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**Review**

# Review: Textile-based natural fibre-reinforced polymeric composites in automotive lightweighting

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## ABSTRACT

Environmental stringent norms, weight reduction, and the ever-depleting mode of petroleum resources have stimulated the use of textile-based natural fibres as reinforcement in polymeric composites. Natural fibres play a significant role in the sustainability of an environmentally friendly future. Natural fibres-based composites have fulfilled the environmental norms and contribute to developing lightweight materials with improved mechanical properties in the automotive sector. The automotive industry is yielding substantial steps towards a more environmentally friendly product by adopting textile fibres as a reinforcement for making various automotive parts, such as door panels, boot lining, instrument panel support, sun visor, wheel box, interior insulation, trunk panel, roof cover, and bumper. The growth rate of natural fibre production is increasing day by day. Each year, high energy-consuming products and synthetic fibres-based composites are being replaced by natural fibre-reinforced polymeric composites because natural fibre-based composites have excellent mechanical properties, relatively low cost (one-third of the cost of glass fibre), low density, and recyclability. This review analysis contributes an overview of the concept of vehicle weight reduction, properties required for composite materials to be used for automotive, most commercially used natural fibres and their use for automotive applications focusing on the matrices for the natural fibre composites (NFCs), natural fibre properties and potential challenges coupled with the use of natural fibres, surface modification methods of some natural fibres being used in the automotive industry and recent advancements in textile fibre-reinforced composites. Thermal properties and processing techniques of natural fibre-reinforced composites (NFRC) are also studied.

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## Introduction

The shortage of fossil fuel is increasing rapidly, while their supply is irresolute and the new necessity of environmental sustainability to counter global warming has employed much enforcement on researchers to develop new materials and manufacturing processes for distribution of goods via air, sea, and land. Lightweight with strength is the biggest challenge for structures, which results in lower energy consumption from the vehicles. While textile-based composite materials and plastic are being used in automotive nowadays, they contribute just about 7.5% of the vehicle's total mass, and their applications are not for the primary vehicle structure [1]. Substantial reasons for the rapid espousal of polymeric matrix composites (PMC) [2] are the light weight (31–40% lighter than aluminium parts of equal strength, 40–60% lighter than metallic components of equal strength), high specific stiffness, and specific strength compared to metals, improved safety and crashworthiness, corrosion resistance, excellent energy absorbing capability by mass, no machining and welding, better damage resistance, reduced tooling cost, part consolidation opportunities, design flexibility, improved internal damping, and material anisotropy, etc. Although the substantial edge of polymer matrix composites has been recognized by the automotive manufacturing sector, there are several crucial defiances before their wide application in primary vehicle structures. Challenges like recyclability, slow production rates, high material costs, and the lack of experience of the auto industries with composite materials are the main issues that auto engineers are facing currently [3–5]. Glass and carbon fibres are the most demanding reinforcements for PMC. Das et al. [5] reported that the glass fibre-reinforced polymeric composites (GFRPC) contribute 1% of total vehicle mass, and its use as structural parts could reduce vehicle weight by 20–36%; more significantly, the carbon fibre-reinforced polymeric composites (CFRPC) contribute 0.007% of total vehicle mass (except special vehicles like F1 cars), and its use could reduce vehicle weight by 40– 60%. While in the automotive industry, the use of GFRPC has been increased to replace conventional metals [6, 7], the usage rate for CFRPC, which are light in weight, stiffer, and stronger than GFRPC, remains low because of its high cost; that's why CFRPC are only used in luxury cars (F1 cars) and aerospace applications. Apart from the aerospace industry, where payload capacity and engine efficiency are the most important concerns, the high-mass production of the automotive sector results in the paramount consideration of being cost beneficial that overwrites any technical factors [8]. Cost-cutting is one of the major tasks which is being continuously faced by automotive manufacturers while fuel-saving and technology transformation is also becoming more important [9]. NFRC are emerging as a feasible alternative to GFRPC, especially in the automotive sector. Natural fibre-based composites have recently attracted the researcher's attention because of their various advantages over GFRPC. Advantages of natural fibres over conventional reinforcement are biodegradability, low cost, superior thermal properties, low density, comparable specific mechanical properties, recyclability, high toughness, lower energy consumption, non-irritation to the skin, reduced tool wear, and carbon dioxide sequestration. Natural fibres are economical and promising as compared to traditional synthetic fibres. This is why NFRC are attracting significant interest due to their potential to reduce carbon emission by replacing conventional synthetically produced materials, such as glass fibre, which costs more and is also harmful to the planet. For developing countries like India, natural fibres provide a possibility to utilize their own natural resources in their various composite processing industries. Industrial ecology, sustainability, green chemistry, and eco-efficiency are forcing automotive manufacturers to seek alternative materials that are eco-friendlier for automotive applications. Many environmental issues will need to be solved for composites fabricated using natural fibres with biopolymers (plastics). Embedding natural fibres with biopolymers such as starch plastic, cellulosic plastic, soy-based plastic, and corn-based plastic are continuously being developed by researchers [10]. Textile structural reinforced polymeric composites (TSRPC) are reinforced by textile structures committed for load-bearing applications. These textile structural composites (TSC) must have a textile-based structure (act as a preform for composites) along with a matrix and must have the potential to withstand primary and secondary load in automotive. The principal objective of (TSC) envisions the utilization of textile-based structures in composite fabrication in order to achieve lightweight composites, advanced composites, and load-bearing composites. In textile structural reinforced polymeric three-dimensional (3D) composites, constituent yarns are arranged in such a manner that they make a right angle to each other in three mutually perpendicular planes, in which two yarns (i.e., warp and weft) are positioned in X and Y directions, whereas the third yarn binds the weft (transverse set of yarns in the fabric) and warp (longitudinal set of yarns in the fabric) yarns in Z direction which provides better structural integrity, having substantial thickness higher than yarn diameter, higher fibre volume fraction (45–50%) without any crimp in the yarns [11]. A minimal effort has been put up so far towards textile fibre-reinforced aluminium metal matrix composites (TFRAMMC) by the scientific community. TFRAMMC are those which are reinforced by textile fibre in aluminium matrix committed for load-bearing applications. These composites must have textile fibre (acting as reinforcement) and aluminium matrix; they must have the potential to withstand primary and secondary load in automotive. Aluminium-based metal matrix composites reinforced with textile fibre in the aluminium matrix have many advantages such as superior strength to weight ratio, high modulus, excellent creep, wear, and fatigue properties. Aluminium-based composite materials have high potential applications in the automotive sector (piston rod, valve train, piston pin, crankshaft, cylinder head, cylinder blocks, and engine blocks).

## Recent market trends of NFRC

Currently, many industries use composites for various products. Initiatives and stringent environmental regulations have been put in place in many countries to push many markets towards more eco-friendly materials and processing. The market sectors that use natural fibre-based composites cover a majority of products. In Fig. 1, market consumption of NFCs in various sectors shows the variety of areas where NFRC are being used. Currently, the biggest market which uses bio-composite materials is the construction sector.

The automotive industry has always been a large driving force to create natural fibre-based composites. With advancements in natural fibre-based composite and bio-composites developed by the automotive industry in the 1990s, the awareness and performance have grown, attracting other markets towards the idea of NFRC to replace man-made fibre-based composites. The production of synthetic fibres depends heavily on the petrochemical-based resources that are quickly draining as well; they produce harmful by-products and waste, which are also a bearing force on the sustainability aspect of landfills [13, 14]. Other sectors, such as the construction sector, are also currently using natural fibre-based composites as well. The market has quickly grown with faster production, increasing demand while maintaining similar properties has attracted the need for sustainable products. Flooring, decking, siding, and railings are examples of products in the construction sector that began to use NFCs successfully in the commercial market. Even though various industries and manufacturers are using more eco-friendly materials nowadays, the auto industry is the most influential. The automotive industry has involved other companies in producing NFRC. The processing methods involved in the manufacturing of natural fibre-based composites are comparable to that of synthetic composites. Extrusion and injection moulding can be used, so no new processing methods need to be developed to manufacture actual final products [15]. By combining these techniques, many auto producers such as Daimler Chrysler have been able to acquaint large-scale production lines using natural fibres. A line has been started by Daimler Chrysler that produces exterior body panels for the Mercedes A-class that consumes 40 MT of NFRC a year. Their product lines provide panels that reduce weight by approximately 8% and decrease costs by 6% from their synthetic counterparts [13].

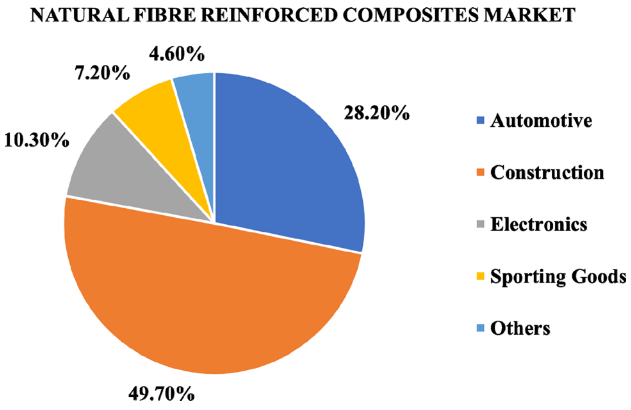


**Figure 1** Market consumption of NFRC [12]. Re-drawn from [12].

## Vehicle weight reduction analysis

The $CO_2$ emission regulation and fuel efficiency of passenger cars are two prime concerns nowadays. To address rising concerns about fuel consumption and greenhouse gas emission (GHG) by passenger vehicles, vehicle weight reduction (VWR) is a well-known strategy. The best way to enhance a car's fuel efficiency without sacrificing safety is to incorporate textile-based fibre-reinforced composite materials in the car body panels because textile fibre-reinforced composite (TFRC) materials have higher specific mechanical properties than those of conventional materials like steel. Vehicle weight reductions can be achieved in three ways:

(i) Material substitution
(ii) Vehicle redesign
(iii) Vehicle downsizing.

