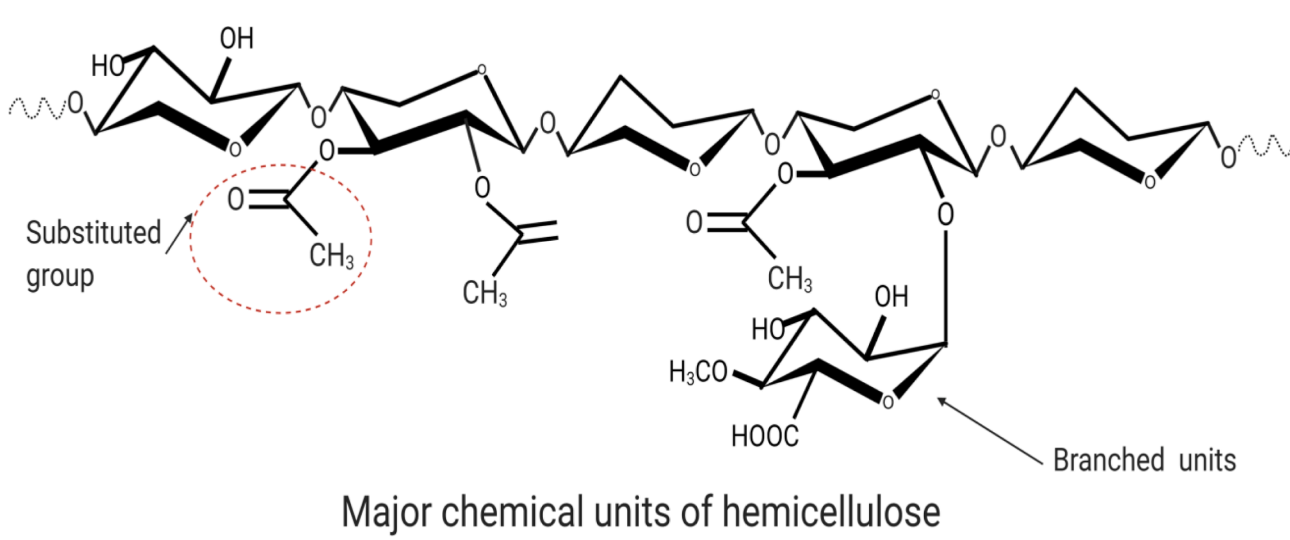

Fig. 17. Major structural units of hemicellulose in natural plant fibres.

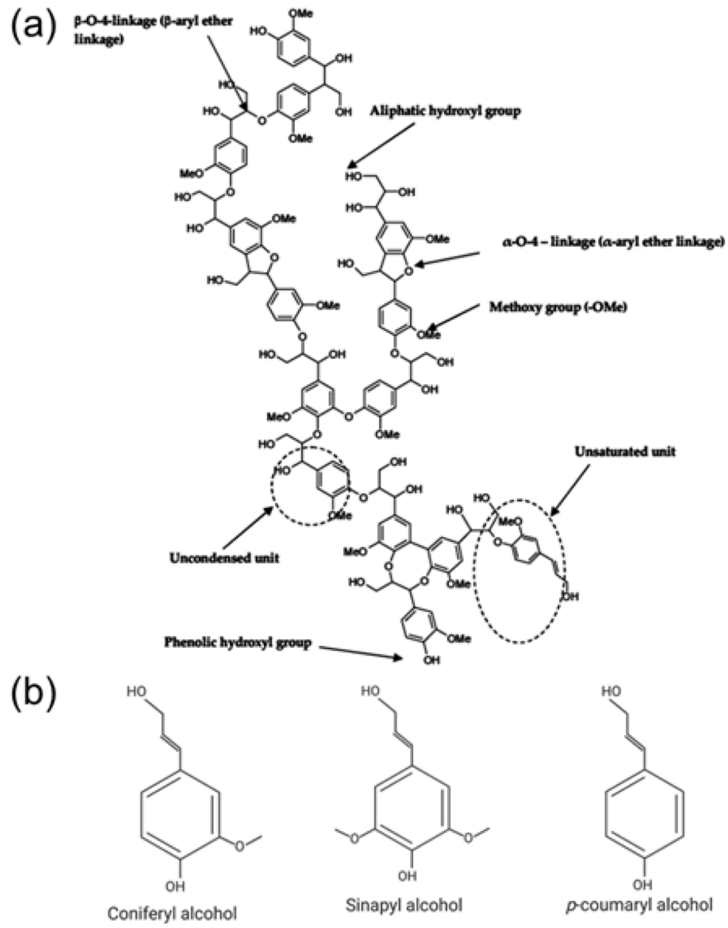

Fig. 18. Major structural units of lignin in natural plant fibres.

degrade at very low temperatures (about 100 °C) but at a very slow rate lasting up to 900 °C with peak degradation between 300 and 450 °C [216,235].

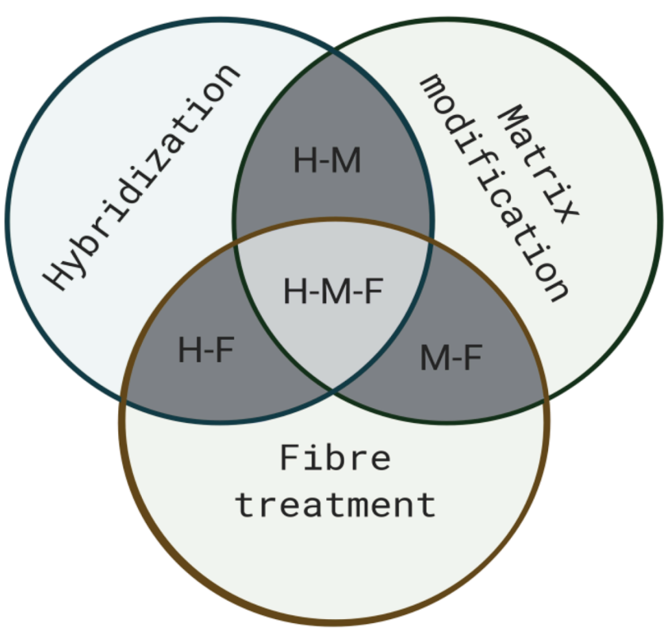

Fig. 19. Conceptual strategies for improving thermal stability of natural fibre composites. H-M, H-M-F, H-F and M-F are combined strategies. H—Hybridisation, M-Matrix modification, F-Fibre treatment.