Weight reduction in a vehicle can be achieved by material substitution; it involves substituting steel and iron used in automotive vehicles with lighter weight-saving materials like polymer composites, plastics, aluminium, and magnesium. By maintaining the same passenger space, vehicle weight reduction can also be achieved by redesigning the vehicle to optimize the engine size and other parts or to reduce exterior vehicle dimensions, followed by improving the vehicle's packaging. Finally, downsizing can also provide further vehicle weight reduction; it involves the transition of vehicles from larger and heavier size segments to compact and lighter segment vehicle categories. The use of composite materials has been increasing rapidly in the automotive sector nowadays. The use of composite materials consists of the bumper, chassis parts, A-pillar, B-pillar, C-pillar, seat frame, engine hoods, driveshafts, doors, rooftop, floor pan, leaf springs, brake discs, fuel tanks, lift gates, and so on. It was reported that a 10% reduction in weight from the vehicle's total weight results in an improvement in fuel consumption by 6–7% [16, 17]. Ishikawa et al. [18] reported that 50% weight reduction could be achieved by using carbon fibre-reinforced composite materials instead of conventional materials in chassis and car body panels. Furthermore, about 20 g/km of $CO_2$ emission reduction occurs for every 100 kg of vehicle's weight reduction [18]. In current times, various automotive industries are trying to shift towards composites. Some of these have been using semi-structural and non-structural automotive components like dashboards, bumpers, door trims, etc. But nowadays, the challenge is to substitute metals in structural and load-bearing components. The use of TFRC materials in structural and load-bearing components is very limited to date. For automotive structural applications, textile fibre-reinforced structural composite materials (TFRSCM) are an excellent substitute due to their resistance to corrosion, high specific strength, low maintenance, and especially fatigue resistance. TFRSCM reinforced with integrated preform structure made of natural fibres, high-performance fibres (glass, basalt, carbon, etc.) provide an effective solution to substitute the metals in automotive in the near future.

## Theoretical analysis of weight reduction in vehicles

It is a known fact that there is a reduction in vehicle's fuel consumption by reducing the vehicle's weight, which results in an improvement in fuel efficiency of the vehicle because as the vehicle mass reduces, the vehicle's engine has to overcome less tractive forces during acceleration, resulting in a lesser amount of work which is needed to be done to run the vehicle. The mathematical Eq. (1), which explains the relationship between vehicle fuel consumption and tractive forces, is given below [19].

$$FC = \frac{\int be.Pdt}{\int vdt} = \frac{\int be.\left(\frac{F_t.v}{\eta}\right)dt}{\int vdt} \qquad (1)$$

where $F_C$: Vehicle fuel consumption (L/km), $b_e$: Engine Specific fuel consumption (L/kWh), P: Engine power output (kW), V: Vehicle instantaneous speed (m/s, km/hr), $F_t$: Tractive force (KN), η: Drive Train Efficiency, T: Time (hr or s).

For a vehicle given time-speed trace and presuming that the engine efficiency and specific fuel consumption which are the functions of load and speed are known, the variable that affects the amount of power output needed from an engine is the amount of tractive forces or resistive forces which the vehicle has to overcome. The total tractive force is the sum of tire rolling resistance, braking or acceleration resistance, climbing resistance, and aerodynamics drag.

For an accelerating vehicle, total resistive or tractive force is given by Eq. 2.

$$F_t = F_{Roll} + F_{Acc} + F_{Drag} = (f.mg) + (ma) + \left(\frac{1}{2}C_D.\rho_{air}.v^2.A\right) \quad (2)$$

where $F_{Roll}$ = Rolling resistance [N].
$F_{Acc}$ = Acceleration resistance [N]
$F_{Drag}$ = Aerodynamic drag [N]
$f$ = Coefficient of rolling resistance
$m$ = Vehicle and payload mass [kg]
$g$ = Gravitational acceleration [m/s$^2$]
$a$ = Vehicle acceleration [m/s$^2$]
$C_D$ = Drag coefficient
$P_{air}$ = Density of air [kg/m$^3$]
$A$ = Frontal area of vehicle [m$^2$]
$v$ = Vehicle instantaneous speed [m/s]

From the above mathematical expression, we can identify how a vehicle's mass has a direct impact on lowering the total resistive or traction force and thus the fuel consumption. However, weight appears in acceleration and rolling components of total tractive forces. The national research council reported a 10% reduction in vehicle weight could enhance fuel consumption by 7–8% [20]. Many automotive industries are trying to explore the possibility of reducing the vehicle's weight by material substitution, and it involves substituting heavier steel and iron used in vehicles with TFRC materials.

## *Weight reduction analysis for automotive components*

On the component level, the amount of mass savings resulting from using composite materials in any vehicle element depends on the design intent and application. For instance, let us assume that a component in the shape of a rectangular bar is made of a particular material (shown in Fig. 2) having a thickness ($t_1$) and it is replaced with another material having a thickness ($t_2$) so that the bending stiffness of both the materials is maintained to be same. In this case, so as to maintain the bending stiffness constant, the volume of the component will change. If the length and breadth of the rectangular bar are unaltered, then the change in total volume will be reflected in the thickness of the component.

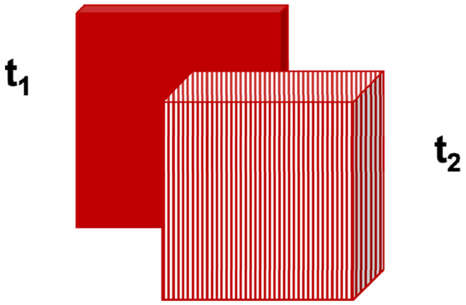


**Figure 2** Two components in the shape of a rectangular bar of different thickness.

Let,

ρ1 and ρ2 be the density of the component before and after replacement.

l and b be its length and breadth, respectively,

t1, v1, and m1 be the thickness, volume, and mass of the component before replacement.

t2, v2, and m2 be the thickness, volume, and mass of the component after replacement.

E1 and E2 be the modulus of elasticity of the two materials before and after replacement.

The volume and mass of the component before replacement will be,

$$\begin{aligned} v1 &= l * b * t1 \\ m1 &= l * b * t1 * \rho 1 \end{aligned} \quad (3)$$

According to the assumption, the bending stiffness of the component should be the same before and after replacement. Then the ratio of thickness can be given by Eq. (4).

$$\frac{t2}{t1} = \left(\frac{E1}{E2}\right)^{\frac{1}{3}} \quad (4)$$

The volume of the component after replacement can be given by,

$$v2 = l * b * t1 * \left(\frac{E1}{E2}\right)^{\frac{1}{3}} \quad (5)$$

Mass of the component after replacement,

$$\begin{aligned} m2 &= v2 * \rho 2 \\ m2 &= l * b * t1 * \left(\frac{E1}{E2}\right)^{\frac{1}{3}} * \rho 2 \end{aligned} \quad (6)$$

Dividing Eq. 6 by Eq. 3,

$$m2 = m1 * \left(\frac{E1}{E2}\right)^{\frac{1}{3}} * \left(\frac{\rho 2}{\rho 1}\right) \quad (7)$$

Equation 7 gives the mass of the component after replacing material 1 with material 2.

## Properties required in composite materials to be used in automotive

There are three prime factors that need to be looked upon before adopting a material for design in the automotive sector. These are:

Performance of material
Government regulations
Customer requirements

The material should be selected in such a manner that it should have the following properties: high strength, low density, stiffness, corrosion resistance, damage tolerance, fatigue resistance, resistance to impact, temperature resistance, toughness, chemical resistance, electrical resistance, and processability. Furthermore, government regulations (lightweight, fuel efficiency, crash performance, and $CO_2$ emission) and customer requirements (quality features and cost) should also be considered while selecting composite materials. The mechanical performance of the composites is a function of the reinforcing phase, but the matrix phase also makes its own significant contribution to properties. The selection of the resin influences the ability to conduct heat and current by the composites. The mechanical strength of the composite materials is not governed by the reinforcing phase alone, but the synergistic effect of both the matrix and reinforcing phase plays a significant role. The behaviour of matrix material is usually ductile in nature. As the fragmented ends of the fibres are pulled out apart, plastic flow or elastic deformation of the matrix phase exerts shear forces, which results in a slow build-up of stresses into the fragments. Because of this type of load transfer, the reinforcing fibres continue to provide some strength to the composite. So, the composite can withstand more stresses without fracturing. The synergy effect between fibres and matrix can thus toughen and strengthen the composite by increasing the work done required to fracture it [21].

## Vehicle mass breakdown

Figure 3 shows the break-up of an automotive component-wise weight, and Table 1 represents the various systems and their sub-components. The mass of a given vehicle can be reduced by its functional vehicle system or by its material composition. An approximate mass breakdown of different vehicle systems and variation seen in the various existing designs of vehicles. The vehicle's body is one of the vehicle's vital systems, or sometimes it is named as the "Body-in-White". The body of the vehicle represents the core structural frame of the vehicle, contributing about a quarter mass of the overall vehicle weight. The other two well-known vehicle categories are the suspension and the powertrain system; both systems contribute about 1/5th to 1/4th of the total vehicle weight. After these systems, the interior, closures, and other miscellaneous (including lighting,

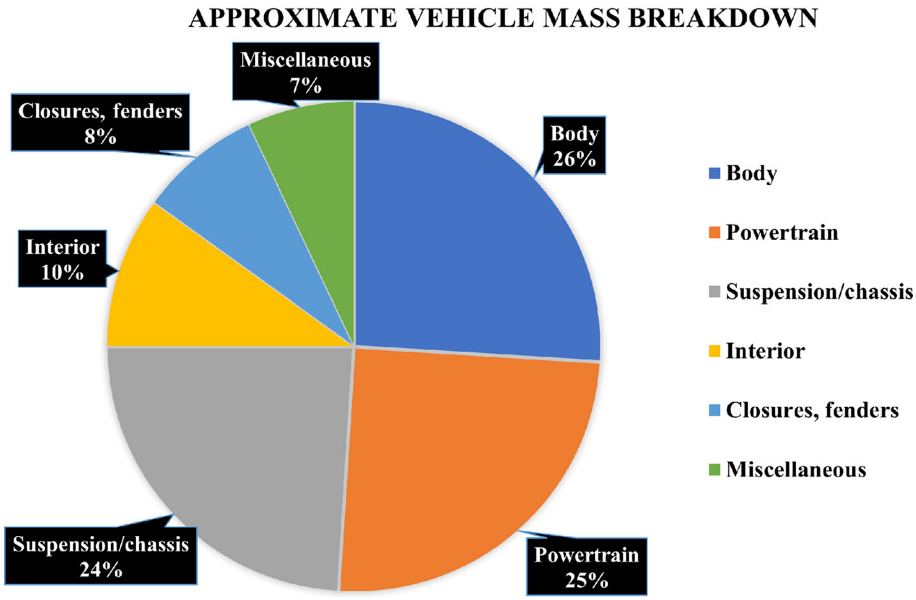


**Figure 3** Break-up of the component wise weight of an automotive [22]. Re-drawn from [22].

**Table 1** Various systems and their sub-components [22]

| S.No | System | Vital components in a system |
|---|---|---|
| 1 | Body-in-white | Passenger compartment frame, dash panel assembly, floor and underbody, front-end structure, body sides, pillars, roof assembly, front structure, fenders |
| 2 | Powertrain | Engine, transmission, fuel tank exhaust system |
| 3 | Chassis | Chassis, brakes, suspension, wheels, tires, steering |
| 4 | Interior | Seats, airbags, instrument panel, insulation, trim |
| 5 | Closures | Front and rear doors, hood, liftgate (decklid) |
| 6 | Miscellaneous | Electrical, glazing, lighting, thermal, windows |

electronic, thermal, etc.) contribute to the remaining vehicle systems.

## Properties of natural fibres and their potential

Figure 4 shows the general structural configuration of natural fibre, and it covers mainly three structural elements, i.e., cellulose, lignin, and hemicellulose [23, 24]. Plant fibres consist of hollow cellulose crystalline microfibrils held together by the lignin and hemicellulose as a matrix; thus, they are considered as composites. Each category of plant fibres has its own distinct fibre attributes where the cell wall is not homogenous, and they possess complex structural configurations made up of several layers. It consists of four walls, i.e., the primary wall at the circumference and three secondary walls located at the innermost side followed by lumen at the core since mechanical properties of the fibre are controlled by its thickness [25, 26]. The primary cell wall is made up of a cellulosic amorphous microfibril network arranged in a disorganized manner. The secondary walls are made up of three different layers in which cellulosic crystalline microfibrils having a length of 10–30 nm are helically arranged in a well-organized manner. The microfibrillar angle is the angle between the fibre axis and the microfibrils that varies from one fibre to another. The mechanical properties and quality (dexterity, smoothness) of any fibre are influenced by microfibrillar angle [27]. In the cell wall, an amorphous matrix is made up of hemicellulose, lignin, and pectin. There is a hydrogen bond between the cellulose molecule and hemicellulose, and this acts as a cementing matrix between the cellulose crystalline microfibrils to form the major structural element, which is known as the hemicellulose-cellulose network arrangement. Due to the hydrophilic behaviour of natural fibres and

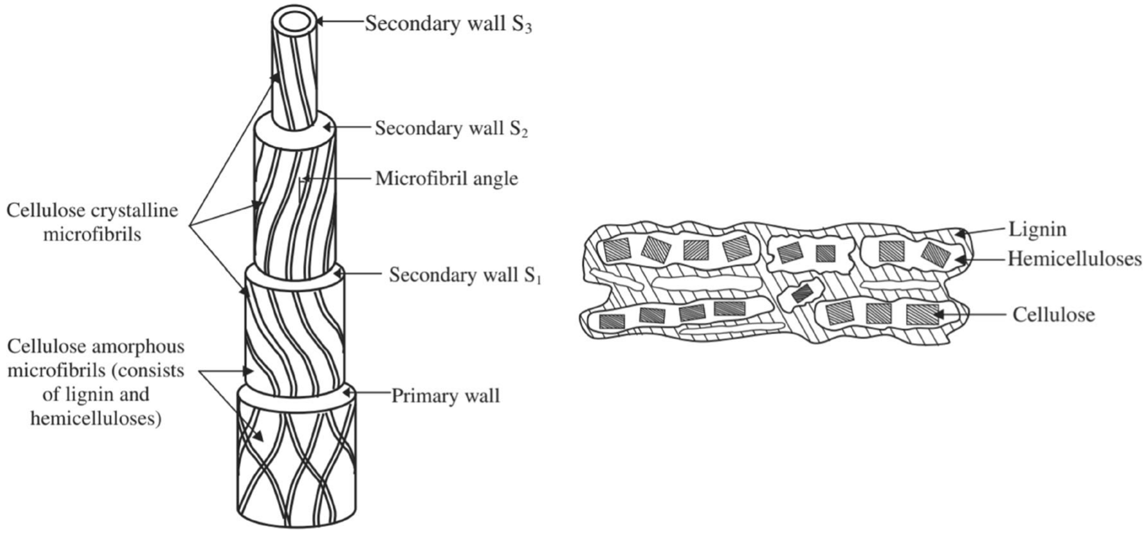


**Figure 4** A schematic structure of a natural fibre. Adapted with permission from [23]. Copyright 2012, Elsevier.

hydrophobic behaviour of the polymer matrix interfacial adhesion is poor between them so natural fibres require some chemical treatment so as to reduce their hydrophilic feature.

Natural fibres are continuous filaments that are employed in the manufacture of rope, yarn, fabric, cords, and carpets. Natural fibres can be compressed into sheets to produce paper or used as a reinforcement phase in composites. Ahmad et al. [28] categorized textile fibres into two types: natural and man-made. Natural fibres are obtained mainly from three subcategories: animals, plants, and minerals. Plant fibres are subdivided into stem or bast, leaf or grass, seed, stalk, and fruit fibres, and these are obtained from the vegetative parts of the plants. Animal fibres are subdivided into wool or hair and silk fibres. Mineral fibre like asbestos is used for housing applications, while animal fibres like wool and silk are widely studied. To get a crystal-clear idea, the classification of textile fibres is presented in Fig. 5. The chemical composition and physical properties of various natural fibres and synthetic fibres are shown in Tables 2 and 3. The physical properties of natural fibres are of great importance. For example, the strength of the composite can significantly be affected by the aspect ratio of fibres (length/diameter ratio); high aspect ratios lead to more strength.

## Other properties

### Thermal properties of NFCs

#### *Thermal conductivity*

In industries such as automotive, packaging, and construction, the use of heat insulating materials is an effective way to cut energy costs and increase industrial efficiency [33]. Lumens, or hollow spaces filled with air are found in natural fibres. These results, as the fibre content in composite increases, the thermal conductivity of the composite material decreases. Several researches have been conducted to examine the thermal conductivity of NFCs. Pujari et al. [34] investigated the thermal conductivity of chopped banana and jute fibres/epoxy composites