Theoretically, thermal stability of natural fibre-based composites can be improved by fibre treatment, hybridisation with fibres of higher thermal stability and functional modification of the matrix system (Fig. 19). Natural fibre treatments for improvement of thermal stability of natural FRP composites usually focus on the removal of less thermally stable substances and increasing the crystallinity of cellulose. Fibre treatment is not the subject of this review. However, treatments which have been employed to improve thermal stability of natural plant fibres include; alkaline treatment, acetylation, benzoylation, silane treatment, acrylation, grafting with acrylonitrile, peroxide treatment amongst others. [212]. The effects of these treatments on thermal stability of natural fibre composites have been reported by several researchers [60, 193,235,236,237–249]. Hybridisation with fibres of higher thermal stability functions by shielding mechanism (Fig. 20c).

When the hybrid material is exposed to a temperature change, the heat generated is transferred mostly to the thermally resistant fibres so that the less thermally stable fibres are to some extent shielded from the heat effect. Onset of degradation and maximum degradation temperatures of bamboo fibres filled polypropylene was found to increase with addition of equal weight fraction of glass fibres [250]. Residue at 600 °C increased from almost 1 to 10%. In this case, glass fibres which are thermally stable than banana fibres served as a shield for the banana fibres increasing the onset of degradation of the composite. Hybridisation of sisal PP composites with glass fibres was found to lead to minimal increase in thermal stability [251,252]. The positive thermal hybridisation effect is attributed to the glass fibres in the composite. Improvement in thermal degradation was also noticed in seaweed fibre thermoplastic starch composites hybridised with sugar palm fibres [253]. Addition of tymol fibres to kenaf-PLA composites did not result in significant improvement in thermal stability [254]. On the other hand,

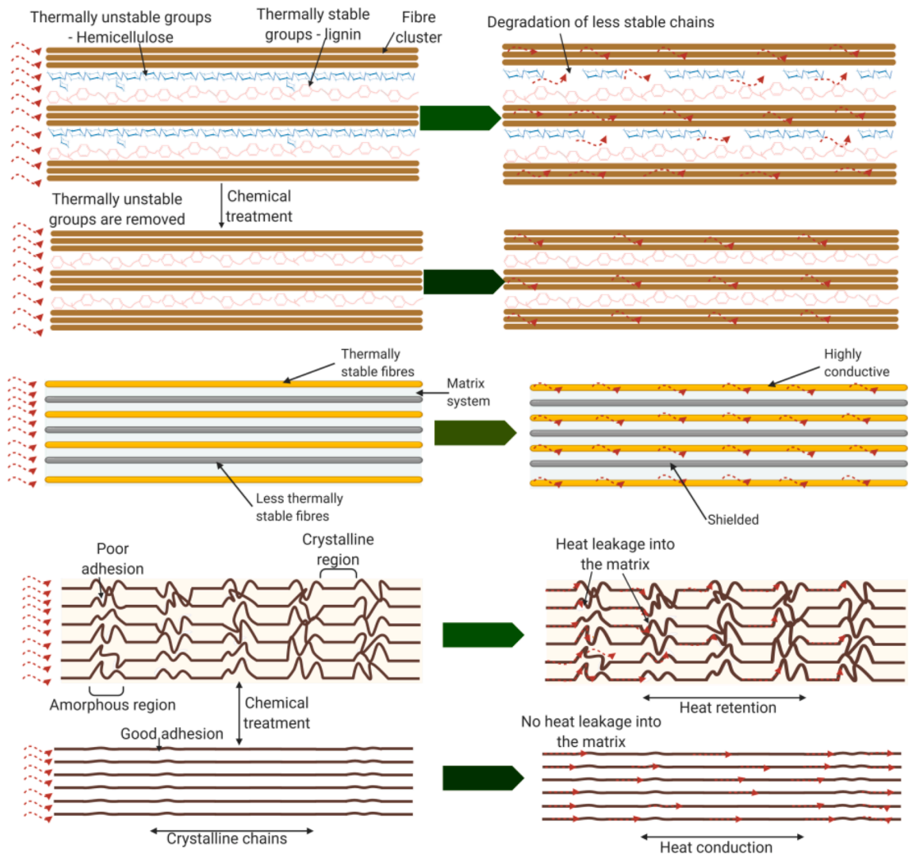

Fig. 20. Various mechanisms of thermal stability enhancement in natural FRP hybrid composites (a) chemical treatment to remove thermally unstable polymeric groups, (b) hybridisation with thermally stable fibres and (c) treatment to increase crystallinity of natural plant fibres.

hybridisation was found to substantially increase the thermal stability of jute-banana hybrid epoxy composites [95] moving the thermal degradation temperature from 200 to 300 °C.

Addition of basalt to jute-epoxy composites resulted to a large increase in thermal stability of the composites [255]. Addition of 7 wt.% glass fibres to jute filled epoxy composites was found to result to about 5% improvement in thermal stability [256]. Hybridisation of curaua polyester composites with glass fibres resulted to improved thermal stability, promising a replacement for glass FRP composites [257]. The degradation temperature of hemp fibre PP composites were found to move considerably upward after addition of 15 wt.% glass fibres [47]. A systematic study of sisal-ramie, sisal-curaua and sisal-glass epoxy hybrid composites shows that hybridisation led to improvement of thermal stability when compared with sisal composites. The highest thermal stability was obtained for sisal-glass hybrid composites [163]. Addition of basalt fibres to short wood fibre HDPE composites resulted to increased peak thermal degradation temperature [258]. It was also shown that addition of thermally stable woven jute fibres to oil palm empty fruit bunch epoxy composites afforded a shift in onset of degradation temperature from 260 to 292 °C and the residue from 9.04 to 12.92%. Lay-up pattern did not show significant effect on thermal degradation behaviour [259]. Addition of kenaf fibres to empty fibre palm bunch PLA composites did not influence thermal stability of the composites [260]. Kenaf and palm fruit bunch possess similar thermal stability such that the combination does not result to improved thermal stability. Addition of glass fibres to sugar palm-thermoplastic polyurethane composites resulted to increased thermal stability [261]. The same effect was realised by addition of glass fibres to date palm wood flour recycled PP composites [262]. Addition of carbon fibres to woven flax epoxy composites also resulted to improved thermal stability of the composites. The thermal stability was found to change slightly with the

Table 3
Thermal degradation behaviour of natural FRP hybrid composite. The data used in this table were obtained from Refs. [66,69,95,255,260,264–266].