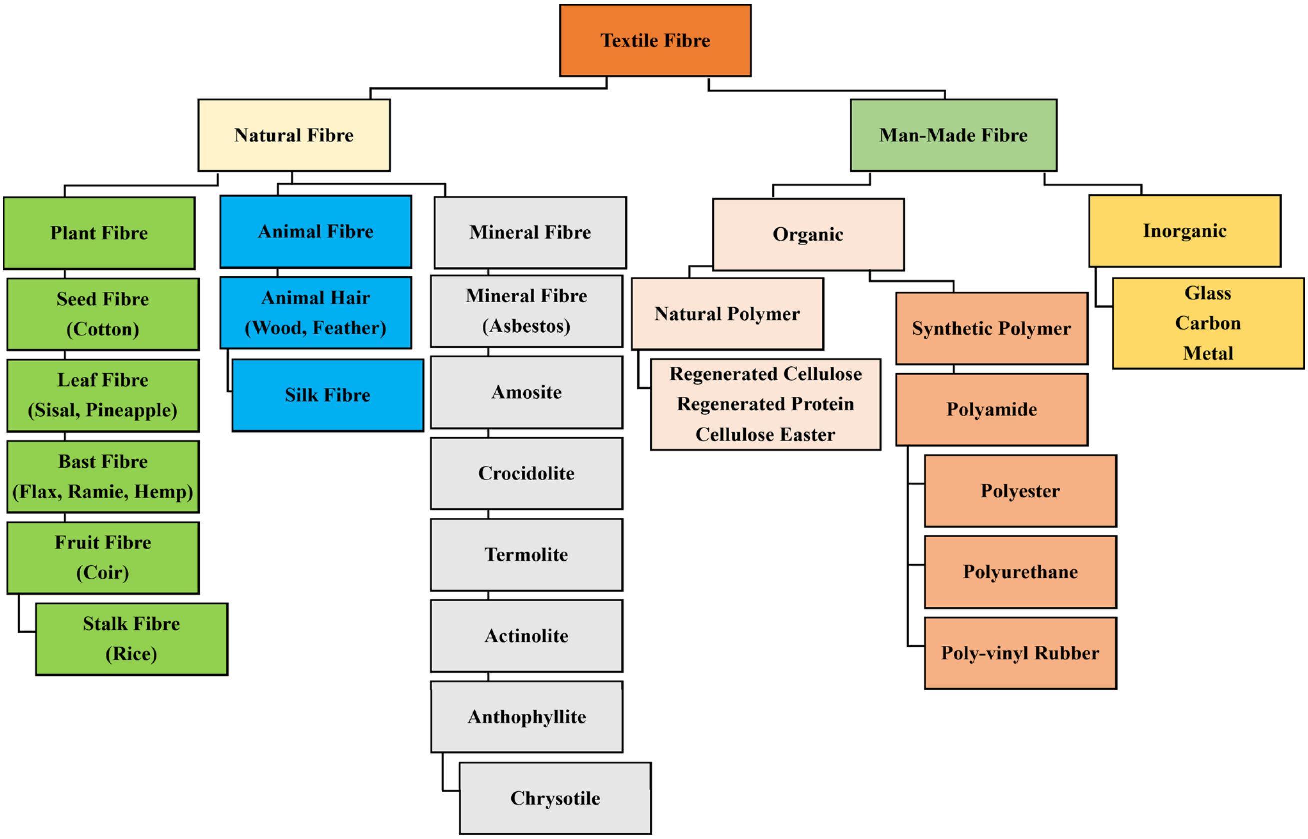


**Figure 5** A basic classification of textile fibres [28]. Re-drawn from [28].

**Table 2** Chemical composition of different natural fibres [29–31]

| Fibre name | Cellulose [wt%] | Lignin [wt%] | Hemi-cellulose [wt%] | Pectin [wt%] | Wax [wt%] | Moisture [wt%] | Ash [wt%] | Micro-fibrillar angle |
|---|---|---|---|---|---|---|---|---|
| Abaca | 55–62 | 7–12 | 16–19 | .2-.9 | .2 | – | 1.1–3 | 21–24 |
| Bamboo | 25–47 | 11–32 | 13–71.3 | 0.38 | – | 9.16 | 1.5–6 | – |
| Banana | 45–61 | 13.4–21.9 | 10.1–14.9 | 2.2–4.4 | 2–6 | 10.71 | 3.1 | 11.1–12 |
| Coir | 20–36.5 | 33.7–52.3 | 12.9–15.3 | 4.5–8 | – | 11.36 | – | 30.46 |
| Cotton | 82.7–90.5 | 0.6–28 | 1.5–5.5 | 0–5.6 | 0.6 | 7.85–8.5 | 0.7–2.1 | – |
| Curaua´ | 73.5 | 7.6 | 9.8 | – | – | – | – | – |
| Flax | 64.2–71.5 | 2–2.2 | 16.5–20.4 | 1.7–2.4 | 1.4–1.7 | 8–1.2 | 13.2 | 5.5–10 |
| Hemp | 54–78.9 | 2.7–13.5 | 13.9–22.4 | 0.9–3.2 | 0.3–0.8 | 6.2–1.2 | 0.4–0.8 | 2–6.3 |
| Jute | 45.7–71.5 | 0.3–26.5 | 12.9–22.4 | 0.2–11.7 | 0.5 | 12.5–13.7 | 0.5–7.9 | 9 |
| Kenaf | 32–57 | 8.5–21.5 | 18.5–23.5 | 3–8.8 | 0.6 | 6.2–12 | 2–5.2 | 2–6.3 |
| Rachis | 42.76 | 26 | – | – | – | – | – | 27–36 |
| Ramie | 68.4–91.5 | 0.5–0.7 | 5–16.6 | 1.9 | 0.4 | – | 5.2 | 68–82 |
| Rice husk | 37–45.5 | – | 12–20.5 | – | – | – | 21 | – |
| Sea grass | 57.5 | 5.2 | 39 | 11 | – | – | – | – |
| Sisal | 47.5–78 | 8–14.5 | 10–23 | 0.8–11 | 0.4–2 | 11 | 0.5–4.3 | – |

**Table 3** Physical and mechanical properties of natural and high-performance fibres [29–32]

| Fibre name | Density (g /cm$^3$) | Diameter (μm) | Tensile strength (MPa) | Tensile modulus (GPa) | Elongation at break (%) |
|---|---|---|---|---|---|
| Abaca | 1.5 | 10.5–30 | 400–820 | 31.3–33.5 | 2.8 |
| Bamboo | 1.2 | 85–122 | 145–230 | 12–18 | 1.42 |
| Banana | 0.9 | 105–250 | 165.5 | 8.85 | 2.36 |
| Coconut | 1.15 | 105–450 | 500 | 2.5 | 20 |
| Coir | 1.2 | 155–257 | 175.5 | 4–7 | 32 |
| Cotton | 1.62 | – | 288–598 | 5.6–12.6 | 7.1–8.2 |
| Curaua´ | 1.4 | – | 158–729 | – | 5 |
| Flax | 1.5 | 24 | 600–1500 | 27.5–85 | 2.8–3.2 |
| Hemp | 1.49 | 24–575 | 550–800 | 70 | 2–5 |
| Jute | 1.48 | 30–260 | 393–800 | 12–28 | 1.17–1.6 |
| Kenaf | 1.45 |  | 930 | 53 | 1.6 |
| Ramie | 1.5 | 22–90 | 405–938 | 62–128 | 3.4–3.8 |
| Sisal | 1.33 | 45–200 | 540–710 | 9.4–22 | 2–5 |
| Softwood | 1.5 | – | 1 000 | 40 | 4.4 |
| E-glass | 2.54 | 17 | 3 300 | 72 | 0.4–3.2 |
| S-glass | 2.5 | – | 4 575 | 84 | 2.7 |
| Aramid (Std.) | 1.43 | 11.9 | 3 100 | 70 | 2.6–3.5 |
| HS carbon | 1.81 | 8.2 | 3670 | 260 | 1.5 |

fabricated by hand lay-up technique and found that the banana and jute fibre chopped composites had thermal conductivities of 0.227 and 0.230 W/m K in the range of −20 °C to 300 °C and at the maximum fibre volume fraction, respectively. The thermal conductivity of NFCs with varying fibre percentage is shown in Fig. 6 [34]. Li et al. [35] reported that an increase in fibre loading decreased the thermal conductivity of a chopped flax fibre/high density polyethylene (HDPE) composite fabricated by extrusion moulding method. Osugi et al. [36] and Ramanaiah et al. [37] found the same result for unidirectional hemp fibre/epoxy composite fabricated by compression moulding method and unidirectional fish

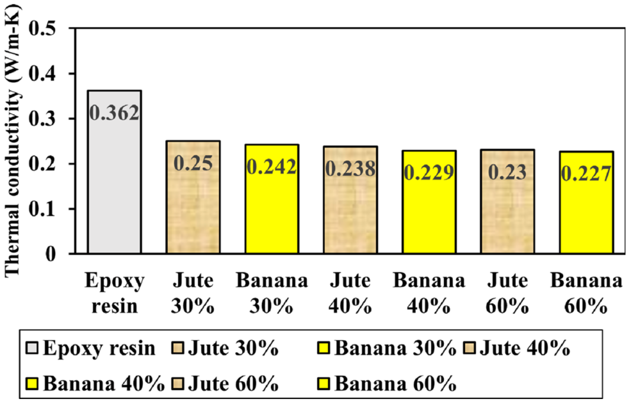


**Figure 6** Thermal conductivity of epoxy resin and different NFCs with varying fibre percentage [34]. Re-drawn from [34].

tail palm fibre/polyester composites fabricated by hand lay-up technique, respectively. The thermal conductivity of chopped banana fibre/polypropylene (PP) composite fabricated by compression moulding method was assessed by Paul et al. [38]. The results revealed that when the fibre percentage in composite increased, the thermal conductivity of the composite decreased. Agarwal et al. [39] studied the effect of chemical treatment of fibre on the thermal conductivity of oil palm fibre/phenolic reinforced composite. The results revealed that alkali and silane treatment improved the thermal conductivity of composite material than acetylation treatment, implying that acetylation treatment is more suitable than alkali and silane treatment to improve the thermal insulation properties of composite materials.

### *Fire resistance*

When exposed to heat, polymer matrix degrades quickly [40]. At high temperatures, fibre reinforcement may improve the thermal stability of polymeric composites. The loss of strength and stiffness of NFCs at high temperature is one of their weakness [41]. When NFCs are subjected to fire, they undergo thermal decomposition and combustion. The flammability of NFCs varies with different types of natural fibres because their microstructures and chemical compositions are different. The fire resistance of NFCs can be improved by lowering the cellulose content of fibre, improving crystallinity, and lowering polymerization of composites [41]. The fire resistance of NFCs can also be improved by using coatings and additives, such as ceramics, silicone, intumescents, ablation, phenolics, and glass mats. Heating the intumescent materials beyond a certain temperature causes foaming and expansion to form a cellular and charred surface, which protects the underlying surface from heat and flames. The fire resistance of the composites can be increased by the addition of talc and nanoparticles as filler to the NFCs by forming heat barriers. The behaviour of NFCs at higher temperature has been investigated by several researchers. Some studies have been reported that natural fibre starts to degrade at about 220 °C [42–45]. However, lignin degrades at around 200 °C, while cellulose and hemicellulose degrades at higher temperature [46]. Table 4 shows the temperature at which major natural fibres decompose, and Table 5 shows melting point and glass transition of some resin used in NFCs.

## Matrices for NFCs

In composites, a matrix is used to bind the reinforcing phase together. The main functions of the matrix are the environmental tolerance, surface appearance, and overall durability of the composites, while most of the structural loads are carried by the fibrous reinforcement phase, thus imparting strength and stiffness to the composite. In composites, stress distribution from a matrix to fibres directly affects mechanical properties [49, 50]. The distribution of fibres and interfacial adhesion across the matrix and reinforcing phases are required to assure good stress transfer in the composites [51]. In previous years, a lot of research has been carried out to find an alternative to the traditional petrochemical-based matrix because of the shortage of fossil fuel resources and

**Table 4** Decomposition temperature of some natural fibres [44, 47]

| Natural Fibre | Decomposition temperature (°C) |
|---|---|
| Pina | 242 |
| Bagasse | 230 |
| Cotton | 231 |
| Hemp | 218 |
| Jute | 218 |
| Kenaf | 230 |
| Rice straw | 237 |
| Rice husk | 233 |
| Bamboo | 225 |

**Table 5** Melting point and glass transition of some resin used in NFCs [48]

| Resin | Melting point (°C) | Glass transition temperature (°C) |
|---|---|---|
| Polyhydroxyalkanoates (PHA) | 162–176 | 3–14 |
| Polylactic acid (PLA) | 152–163 | 57 |
| Epoxy | – | 72–170 |
| Starch | 109–116 | 59 |
| Phenolic | – | 172 |
| PP | 158–175 | 0.8–1.54 |
| Low-density polyethylene (LDPE) | 104–115 | 118 |
| HDPE | 122–142 | 78 |
| Polystyrene (PS) | – | 102–134 |
| Nylon 6 | 220 | 42 |
| Nylon 6,6 | 248–270 | 52 |
| Polyester | 252–298 | 62 |
| Vinyl ester | – | 102–120 |

the adverse effect on the environment [52]. Classification of matrices for NFRC is presented in Fig. 7. When natural fibres are used with petroleum-based polymers, then it is called partially biodegradable composites. When they are used with a fully degradable matrix, then it is known as green composites. Load transfer takes place uniformly from a matrix to the fibres [33].

## Petroleum-based matrix

A petroleum-based resin is a chemical product obtained from fossil fuels like natural gas and coal [52]. Thermosets and thermoplastics are used as petroleum matrices for NFRC. Epoxy, polyester, phenolic (phenol–formaldehyde), and vinyl ester are utilized as thermoset matrices, whereas PS, polyethylene (PE), polyvinyl chloride (PVC) and PP are used for thermoplastic matrices [33, 52]. The mechanical properties of different thermoplastic and thermosetting polymers are presented in Table 6.