Fibres	Fraction of fibres	Polymer	T_{onset} (°C)	T_{max} (°C)	Final temp. (°C)	Residual mass (%)
Kenaf-EFB	60	PLA	240		800	20
Untreated banana-sisal	30	PLA	342	373	800	2.32
Treated banana-sisal	30	PLA	349	378	800	0.72
Sugar palm-cassava baggasse	1 - 8	Starch	150	308 - 311	500	25.1 – 26.0
Kenaf-Luffa	–	PHB	250	382 - 385	700	–
UD flax-carbon	–	Epoxy	321	358	550	–
Cross ply flax-carbon	–	Epoxy	339	367	550	–
Banana - glass	30	PP	270	475	600	10
EFB-kenaf	60	PLA	240	–	800	20
Sisal-nanoclay	–	PLA	295	387	600	9.55
Sugar palm-seaweed	20	Starch	256 - 259	292 - 300	900	10.23 –11.62
Jute - banana	50	Epoxy	200	377	–	
Basalt - jute	40	Epoxy	330	375	700	20
Hemp - glass	40	UP	300	345	500	19.5

fabric density of the flax fibres [263]. Others results are presented in Table 3.

A systematic study on the effect of hybridisation and testing environment on the thermal stability of bamboo-kenaf epoxy hybrid composites shows that the hybridisation did not have any positive effect on the thermal stability of the composites [267]. Thermal stability of pineapple/betel-nut-husk-PP, banana-betel-nut-PP, banana-coir LDPE, alfa-clay-PP, sisal-oil palm fibre-natural-HDPE, oil palm/clay HDPE, bamboo-glass PP, hybrid composites [94,164,268–272] are also reported to improve considerably, owing to hybridisation effect. It is evident that thermal stability of hybrid composites depends on the fibres and their composition, matrix used and the volume fraction of the fibres in the matrix. Proper design for thermal stability should be application driven. The design should take into consideration the difference in thermal decomposition of the various components of the hybrid composites. Based on the thermal stability requirement, the designer can predict a suitable pair that will serve the purpose using the thermal chart (Fig. 21).

Functional modification of the matrix system can also be targeted to improve thermal stability of natural FRP hybrid composites. Matrix modification can be achieved via addition of functional filler particles, where the fillers function both as a thermally stable reinforcing phase and a matrix modifier (Fig. 22a). In either case, the network structure of the matrix is made robust resulting in increased thermal stability. The matrix can also be modified by grafting of the polymer chains with external monomers, which functions either by increasing the network structure of the polymers and surface adhesion to fibres both resulting in improved thermal stability. Adding talc particles to newspaper - PP composite was found to result to a substantial improvement in thermal stability of the composites [305]. Talc particles function as a reinforcing phase but at the same time modifying the matrix system to impart improvement in other properties. Replacing the talc with styrene–(ethylene–butene)–styrene triblock copolymer grafted with maleic anhydride resulted to a slight increase in thermal stability of the hybrid composites [306]. Addition of clay fibres to pine cone fibre-PP composites resulted to a reduction in thermal stability [307]. Clay fillers in this case functions to softens the matrix network structure, bringing about a reduction in thermal stability.

A combination of strategies can be used to enhance the thermal stability of natural FRP composites (Fig. 19). Thermal stability of sisal-banana fibres PLA hybrid composite increase after treatment with sodium hydroxide and benzoyl peroxide [264]. Empty palm bunch-jute epoxy composites experience a substantial improvement in maximum degradation, but minimal increase in onset of degradation after hydroxyl ethyl acrylate treatment of the fibres [308]. Grafting of iPP with MAPP result to increased onset of degradation in cotton/Kapok fibres PP-hybrid composites having some amount of glass fibre mats [309]. The report also shows that acetylation of cotton and Kapok fibres also resulted in improved thermal stability. Modification of jute by alkali treatment and bagasse by grafting furfuryl alcohol led to increase in thermal stability of jute-bagasse epoxy hybrid composites by about 36 °C [310]. Hybridisation with glass fibres and alkaline fibre treated hemp-unsaturated polyester composites did not show any significant change in thermal degradation behaviour except in residue [69]. Addition of nanoclay to silane treated sisal PLA composite resulted to higher thermal stability [266]. It can be established from the aforementioned reports that improving particle size reduction methods to obtain nano-scaled natural fibre particles is required to leverage on application of nanoparticles to enhance both properties and performance of the natural FRP hybrid composite structures [129]. the Hybridisation of treated kenaf-pineapple fibre reinforced phenolic resin composites result to improved thermal stability of the composites [311]. Hybridisation of bamboo-glass and sisal-glass fibres in PP matrix modified with MAPP resulted to improved thermal stability of the