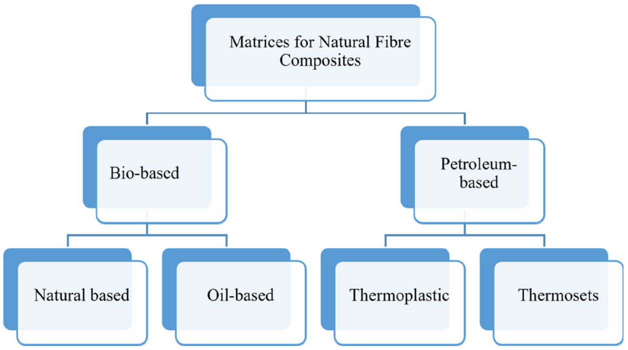


**Figure 7** Classification of polymeric matrices for NFRC [33]. Redrawn from [33].

### *Thermosets*

Thermoset matrices are insoluble and infusible materials that are cured by a catalyst or heat [54]. Thermosets cannot be reshaped and melted by heating [55]. Polymer chains are connected by a three-dimensional covalent bond; this type of matrix has higher thermal stability, higher modulus, higher chemical resistance, and improved creep resistance than thermoplastic resins [52]. At room temperature, they are brittle and show low fracture toughness. The advantages and disadvantages of the thermoset matrix are presented in Table 7.

### *Thermoplastics*

Thermoplastic matrix is based on polymers that can be reshaped and melted by heating (physical change) [60]. Thermoplastic resins have higher viscosity (approximately 500–1000 times) as compared to the uncured thermoset resins in the melted condition. They can be reshaped and reformed without chemical reaction by applying heat, and they are solid at room temperature [52]. These resins have more reform-ability, higher impact resistance, higher processing temperature, and high damage tolerance than thermoset resins [33]. The advantages and disadvantages of the thermoplastic matrix are presented in Table 8.

## Bio-based resins

These matrices are polymers that are partially or fully biodegradable and obtained from sustainable

**Table 6** Mechanical properties of different thermoplastic and thermosetting polymers [53]

| Resin | Type | Specific gravity | Tensile strength (MPa) | Yield strength (MPa) | Tensile modulus (GPa) | Elongation at break (%) |
|---|---|---|---|---|---|---|
| PVC | Thermoplastic | 1.28–1.56 | 40.5–52 | 40.5–14.6 | 2.3–4 | 41–81 |
| HDPE | Thermoplastic | 0.951–0.964 | 22.2–31.1 | 26.1–33.2 | 1.05–1.08 | 11–1200 |
| LDPE | Thermoplastic | 0.916–0.933 | 8.2–31.5 | 8.9–14.6 | 0.16–0.29 | 101–652 |
| PP | Thermoplastic | 0.91–0.92 | 31.1–41.5 | 31.1–41.5 | 1.15–1.56 | 101–602 |
| Polytetrafluoroethylene (Teflon) | Thermoplastic | 2.13–2.21 | 20.6–34.4 | – | 2.15–2.21 | 201–400 |
| PS | Thermoplastic | 1.03–1.05 | 35.8–51.6 | – | 2.27–3.29 | 1.1–2.4 |
| Polycarbonate | Thermoplastic | 1.19 | 62.6–72.3 | 62.4 | 2.37 | 111–151 |
| Nylon 6,6 | Thermoplastic | 1.12–1.14 | 75.7–94.3 | 44.6–82.7 | 1.57–3.82 | 14–305 |
| Polyester (PET) | Thermosetting | 1.28–1.41 | 48.2–72.2 | 59.2 | 1.28–1.42 | 32–301 |
| Phenolic (phenol–formaldehyde) | Thermosetting | 1.22–1.31 | 34.4–62.3 | – | 2.75–4.82 | 1.4–2.1 |
| Epoxy | Thermosetting | 1.12–1.18 | 41–84 | – | 2.2–5.4 | 4 |
| Vinyl ester | Thermosetting | 1.02–1.05 | 16–94 | – | 3–3.8 | 2.4–9 |

**Table 7** Advantages and disadvantages of thermoset matrix [56–59]

| Matrix | Advantages | Disadvantages |
|---|---|---|
| Polyester | Lowest cost and easy to use | The range of working times are limited, and high curing shrinkage |
| Epoxy | High mechanical and thermal properties, low curing shrinkage, high resistance to moisture absorption, and long working time ability | Expensive than vinyl ester, difficult to process, and corrosive amine hardener |
| Phenolic | High fire resistance | Difficult to process |
| Vinyl ester | Higher mechanical properties than phenolic and high environmental and chemical resistance | High styrene content, more expensive than phenolic, high curing shrinkage, and required post-curing for good mechanical properties |

**Table 8** Advantages and disadvantages of thermoplastic matrix [61]

| Matrix | Advantages | Disadvantages |
|---|---|---|
| PP | High dielectric resistance, high-temperature resistance, high fatigue resistance, and chemical resistance | Difficult to process, limited availability, and comparatively expensive |
| PE | Lightweight, excellent fatigue resistance, high impact resistance and ductility, low cost, and low moisture absorption | High thermal expansion, flammable and poor weathering resistance |
| PVC | Good chemical resistance, high impact resistance, flame retardant, good dimensional stability, versatility, and low cost | Poor resistance at high temperature and poor resistance to UV |
| PS | High resistance to stress cracking, low moisture absorption, weather resistance, and excellent chemical resistance | Low impact resistance, brittle and flammable |

resources [33]. Bio-based resins are obtained from plants (e.g., cellulose and starch) or through the polymerization of plant-based oils and sugars (e.g., polyethylene terephthalate, PP, and PLA) [52]. Bio-based resins are of three types: fully biodegradable, e.g., starch, PHA, partially biodegradable, e.g., PLA, cellulose, and non-biodegradable, e.g., bio-polypropylene, bio-polyethylene, and bio-polyethylene terephthalate [33, 52]. The advantages and disadvantages of bio-based resins are presented in Table 9. In 2011, approximately 236 million tons of petroleum-based polymers were produced, whereas the production of bio-based polymers was 3.5 million tons in the same year. The estimated growth rate of bio-based polymers production will reach 12 million tons annually by 2022 [33]. However, this amount is lower than the petroleum-based polymers production, and it is required to increase this amount to lower the adverse effect of petrochemical-based polymers on the environment. Fully biodegradable matrices contain regenerative carbon, which has been drawn from the atmosphere, followed by reverting to the environment as the polymer decays [52]. Bio-based resins like bio-polyethylene, bio-polyethylene terephthalate, and bio-polypropylene, which are chemically similar to petroleum-based resins, can be conventionally reprocessed [33]. Bio-based polymers offer various advantages over petroleum-based polymers: they are completely renewable, energy-efficient during production, safe (non-toxic), and environmentally friendly [62]. However, their production cost is 10–11% higher than petroleum-based resins [63].

## Challenges of using natural fibres as reinforcement

Presence of impurities on the fibre surface and water degradation are the biggest challenge associated with NFCs. Although there are various advantages of using natural fibre-based polymeric composites, there are also many negative aspects of using NFCs like moisture absorption, poor mechanical performance, and weak interfacial bonding between fibre and matrix [68–70]. The presence of impurities such as hemicellulose, lignin, pectin, and wax in natural fibres deteriorate its mechanical properties because the presence of these impurities on the fibre surface hampers the interfacial adhesion between matrix and reinforcing phase. Advantages and disadvantages of natural fibres in automotive applications are presented in Table 10. For instance, natural fibres are sensitive to moisture and temperature, which restricts their use to interior parts (e.g., door panels, trim in dashboards, seat cushions, parcel shelves, cabin lining, and backrests). Water degradation is the biggest challenge associated with NFCs. They absorb moisture in the external environment due to their hydrophilic nature. The main constituent in the natural fibre is hemicellulose, which absorbs moisture. The fibre shrinks when it dries and swells when it absorbs moisture, which ultimately results in cracks within the composites [71]. Absorbed water by fibres makes a bond with the $OH^-$ group of fibre, which weakens the interfacial bonding of matrix and fibre, causing poor mechanical properties of the composite [72]. In natural fibres, the amount of moisture content could be revealed in terms of moisture regain [73]. Thickness swelling of the composite samples is measured as per mathematical Eq. 8, water absorbency by Eq. 9 and moisture regain by Eq. 10 [74].

$$T_s = \frac{Tw - Td}{Td} \tag{8}$$

where $T_s$ represents thickness swelling, $T_d$ is the initial thickness swelling of sample before being immersed in water, $T_w$ is the final thickness of swelled sample after being immersed in water.

$$W_a = \frac{Ww - Wd}{Wd} \tag{9}$$

**Table 9** Advantages and disadvantages of bio-based resins [64–67]

| Matrix | Advantages | Disadvantages |
|---|---|---|
| PLA | High strength, high modulus and nontoxic | Poor impact strength and brittle in nature |
| Cellulose | Moderate impact resistance, low cost, abundant, moderate heat resistance, and ease to modify | Low decomposition temperature and high moisture absorption |
| PHA | Completely biodegradable, high molecular weight | Low decomposition temperature, brittle in nature, and low dimensional stability |
| Starch | Completely biodegradable and low cost | Difficult to process, brittle in nature, and water sensitive |

**Table 10** Advantages and disadvantages of natural fibres in automotive applications [78, 79]

| Advantages | Disadvantages |
|---|---|
| Low density leads to the mass reduction of 12–35% in automotive parts | Moisture absorption causes swelling of fibres |
| Higher specific mechanical properties than glass | Mechanical properties are lower than glass fibre composites, especially impact strength |
| Good acoustic and thermal insulating properties | The degradation process causes odour generation |
| Non-abrasive effect over metallic parts and screws | The maximum acceptable temperatures are limited as compared to glass fibre |
| Sustainable and renewable resource | Due to weathering and fungus attack relatively less durable |
| Low energy consumption (1/3 of glass fibres) | Price fluctuations due to agricultural policies |
| Biodegradable | High variability in properties |

where $W_a$ represents water absorbency, $W_d$ is the initial weight of sample before being immersed in water, $W_w$ is the weight of sample after being immersed in water.

The moisture regain is defined as the amount of moisture present in a dried material at standard conditions of humidity and temperature compared to the weight of dried material. The value of moisture regain must be known to evaluate the moisture regain or moisture absorption of natural fibres. Hence, the mathematical Eq. (10) to evaluate moisture regain for natural fibres can be given as

$$\mathrm{MR} = \frac{100MC}{(100 - MC)} \tag{10}$$

or

$$\mathrm{MR} = \frac{A}{B} \times 100\%$$

where MC represents the percentage of moisture content, MR is moisture regain; A is the mass of water, and B is the dry mass. The moisture absorption behaviour of NFCs limits their use for exterior parts of automotive. Several chemical treatment techniques are used to reduce the water absorption content and impurities present on the natural fibre surface and to enhance their mechanical properties. It was reported that lower moisture content in fibres results in higher mechanical properties of natural fibre-based composites [28, 75–77]. In the next section, surface treatment methods are reviewed.

## Surface treatment of natural Fibre

The main drawbacks of using natural fibres as reinforcement in composites include high moisture absorption by the fibres and poor adhesion at the matrix and fibre interface. The presence of non-cellulosic compounds such as hemicellulose, lignin, pectin, wax, etc., in natural fibres deteriorate its mechanical properties because the presence of these non-cellulosic compounds on the fibre surface hampers the interfacial adhesion between matrix and reinforcing phase. Therefore, modifications of natural fibres surface properties are necessary to improve their bonding with various matrices. There are two methods by which the surface of natural fibres can be modified to enhance the adhesion at the matrix and fibre interface.

1. Physical method
2. Chemical method

### Physical treatment method

The surface conditions of natural fibres are changed by physical treatment methods without influencing their chemical composition. Physical treatments involve laser treatment, argon treatment, heat and plasma treatment [80]. The advantages of using physical treatments over chemical treatment methods are improved mechanical, thermal, and physical properties of surface-modified natural fibres. Nowadays, the scientific community gives more preference to chemical treatment methods over physical treatment methods because physical treatment methods are expensive than chemical treatment methods [81].

**Table 11** Recent works on the effect of alkaline-treated fibre-reinforced polymeric composites on thermal and mechanical properties [96–99]

| Fibre-matrix composites | Treatment methods | Effects on thermal and mechanical properties |
|---|---|---|
| Hemp fibre | 8% NaOH treatment | 5% increment in thermal stability was observed |
| Coir-polyester | 5% NaOH treatment for 70 h | Impact and flexural strength was increased by 50% as compared to the untreated fibre-reinforced composites |
| Sisal-polyester | 0.5%, 1%, 2%. 4%, 8% NaOH treatment at ambient temperature | Maximum tensile strength was reported for 4% alkaline-treated sisal-polyester composite |
| Flax-epoxy | Alkaline treatment | 28% increment in tensile modulus and strength with the removal of wax and pectin |
| Jute-vinyl ester | 6% NaOH for 5, 7, and 9 h | 5 h alkaline-treated fibre-reinforced composite accounted for 20% and 19% increase in interlaminar shear strength and flexural properties |

## Chemical treatment methods

The main problem with NFRC arises from the hydrophilic nature of the fibre and the hydrophobic nature of the matrix. The incompatibility between natural fibre and polymer matrix results in poor interfacial bonding. The hydrophilicity of reinforcing natural fibres can be reduced by giving chemical treatments, which improves interfacial adhesion with the matrix phase [82, 83]. Much research has been conducted to enhance the interfacial adhesion between the matrix and reinforcing phase through various chemical treatments. Various chemical treatment methods used in order to reduce the hydrophilic nature of the fibre and their effects on composite properties are presented as follows.

(i) Alkaline treatment
(ii) Silane treatment
(iii) Acetylation
(iv) Maleated coupling
(v) Benzoylation treatment
(vi) Enzyme treatment

### *Alkaline treatment*

In the alkaline treatment method, natural fibres are treated with sodium hydroxide (NaOH) solution so as to remove non-cellulosic compounds such as lignin, pectin, hemicellulose, wax, and oils which are covering the outer surface of the fibre cell wall and hence modify its cellulosic molecular structure when used to reinforce with thermosets and thermoplastics. Alkaline reaction on fibre is given in Eq. 11 [84]. This treatment can be done in four different ways, such as (a) taking different concentrations of NaOH solution for a different period of time [85], (b) keeping constant NaOH solution concentration for a different period of time [86–88], (c) using constant NaOH solution concentration for a constant time period [89–91], (d) using different NaOH solution concentration for a constant time period [92]. The first and second methods are the most commonly used treatments to evaluate the most favourable states for natural fibre modification. By using different NaOH solution concentrations for a constant time period, the natural fibres need to be treated with NaOH solution (2%-6% by wt./ by vol.), maintaining temperature around 24 °C for a constant period of time that permits to eradicate lignin, hemicellulose, and wax. After this chemical treated process, the fibres are dried, neutralized, and cleaned [92, 93]. By using constant NaOH solution concentration for different time periods, the fibres are treated with NaOH solution (5% by wt./ by vol.) by varying the time (i.e., 16, 31, 45, 65, 75, and 95 min.) [86, 87, 94]. After this chemical process, the treated fibres are cleaned with deionized water by incorporating a few drops of 0.2 N hydrochloric acid to separate the surplus impurities [85, 88, 95]. Table 11 summarizes the effect of alkaline treatment on the thermal and mechanical performance of composites.

$$\text{Fibre} - \text{OH} + \text{NaOH} \rightarrow \text{Fibre} - \text{O} - \text{Na} + \text{H}_2\text{O} \quad (11)$$

### *Silane treatment*

The hydrophilic nature of the fibre is associated with the surface energy of fibres. Some investigations reported the methods to decrease the hydrophilic nature of fibre. Silane acts as a coupling agent, a multifunctional molecule used to modify the surface of fibre [100–103]. The aminopropyl triethoxy silane and vinyltrimethoxysilane are the commonly used silanes that may contribute hydrophilic properties to the interface [104–106]. In this treatment, the ethanol–water mixture is mixed with some amount of vinyltrimethoxysilane or aminopropyl triethoxy silanes in the ratio (2:3). Keeping the pH value of this solution at 4, acetic acid is added, followed by keeping this solution for 1 h. The fibres or fabric were immersed in the above solution for 3 h then the treated fibres or fabric was dried for 8 h at 65 °C [107–109]. Natural fibres possess micro-pores or voids on their surface. Silane coupling agents act as a surface coating. This coupling agent penetrates into the voids, or micropores and hence interlocked coatings are developed on the fibre surface. It was reported that silane-treated NFRC exhibit superior tensile properties than the alkaline-treated NFRC [110]. Silane reactions on fibre are given in Eqs. 12 and 13 [84]. The researcher investigated the silane effect (1% oligomeric siloxane with 97% alcohol solution for 2 h) and alkali (5% NaOH for 2 h) treatments on flexural strength of jute polyester and jute epoxy composites. Results showed that for jute polyester composites with silane treatment, strength and modulus properties were enhanced by 20% and 8%, respectively, as compared to the alkaline treatment alone. It was also reported that tensile strength and modulus were increased by 12% and 7% for the similar treatments compared to the alkali treatment alone [111]. The surface of the kenaf fibre and its interfacial adhesion with the PS matrix was modified by using a silane coupling agent. The condensation reaction between alkoxysilane and hydroxyl network of kenaf cellulose improved interfacial adhesion between fibre and matrix phase. Due to the kenaf fibre modification, kenaf/PS-based composites exhibited lower tan δ and higher storage modulus than those with untreated fibre [112]. Similarly, the coir fibres and oil palm empty bunch of fruits were treated with silane coupling agents by Ismail et al. [113, 114]. It was reported that the tensile strength, modulus, fatigue life, hardness and tear strength of coir fibre and oil palm empty fruit bunch (OPEFB) reinforced natural rubber and polyester composites were enhanced. Two types of flax fibres (flax pulp and natural flax) were used as a reinforcing phase with PP matrix to fabricate flax/PP composites. The flax fibres were treated with maleic anhydride-polypropylene copolymer (MAPP) and maleic anhydride (MA). These treatments reduced the polar component of the surface energy of the flax fibre. It was observed that MAPP-treated Flax/PP-based composites exhibited the highest mechanical properties, while the MA-treated fibres obtained similar results to those of the untreated ones [115]. Table 12 summarizes the effect of silane chemical treatment on the mechanical performance of NFRC.

$$\mathrm{CH_2CHSi(OC_2H_5)_3} \xrightarrow{\mathrm{H_2O}} \mathrm{CH_2CHSi(OH)_3} + \mathrm{3C_2H_5OH} \tag{12}$$

$$\begin{aligned}&\mathrm{CH_2CHSi(OH)_2O} + \mathrm{Fibre} - \mathrm{OH}\\ &\quad\rightarrow \mathrm{CH_2CHSi(OH)_2O} - \mathrm{Fibre} + \mathrm{H_2O}\end{aligned} \tag{13}$$

### *Acetylation*

Acetylation is another chemical method of fibre treatment that replaces the hydroxyl ($OH^-$) group of natural fibre with the acetyl group and makes them more hydrophobic. The main motive of this treatment is to coat the $OH^-$ groups of natural fibres and make them hydrophobic in nature. As a result, the hydrophilicity of the fibre was reduced by enhancing the dimensional stability of the NFRC [119]. Moreover, this chemical treatment makes the fibre surface rough with fewer voids that give better interfacial adhesion with the matrix [96, 120]. In this treatment, the cellulose structure of fibre is grafted with and without a catalyst by an acetyl group. In general, acetic anhydride and acetic acid do not react adequately with the fibres. Initially, fibres are immersed in acetic anhydride and consequently acetic acid for 1–4 h with higher temperature. Acetylation reactions on fibre with and without catalyst are given in Eqs. 14 and 15 [121]. Acetylation on alkaline pretreated (5% and 10% NaOH concentration solution for 2 h at 280 °C) sisal fibre was performed, which reported improvement in fibre-matrix interfacial bonding of the composites [122]. Acetylation treatment with unlike concentration of catalyst on flax fibre was studied. Damage in the fibres was observed when more than 0.054% catalyst was used during acetylation. The hydrophilicity of the flax fibre was decreased by using a higher degree of acetylation. It was also noted that the flexural and tensile properties of flax fibre-reinforced polymeric composites were enhanced by using an 18% degree of acetylation [80]. Seena et al. [123] studied the acetylation-treated