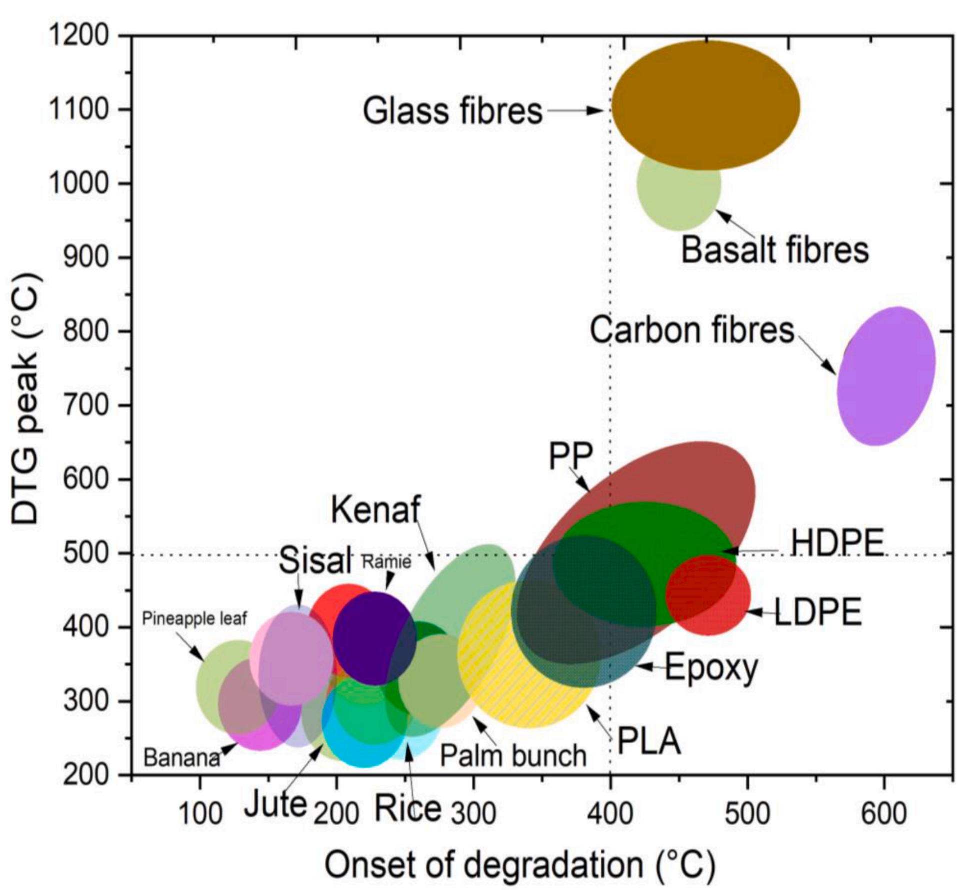

Fig. 21. Thermal chart for hybrid fibre systems. Thermal stability of various fibres is from various sources [90,216,219,236,273–304]. It should be noted that most of the data were acquired under different heating rates. For natural plant fibres, only data acquired under inert atmospheres are presented. Contrary, data for synthetic fibres were acquired under oxygen atmosphere. This is because, most published data on thermal decomposition of carbon, basalt and glass fibres are from thermo-oxidative experiments.

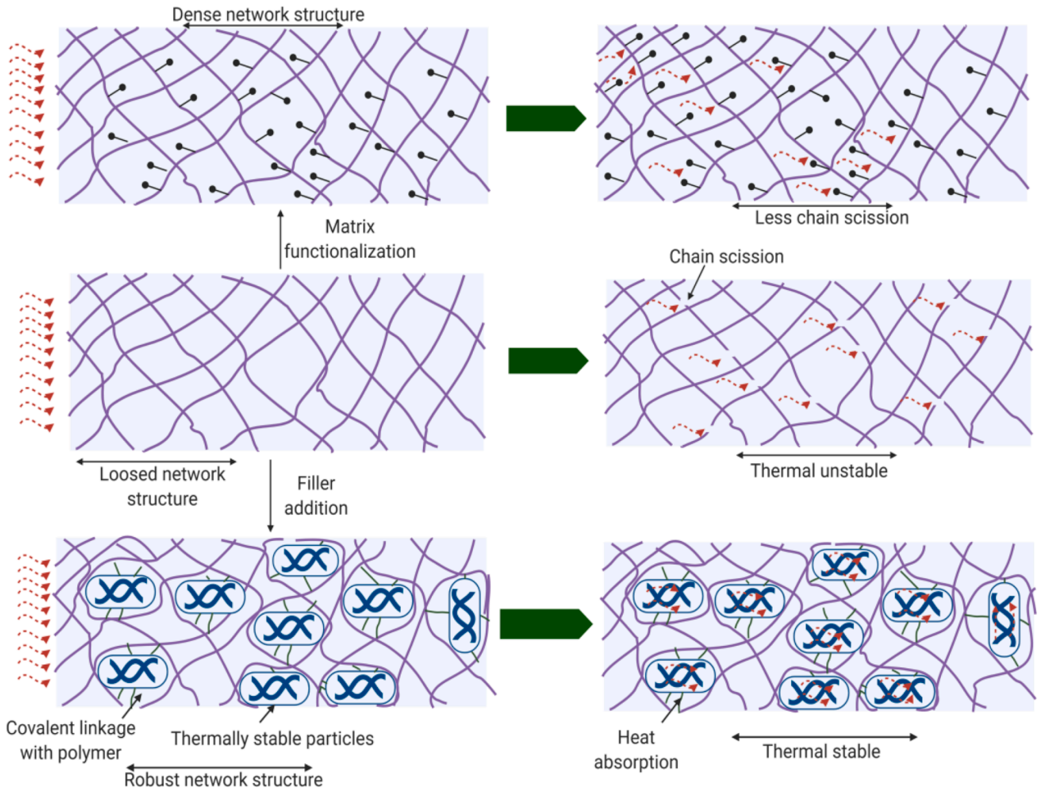

Fig. 22. Matrix modification by filler addition and functional grafting of the matrix.

hybrid composites [103,312]. However, replacing the bamboo fibres with short banana fibres resulted to a decrease in thermal stability [104]. This could be attributed to the poor hybrid effect of banana fibres coupled with the lowering of crystallization of PP by addition of MAPP. Thermal properties of pineapple-PLA composites did not show any impressive change in thermal stability when hybridised with coir fibres [313]. When the coir fibres were treated, thermal stability was found to improve considerably [314]. Alkali treated coir fibres possess better thermal stability than pineapple leaf fibres, because it contains a higher amount of lignin. Effect of tri-hybridisation in composites with flax-banana-glass fibre reinforcement in epoxy matrix show better thermal stability than hybrid flax-glass and banana-glass composites [128]. A combination of matrix functionalisation, fibre treatment and hybridisation result to a substantial improvement in thermal stability of kenaf core-empty palm bunch PLA composites. Kenaf and empty fruit palm bunch fibres were treated with borax and the PLA was functionalized with MAPP [315]. The fibre treatment led to a reduction in the hemicellulose content of empty fruit palm bunch, whereas matrix functionalisation led to improved interfacial adhesion with the fibres resulting to improved thermal stability. A systematic study on the effect of treatment and hybridisation of natural plant fibres in epoxy resin has shown that both treatment and hybridisation affect thermal stability of the composites [316]. Jute fibres were hybridised with each of ramie, sisal and curaua fibres in epoxy matrix. Treatments included alkaline and silane treatments. Alkaline treatment of sisal gave the better thermal stability when hybridised with jute.

8. Modelling and simulation of natural FRP hybrid composites

The general idea behind the hybridisation of fibres in a single composite is to alleviate the disadvantages of the natural plant fibres while maintaining their advantages. However, this is not always the case because of the presence of synergistic effects which exceeds the rules of mixture. Although, scientific explanations cannot be provided for every hybrid effect noticed in hybrid composites, predicting the occurrence of these effects are somewhat challenging. On the other hand, these effects do not exist monotonously but are accompanied by others which can either be negative or positive. Application of experimental methods to observe characteristics of various fibres and matrices within natural FRP hybrid composites is quite common. However, these methods require fabrication of composites with required parameters, which can often have significant resource requirements and limitations. Hence, modelling and simulation approach is an alternative method, whereby hybrid composites are modelled with required properties already pre-assigned in order to predict their desired properties.

Various computational approaches are generally applied in composite technology. These include, but are not limited to, (a) multiscale hierarchical modelling and simulation (continuum mechanics): micromechanics models (multi-phase models: 2 and 3 phases), finite element analysis / representative volume element (RVE) and equivalent continuum models, (b) analytical modelling and numerical simulation: Voigt upper bound and Reuss lower bound (V-R), Hashin and Shtrikman upper and lower bounds (H-S), Halpin-Tsai model (H-T), Hui-Shia model (H-S), Wang-Pyrz model (W-P) and Cox (Shear lag) models, as well as (c) molecular dynamics modelling and simulation.

Unfortunately, a few approaches are commonly applied to predict characteristics of natural FRP hybrid composites. These include rule of mixtures, Halpin-Tsai and finite element methods. Rule of mixtures equation is usually selected based on ease of computation to predict behaviour of individual fibre-based composites. This method depends on properties of individual fibres within the composites. Mechanical characteristics of natural FRP hybrid composites can be assessed with application of law of hybrid mixtures equation. This method also works most effectively with longitudinal predictions of tensile strength and modulus of hybrid composites [317]. FEA works on the principle that volume of evaluated object is broken down into individual units. Hence, properties of whole object can be expressed as aggregate of an individual unit; also known as finite elements [83].

Moving forward, in order to conduct finite element simulation, this process requires initial input of experimental properties of hybrid composites into FEA models to ensure simulation of the various behaviours of the hybrid composites, in comparison with real experimental design [318]. Progression of FEA is divided into three main sections: pre-processing, analysis and optimisation or post processing. These steps also involve development of 1D, 2D and 3D modelled specimens. Furthermore, selection of material models and properties, meshing and setting of boundary conditions are subsequent steps involved in FEA modelling [319].

Ramesh et al. [320] reported an experimental analysis on tensile strength of kenaf/glass hybrid composites in various fibre arrangements, using universal testing machine. It is observed that their tensile strengths were approximately 47.75 MPa. Also, results show that perpendicular arrangement of fibres within hybrid composites display improved tensile strengths over parallel fibre arrangement. FEA simulation is further performed under similar conditions observed from experimental analysis. Maximum tensile stress on the hybrid composites is observed to be averagely 40.24 MPa, with linear buckling within elastic region. Average maximum tensile stress on FRP hybrid composites arranged in perpendicular direction is observed to be 53.65 MPa. Linear buckling within elastic region is likewise observed, indicating relative similarity in results of the experiment and FEA analysis. Experimental and simulation analysis results are compared and presented in Table 4. Moreover, comparative tests on tensile strengths of natural FRP hybrid composites of jute and banana, using experimental techniques are obtained [321]. These are compared with FEA using SolidWorks and Analysis System (ANSYS) software packages. Boundary conditions are also set for tensile test conditions. Furthermore, material parameters from experimental results are applied for simulation. Results from experiment and numerical simulations yield similar outcomes [321]. In another analysis, numerical simulations are done to investigate impacts of square/rectangular sections on buckling characteristics of graphite-based epoxy hybrid composites, which are impacted by different compressive stresses. It is observed that stresses and boundary states record a significant impact on buckling capacity on the lamina sections [322].

FEA, using RVE method is applied to observe random orientation and volume fraction of fibres within carbon/glass FRP hybrid composites. Randomly arranged fibres depict no significant impacts on their tensile strengths. Results obtained from micromechanics further show that there are similarities between numerical and experimental measurements, considering their moduli [317]. Impact of fibre particulates and lamina on tensile characteristics of FRP hybrid composites is observed, using finite element simulation. This is done with nano calcium carbonate and poly propylene matrix, followed by prediction of tensile characteristics and simulation of their fibre/matrix bonding. Numerical simulation based on tensile properties of FRP hybrid composites consider assumptions of regular distribution of fibre reinforcements within matrix. This method involves use of RVE. To simulate tensile characteristics of FRP hybrid composites, properties of matrix are assigned as isotropic and elastic/plastic. Finite element simulation is also performed at various mass fractions of fibre reinforcements, using ANSYS software. From results obtained, finite element data around their elastic area is similar to experimental results, unlike within the plastic area. It is observed that at high strain, finite element models are not able to fully predict their tensile characteristics [324].

Table 4
Comparison between experimental and numerical results of tensile property [323].