**Table 12** Recent works on the effect of silane-treated fibre-reinforced polymeric composites on mechanical properties [110, 116–118]

| Agents used | F/M | Quantity | Results |
|---|---|---|---|
| NaOH + methoxy-ethoxy silane + dicumyl peroxide | Henequen/HDPE 20/80 | 2% + 1% + 0.5% | Increase in tensile strength by 23% |
| NaOH + amino silane | Pineapple/PLA 40/60 | 5% + 5% | Increase in tensile modulus and impact strength by 45% and 86%, respectively |
| Amino silane | Pineapple/PLA 40/60 | 5% | Increase in tensile modulus and impact strength by 27% and 47%, respectively |
| NaOH + methoxy-ethoxy silane | Henequen/HDPE 20/80 | 2% + 1% | Increase in tensile strength by 23% |
| Glycidoxypropyl silane | Kenaf/PLA 60/40 | 4% | Increase in tensile strength parallel to fibre axis by 20% and increase in tensile strength perpendicular to fibre axis by 20% |

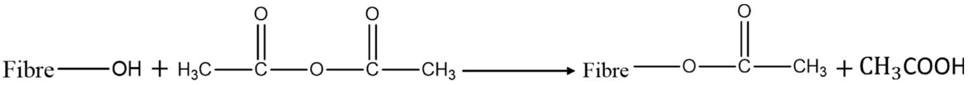
abaca fibre-reinforced PF composites and the results revealed an improvement in the tensile strength, modulus, and impact strength as compared to untreated abaca fibre-reinforced composites. In another study, acetylation treatment was applied to remove non-crystalline constituents of the banana fibres, and improved adhesion between the fibre and matrix interphase was observed. Moreover, the tensile properties of the composite were enhanced, but the tensile property of the fibre itself was not significantly improved [25]. Zafeiropoulos et al. [124] investigated the influence of acetylation at the interface of flax fibre/PP-based composites and reported improved surface topography and stress transfer from matrix to fibres in the composite. In another study, the weight of the natural fibres (up to about 16.6%) was increased due to acetylation treatment, which completely changed the bulk properties of the natural fibre itself [125]. Table 13 summarizes the influence of the acetylation treatment method on the mechanical performance of NFRC.

### *Maleated coupling*

The maleated coupling method is widely used to make natural fibres hydrophobic in nature. MA is used to modify the surface of fibre so as to achieve better interfacial adhesion in between fibre and matrix phase, which results in better mechanical properties of composites. In this process, MA removes the $OH^-$ groups from the amorphous region of the cellulose network to make it compatible with the polymeric resin. This makes the fibre surface coated, by reducing its hydrophilicity. Therefore, carbon–carbon covalent bond formation takes place between the anhydride groups of the maleic agent and $OH^-$ groups of fibre by maleated coupling agent. This covalent bond makes a bridge interface, which improves bonding at the interface of fibre and polymeric matrix [128]. For instance, the polypropylene chain makes the maleic anhydride coupler to be cohesive by the treatment of cellulose structural fibres with hot MAPP copolymers that makes a covalent bond at the interface. The reaction of MAPP

$$\text{Fibre} - \text{OH} + \text{CH}_3\text{COOH} \xrightarrow[\text{Conc.}\,\text{H}_2\text{SO}_4]{(\text{CH}_3\text{CO})_2\text{O}} \text{Fibre} - \text{OCH}_3 + \text{H}_2\text{O} \qquad (14)$$

**Acetylation with an acid catalyst**



$$\text{Fibre}-\text{OH} + \text{H}_3\text{C}-\overset{\displaystyle O}{\overset{\|}{\text{C}}}-\text{O}-\overset{\displaystyle O}{\overset{\|}{\text{C}}}-\text{CH}_3 \longrightarrow \text{Fibre}-\text{O}-\overset{\displaystyle O}{\overset{\|}{\text{C}}}-\text{CH}_3 + \text{CH}_3\text{COOH} \qquad (15)$$

**Acetylation without acid catalyst**

**Table 13** Recent works on the effect of acetylation-treated fibre-reinforced polymeric composites on mechanical properties [80, 123, 126, 127]

| Agents used | F/M | Quantity | Results |
|---|---|---|---|
| NaOH pre-treated + acetic acid | (a) Banana fibre<br>(b) Banana/PF | 4% for 2 h + 50% for 5 min | (a) Decrease in tensile strength and modulus by 27% and 80%, respectively<br>(b) Increase in tensile strength and modulus by 36% and 800%, respectively |
| Acetic anhydride | (a) Flax/PP 5% fibre | 18% | (a) Increase in tensile strength and modulus by 35% and 20%, respectively |
| NaOH pre-treated + acid acetic | (a) Cellulose/PP (10% fibre)<br>(b) Cellulignin/PP (10% fibre) | For 1.2 h + (470 g for 95 g fibre, additional 170 g acetic acid) | (a) Decrease in tensile strength and flexural strength by 1% and 1.25%, respectively<br>(b) Decrease in tensile strength and flexural strength by 1.01% and 1.14%, respectively |
| NaOH pre-treated + acetic acid | (a) Banana/phenol formaldehyde | 5% for 3 h + 50% for 5 min | (a) Increased tensile strength in outdoor weathering and soil burial by 56% and 75%, respectively |

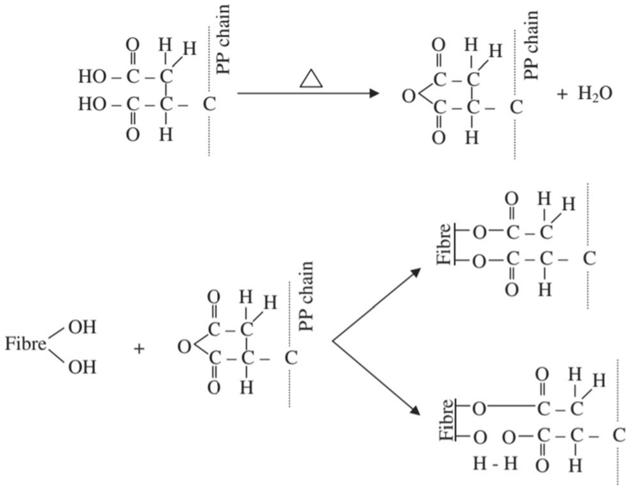


**Figure 8** The reaction mechanism of cellulose structural fibre with MAPP copolymer. Adapted with permission from [23]. Copyright 2012, Elsevier.

and the cellulosic structure of fibre (shown in Fig. 8) can be explained by esterification of cellulose structure of fibre and activation energy of the copolymer at 180 °C. This fibre surface modification method improves wettability and bonding between the fibre and polymeric matrix at the interface [129]. Mohanty et al. [130] used 0.5% MAPP as a coupling agent impregnated in toluene for 5 min with jute fibre (6 mm fibre length with 30% fibre loading) reinforced in PP matrix. It was reported that the treated jute/PP composite revealed 72.2% higher flexural modulus as compared to the untreated fibre-reinforced composites. In addition, the hydrophilic tendency of the treated fibre was also reduced. In another study, Mishra et al. [131] studied that maleated coupling treatment reduced hydrophilic content to a large extent in abaca, sisal, and hemp fibre-reinforced composites. Results showed higher hardness, young's modulus, flexural modulus, and impact strength of NFRC as compared to untreated fibre composites. Yang et al. [132] studied the effects of MAPP coupling agent on rice-husk/PP composites. It was reported that the increment in filler loading rate decreased the tensile strength of the composite, but by incorporating MAPP coupling agent, the tensile strength of the composite was improved and izod impact strength of both notched and unnotched specimens remained almost the same. In addition, the positive effect of a coupling agent on bonding between fibre and matrix across interfaces was revealed by the morphological study. The effects of 1% MAPP coupling agent on sisal fibre-PP composites were evaluated by Mohanty et al. [133]. It was reported that tensile, impact and flexural properties were enhanced by 50%, 58% and 30%, respectively. Keener et al. [128] suggested that 3% was the optimum amount for using maleated coupling agents on flax and jute fibres. Table 14 summarizes the effect of maleated treatment on mechanical performance of NFRC.

**Table 14** Recent works on the effect of maleated coupling treated fibre-reinforced polymeric composites on mechanical properties [134–137]

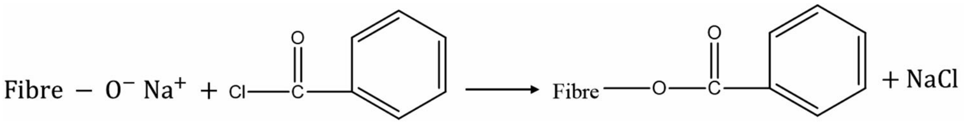
| Agents used | F/M | Quantity | Results |
|---|---|---|---|
| Maleated anhydride polyethylene (MAPE) | (a) Bamboo/HDPE 29.5/68.8 | 1.7% | (a) Increase in tensile strength and modulus by 30% and 5%, respectively |
| | (b) Bamboo/HDPE 29/67.5 | 3.5% | (b) Improved in tensile strength by 44% and decrease in tensile modulus by 18% |
| MAPP | (a) Aspen/PP 30/68 (25 °C) | 2% | (a) Increase in tensile strength and flexural strength by 32% and 19%, respectively |
| MAPE (226D) | (a) Thermomechanical pulp/HDPE 48/50 | 3% | (a) Increase in tensile strength and modulus by 58% and 11%, respectively |
| MAPP | (a) Hemp/PP 30/66 | 4% | (a) Increase in tensile strength, modulus and flexural modulus by 36%, 58% and 44%, respectively |

### *Benzoylation treatment*

Benzoylation process makes use of benzoyl chloride solution to lower the moisture absorption in the fibre cell wall, resulting in better adhesion at the fibre and matrix interface, increased composite strength and enhanced thermal stability of the natural fibre [96, 138]. During this treatment, alkaline pre-treated fibres are used. Benzoyl is responsible for extracting materials such as lignin, hemicellulose, waxes and oil covering materials from plant cellulosic structure, and a large number of $OH^-$ groups are exposed on the natural fibre surface. During this process, the benzoyl group replaced the $OH^-$ group of the natural fibre and coupled with the cellulosic structure of the fibre (shown in Eq. 16) [139]. This resulted in decreased hydrophilic tendency of the treated fibre and improved interfacial bonding with the hydrophobic matrix [96]. Joseph et al. [140] used benzoyl chloride to decrease hydrophilicity of alkali pre-treated sisal fibre, and results revealed that the thermal stability of treated fibre composites was improved as compared to the untreated fibre-reinforced composites. Wang et al. [141] investigated similar treatment on flax/PP composites, and results revealed that the tensile strength of the treated flax fibre-reinforced composites was enhanced by 6%. In addition, the positive effect of a benzoylation treatment on interfacial bonding between matrix and fibre was revealed by the morphological study.