S/ No	Composition of specimen	% of elongation (experimental)	% of elongation (numerical)	% of deviation
1.	20% S – 15% B – 65% E	2.64	2.446	7.35
2.	25% S – 10% B – 65% E	1.69	1.799	6.45
3.	30% S – 5% B – 65% E	1.58	1.700	7.59

In addition, natural FRP hybrid composites are simulated using SolidWorks and ANSYS software packages. Characteristics of various jute fibre contents within hybrid composites are imputed for FEA analysis. Estimations of the physical properties of the matrix were obtained from experimental tensile tests, using Instron testing machine. Furthermore, fine meshing is carried out with simulation. It is observed from FEA that there is a positive correlation between the fibre contents and tensile strengths. However, there is a disparity between finite element and experimental results. This is linked to the presence of voids within the composites, which is not accounted for by the FEA model [325].

FEA simulation and experimental analysis are carried out on glass/carbon-based hybrid composites used in power transmission. FEA model displays greater tensile strength and modulus, which is attributed to zero porosity model assumption as well as assumption of no fibre breakage during fabrication. Model and experimental results differ when fibre length is increased (Table 5). Model is however deemed viable for application on tensile strength tests of composite specimens. This can also be applied on power transmission couplings design for estimating median and localised stresses on the FRP hybrid composite couplings [326].

Micromechanical analysis with RVE method is used to study the effect of fibre volume fraction on mechanical properties of glass/carbon hybrid composites. Results show that there is a linear correlation between stiffness characteristics and fibre volume fraction. Furthermore, the arrangement of various fibres does not have significant impact on their stiffness characteristics. This is due to averaging effect observed in their stiffness quality, which is a factor of relative fibre volume and not a change in fibre arrangement. Also, results show that rule of hybrid mixtures is a good predictor of longitudinal tensile modulus. Halpin–Tsai equation also produced similar results [317].

Besides, there are many applications of FEA to analyse the properties and performance of synthetic FRP composites and hybrid composites. For instance, FEA on effects of temperature on low velocity impact damage in woven carbon/epoxy composite sandwich structures at energy levels of 10 and 50 J have been reported [327], whereby the composite panels were exposed to various temperature conditions. The greater damage areas were caused by the highest temperature of 82.2 °C, showing visible damage with high penetration rate and indent or impact depth. The FEA or simulation results for both energy levels are shown in Fig. 23. However, using FEA in natural FRP hybrid composites is not common, due to the factors that are later discussed. However, there are a few relevant studies on natural FRP composites. 3D FEA has been employed to examine the water diffusion behaviour of jute/PLA composite [328], using X-ray techniques (Fig. 24).

Importantly, there is need for special attention during numerical modelling of natural FRP composites, due to their inherent property variations. Discrepancy in properties of heterogeneous natural plant fibre dimensions is significantly high, especially in their lengths and

Table 5
Comparison between experimental tensile test and FEA model results [326].

Run	Young's modulus (GPa)		% Tensile strength (MPa)	
	Experimental	FEA model	% Experimental	FEA model
1	7.5	6.7	59.1	66.5
2	12.4	14.3	131.9	185.0
3	24.2	32.4	310.5	405.6
4	8.7	10.2	115.8	158.9
5	15.1	19.8	210.5	312.0
6	21.1	21.3	185.6	217.0
7	16.2	16.0	210.8	285.6
8	14.1	14.4	148.6	183.0
9	26.1	31.1	298.5	385.6

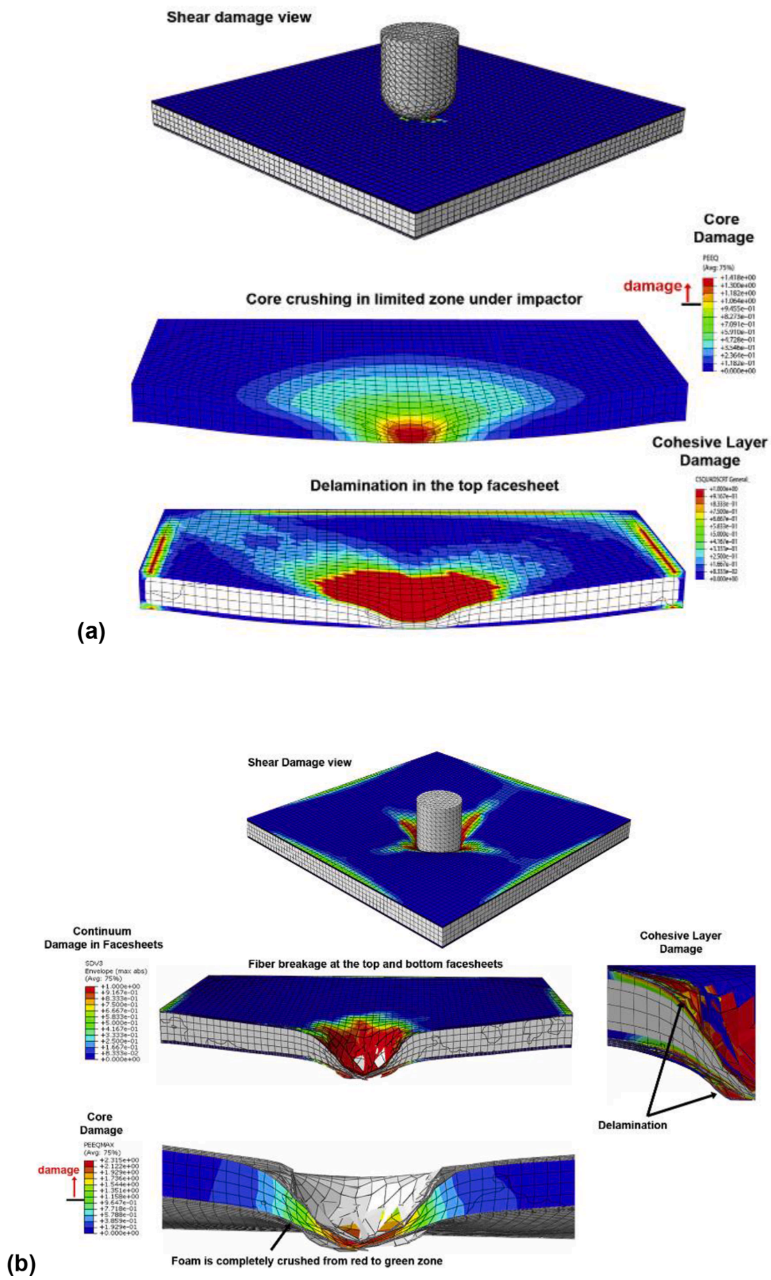

Fig. 23. FEA results of low velocity impact damage, showing (a) barely visible and (b) visible impact failure, at 10 and 50 J, respectively [327] (Reprinted with permission from Elsevier, Permission Number: 5,415,651,372,335).

diameters. Both properties and modelling parameters can be influenced. Therefore, numerical simulation faces a challenge of variation in properties of natural plant fibres. In other words, correct input parameters are essential to obtain desired accurate numerical results. Unfortunately, accuracy of modelling/numerical prediction can be compromised whenever there are large dimensional variations and incorrect data input. These often lead to large disparity between numerical/simulation and experimental results. Thus, experimental results are in these cases more accurate than numerical/modelling results. This could lead to compromise of natural FRP composite system safety, when the design and fabrication are based on modelling results. Hence, experimental and analytical studies are necessary to compliment and validate simulations.

Also, drawbacks of natural plants include quality variations, non-uniform diameter, susceptibility to moisture absorption and microbial growth. These affect the accuracy of numerical modelling/simulation. Modelling of mechanisms and failure modes of natural FRP composites is often challenging, because of their heterogeneous behaviours.

9. Environmental performance of natural FRP composites

For any new product or service, environmental as well as social and economic aspects has to be considered at the design stage. The environmental performance of natural FRP composites is one of the key attributes that has attracted their popularity in various applications. Life cycle assessment (LCA) is a typical methodology used to evaluate the environmental performance of products and services from raw materials extraction to its end-of-life stage. LCA uses different scopes, such as cradle to grave, cradle-to-cradle and cradle to gate. LCA normally involves five stages, including raw materials extraction, processing/production, transportation, use and disposal, according to the International Standardisation for Organisations (ISO) standards 14,040). Using these five stages, key impact indicators such as Global warming potential,

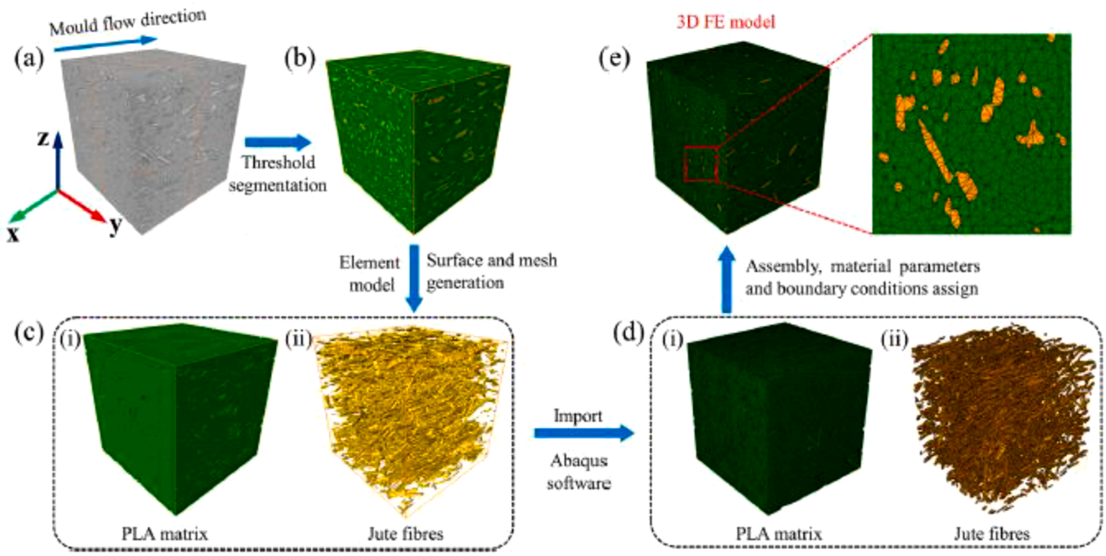

Fig. 24. Application of 3D FEA of water diffusion response of jute fibre and PLA matrix [328] (Reprinted with permission from Elsevier, Permission Number: 5,415, 651,022,237).

ozone depletion, acidification potential, damage to human health and natural resource depletion, amongst others are evaluated using four different phases of LCA. Fig. 25 shows the life cycle stages of natural FRP composites, showing potential of re-sue, recycling and conversion to renewable energy. In the case of natural FRP hybrid composites, new recycling and reuse strategies must be developed as some of the hybrid fibres are nondegradable. This calls for research in the development of natural FRP hybrid composites containing high strength degradable polymeric fibres instead of synthetic fibres.

For the last decade, the environmental awareness in the society and business as a whole has increased significantly. With this, the growing interest in using sustainable materials with their improved life cycle properties (ability to be recycled at the end of their life) is greater, when compared with synthetic glass and carbon fibres. In this context, the importance of using natural fibre as reinforcements over conventional synthetic fibres has become prevalent. The potential of using sustainable, cost effective and high-performance materials with higher green content has attracted considerable interest in key industrial sectors [56].

A report on the environmental impact of natural FRP composites versus glass FRP composites suggest that environmental damage caused by glass FRP composites are far higher than that of natural FRP composites [330]. The LCA study conducted by Rosa [330] on two composite systems namely glass fibre thermoset composite versus glass fibre-hemp thermoset hybrid composites concluded that hemp-glass hybrid system exhibited better environmental impact when compared with glass fibre reinforced composites.

Comparative cost of natural plant fibres against conventional fibres

Costs of natural plant fibres are evidently lower than that of conventional reinforcements such as glass and carbon fibres. The general comparison presented by Huda et al. [37] clearly shows that natural

Fig. 25. Life cycle of natural FRP composites showing the life cycle stages, potential of re-using and recycling [329].

Table 6
Cost comparison of natural fibre against conventional fibres [37].

Fibre types	Cost (US$/ton)	Energy (GJ/ton)
Natural	200–1000	4
Carbon	12,500	130
Glass	1200–1800	30

fibres offer cost effective option in comparison so glass and carbon fibres (Table 6). It is worth noting that the price variation can be expected based on the fibre types and other marketing situations.

10. Future prospects

Over the past decade, natural FRP composites have been used as sustainable materials in many engineering applications, which offer sustainability attributes with a cost-effective alternative to non-renewable conventional glass and carbon FRP composites. The development of sustainable composite materials using renewable, biodegradable reinforcements such as flax, hemp, jute amongst others provide a tremendous opportunity for the use of eco-friendly green materials in engineering applications. Moreover, the renewable reinforcements offer a significant opportunity of reducing carbon footprint with their unique features such as low energy requirements for processing and production and credible end of life options. However, due to their inherent hydrophilic nature and natural variability, these materials struggle to meet the necessary mechanical and thermal properties required for semi-structural and structural members. To realise the full potential of these sustainable lightweight composites, overcoming their drawbacks through the understanding the fibre morphologies, fundamental structure property relationships and the enhancement of fibre-matrix adhesion are crucial.

A hybrid approach can be employed to overcome some of the drawbacks found in natural FRP composites. For example, with a hybrid approach, the water repellence behaviour along with mechanical and long-term durability characteristics of natural FRP composites can be significantly improved. In order to fully exploit the hybrid approach, understanding the hybridisation design, critical processing parameters, manufacturing processes and various fibre optimisation techniques is important.

There are not many established manufacturing techniques suitable for natural FRP composites as these fibres start degrading approximately from 270 °C. This low degradation temperature limits their use for high temperature applications. The natural FRP composites are vulnerable in harsh and high temperature applications. The following challenges give opportunities for further studies: (a) understanding the evolution of thermal stresses arising from the mismatch of two or more fibre types in a single matrix. Moreover, the overall performance of hybrid composites largely depends on the properties of individual fibres and their qualities, (b) an in-depth understanding of the interaction between the hybrid reinforcements, their thermal expansion relationships and synergic mechanisms is crucial. Problems associated with long term exposure to various environmental conditions such as UV radiation and cryogenic conditions are essential to designing and developing structural natural FRP composites so that these materials are resilient in harsh environments, (c) to fully realise the potential of these composites, understanding manufacturing parameters and the development of cost-effective manufacturing techniques is important. The morphological structure and property variation and heterogeneity of fibres bring further challenges in designing and modelling of these new classes of lightweight composite materials and (d) better understanding of the end-of-life options of these composites using LCA in comparison to conventional composites incorporating key mechanical and thermal properties is important. Often, reliable inventory data is not available for these novel materials. Other inherent issues such as long-term durability and improving compatibility between hydrophilic reinforcements and hydrophobic matrices still pose a challenge when making maximum use of natural FRP composites. The understanding of end-of-life of hybrid composites brings a further challenge as various types of reinforcements are comprised in hybrid composites, which requires the use of various fibre separation techniques when dealing with end-of-life scenarios.

Environmental damage responses such as greenhouse gas effects, climate change and other negative environmental impacts caused by high energy consumption and the use of non-renewable raw materials has led to the development and exploitation of more environmentally friendly and less energy consuming materials, such as natural FRP composites. Consequently, the introduction of new environmental legislation demands research, development and the use of renewable materials. Finally, several works on plant-plant FRP hybrid biocomposites are extensively reported, but limited studies are available on animal-animal based hybrid biocomposites and animal-plant FRP biocomposites. Greater challenges in compatibility between plant and animal-based reinforcements are anticipated, which can lead to poor fibre-matrix adhesion and consequently, weak mechanical properties, when compared with plant-plant and/or animal-animal interfacial bonding.

11. Concluding remarks

In this review, the crucial aspects of natural fibre composites, their benefits and drawbacks with special reference to fibre structure and morphological characteristics have been assessed and critically discussed. There are many industrial applications of natural FRP hybrid composites, ranging from building industry, medical devices, automobile and aircraft parts. For natural FRP composites to be used in structural and semi-structural applications, the fibre hybridising approach has been considered as one of the optimising techniques. This approach not only provides the property enhancement opportunities, but also provides a cost-effective way to minimise the drawbacks of natural FRP composites. This review focused on investigating the property enhancement, damage characteristics and mechanisms of using the hybrid approach. It is evident from this critical review that the hybrid approach provides an exceptional opportunity to address some of the shortcomings of natural plant fibres as reinforcements. Additionally, fundamental structure-property relationships and their influence on various properties are critically analysed and discussed with an explanation of related mechanisms. Critical factors influencing long-term durability and use of natural FRP hybrid composites in harsh environmental conditions are well explained. Furthermore, the following critical points are identified and highlighted from this review.

- Key parameters that influence the properties of natural FRP composites are fibre geometry, morphological structure, types of matrix used and fabrication methods utilised. A better understanding of fibre miss-match, failure mechanisms and their influence on important properties of hybrid composites is important.
- Exposure to various harsh environments considerably lowers the load bearing capability of natural FRP composites as a result of weak fibre-matrix interfaces due to moisture ingress. Fibre hybridisation of natural FRP composites systems significantly provides the protection and helps to withstand these harsh environmental conditions.
- Natural FRP composites have significant potential to be used as the materials of the future where environmental credibility is of paramount importance.

Improved compatibility of a single matrix with different fibres using appropriate fibre surface modification/treatments, improved manufacturing processes, treatments and techniques as well as use of hybridisation designs/techniques and processes are possibilities for continuous enhancement of natural FRP composites hybrid composites for several advanced structural applications.

Potential improvement in natural FRP composites hybrid composites include use of hybrid /treatments, improved manufacturing processes, treatments and techniques as well as use of hybrid designs/techniques and processes, coupled with robust analytical, numerical, finite element and/or experimental predictive models/simulation. Also, more investigations should be geared towards animal-animal based hybrid biocomposites and animal-plant FRP biocomposites, since they are abundantly and naturally available as waste products. The aforementioned focuses are possible advanced research gaps; hence, they are hereby recommended for future research in the thriving field of composite technology.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jcomc.2022.100322.

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