### *Enzyme treatment*

Enzyme treatment is widely used to make natural fibre hydrophobic in nature. Enzyme treatment is used to extract materials such as lignin, waxes and oil covering materials from plant cellulose structure by the action of enzymes. White rot enzyme produces oxidase enzymes that react with wax and lignin parts of the natural fibre. This results in removal of the non-cellulosic constituents from fibre. It also enhances hemicellulose solubility and thus makes the fibre hydrophobic in nature. Furthermore, enzymes produce hyphae, which creates micropores on the surface of fibre and makes a rough interface for better adhesion between the fibre and matrix across the interface [142, 143]. In this treatment process, the fibres are degummed while improving the fineness, homogeneity, softness and cleanliness. This treatment is completely environment friendly and efficient. The process is rapid but exquisite over other chemical treatment processes since it should be performed at 100 °C below atmospheric pressure with a pH of 5–9, while the addition of ethylenediaminetetraacetic acid (EDTA) to fungi mixtures can enhance the effectiveness of this process [144]. Bledzki et al. [145] studied the effect of enzyme treatment on abaca/PP composites using fungamix and reported 46% increment in tensile strength. Furthermore, the



(16)

tensile strength was enhanced up to 41% using MAPP coupling agent at the same conditions. Pickering et al. [142] studied the effect of enzyme treatment on hemp/PP composites and reported 22% increment in composite strength as compared to untreated fibre. In addition, enzyme-treated hemp/PP composite showed 33% improvement in composite strength over alkali-treated fibres. When fungi treatment was given with a pre-treatment using ethylene diamine tetramethylene phosphoric acid, more amount of lignin, wax, hemicellulose, and other non-cellulosic components were separated from hemp fibre [134, 146]. In addition, 270% increment in the porosity of the hemp fibres with deterioration in mechanical properties was observed [147].

## Biodegradation mechanisms in NFCs

In NFCs, the polymer contains a carbon or hetero-chain backbone. Chemical hydrolysis, or enzyme-catalyzed hydrolysis, is the method of degradation for hetero-chain backbone polymers [148]. The hydrolytic enzymes generated by physico-chemical characteristics of the polymer and microorganisms are the major factors in hydrolytic biodegradation. Polymer biodegradation process can occur up to a month using this method [149]. The hydrolytic biodegradation process of polymers can be restrained by using chemicals or additives in order to use for several practical applications. Some natural biopolymers such as proteins and polysaccharides, plant-derived polymers like polybutylene succinate (PBS), and PLA and microbially derived polymers such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) undergoes hydrolytic biodegradation [148]. Chemical bonding, thickness, co-polymer type, and morphology may affect the hydrolytic degradation rate under enzyme-mediated or non-enzyme-mediated conditions. When comparing the biodegradation of carbon chain and hetero-chain polymers, the carbon-chain backbone polymer takes longer time to decompose [148]. Chemical oxidation is the mechanism through which carbon backbone polymers degrade. Some natural biopolymers such as lignin, and natural rubber undergoes oxidative biodegradation. The oxidative biodegradation process of polymers may take several years, which is significantly longer than hydrolytic biodegradation.

## Processing methods

The processing methods used for fabricating NFRC are mostly determined by the polymer matrix employed. Moisture, fibre type, fibre volume fraction, and composite temperature are the primary factors that influence the processing of NFCs. The natural fibre must be free of moisture and the required surface treatment of fibre must be performed if fibre contains moisture [33]. Processing methods such as compression moulding, extrusion moulding, injection moulding are suitable for thermoplastic matrices. Processing methods such as hand lay-up, resin transfer moulding, vacuum-assisted resin transfer moulding are suitable for thermoset matrices.

### Processing methods for thermoplastic based composites

#### *Injection moulding*

Injection moulding is the most prevalent method for mass-producing composites. This technique begins with the polymers being placed in the hopper as pellets or granules and being heated until molten. The molten ingredients are then injected into and held in a chamber produced by a split die mould. Before opening the mould, the molten material is chilled down to solidify [150].

#### *Compression moulding*

Since the 1990s, compression moulding has been employed to make thermoplastic composites as the demand for lightweight, high-performance materials has grown [33]. Composite is made by mixing the reinforcement and matrix in the metallic mould of required shape and size [151]. The compression mould is made up of two parts: a stationary bottom plate and a moveable upper plate. Moulds are available in different shape and size, or it may also fabricate as per the intricacy of the profile which needs to be developed. After putting the sample in the mould, mould is placed between the two heating platen, which are set to the required temperature and pressure as per the matrix materials used during the process [152]. The curing procedure is carried out at ambient temperature, and the composite is taken out of the mould [33]. Compression moulding is used to make vehicle body panels and structures that are thin, lightweight, and strong.

### *Extrusion*

Extrusion is a high-speed processing method that is commonly used to make thermoplastic polymer composites [153]. This processing method is chosen because of the high strength and stiffness of the composite, as well as the ease with which the composites may be formed [33]. During this process, the polymer material in the form of granules or pellets are fed into a hopper of an extruder. A single screw or twin-screw extruder can be used. The melt flows into the extruder's barrel and is forced out via a die to form the required shape [151, 154, 155]. Extrusion is a fully automated, continuous fabrication technique. Delivery rate, Pressure, and temperature are all critical parameters. Any air trapped between the grains is extruded out [151].

## Processing methods for thermoset based composites

### *Hand lay-up*

Hand lay-up is the common, easiest, and least expensive method of manufacturing composites [156]. In this method, a release agent is first applied to an open mould as an anti-adhesive agent, and then the fibres are placed in the mould. Resin is poured and brushed onto the fibres with a roller or brush. Layer upon layer of lay-up is building until the desired thickness is achieved. Squeegees or rollers are used to remove trapped air in the laminate. The laminates are then allowed to cure in atmospheric conditions [157].

### *Resin transfer moulding*

In resin transfer moulding (RTM) method, instead of pouring the polymer into an open mould, the resin is preheated and loaded into the holding chamber [158]. This method is suitable for fabricating of large components in medium-volume production. The process diagram of RTM method is shown in Fig. 9 [159]. The resin is injected to impregnate the preform after the textile fabric layers are placed in the solid mould. Vacuum is frequently utilized to prevent air bubbles and help in the drawing of resin into the cavity [160].

### *Vacuum assisted resin transfer moulding (VARTM)*

VARTM method is modified version of RTM method in which top mould is replaced with vacuum bagging [161]. In this process, resin flow is assisted with vacuum to maintain the atmospheric pressure for curing of the specimen. Basic accessories used in VARTM method includes peel ply, mesh, spiral, vacuum bag and sealant tape. In this process, preform is first placed on bottom mould of required shape and size, then the flexible tool face is forced down over the composite object. Mesh which is placed above the peel ply controls and limits the flow of resin. Spiral tube is used to guide the flow of resin through the fibre preform. The liquid resin is pumped into the mould at a moderate pressure, suturing the fibres. A vacuum can be applied to the mould to reduce air pockets and improve the

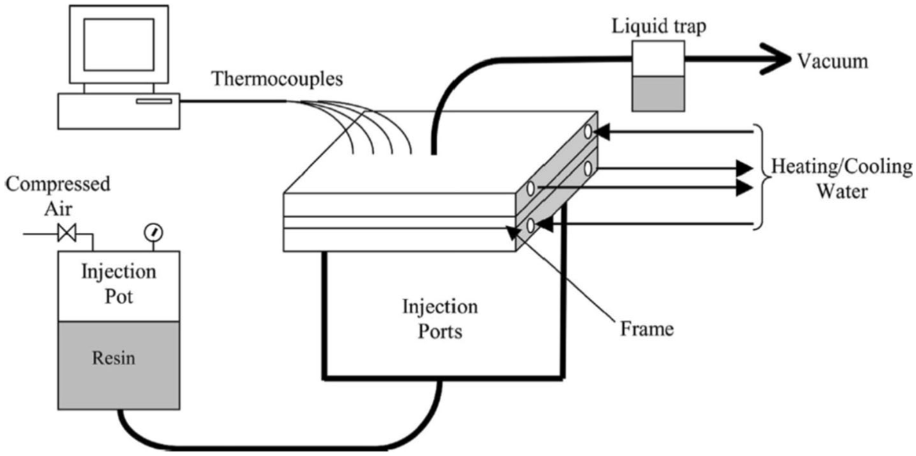


**Figure 9** Process diagram of RTM method for composite manufacturing. Adapted with permission from [159]. Copyright 2014, Elsevier.

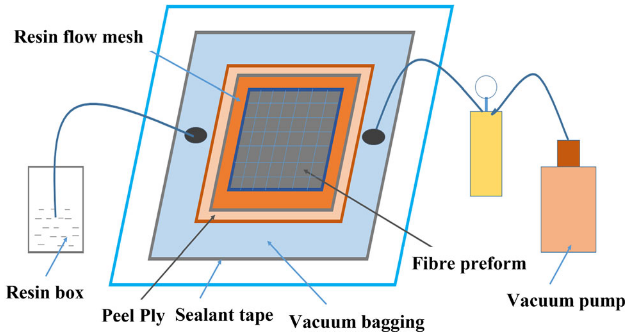


**Figure 10** Schematic diagram of VARTM.

composites quality [162]. Figure 10 illustrates a typical setup used for VARTM method.

## Morphology

Optical microscope and SEM are the major approaches to study the morphology of composites. SEM gives detailed information on the topography and composition of composites at the micro-scale through high magnification level whereas optical microscopy is appropriate for general inspection [163]. The morphology of NFCs has been studied extensively. This review article includes some of these studies. The morphological study of unidirectional bamboo/epoxy composites fabricated by compression moulding method with a combination of heat and pressure was studied through optical microscopy by Hebel et al. [164]. Optical micrographs of the fractured surface of composite fabricated at 100 °C and pressures of 15, 20, and 25 MPa are shown in Fig. 11a-c [164]. The results revealed that the composites fabricated at a pressure of 20 MPa have smooth surface, homogenously covered by matrix and higher tensile strength than 15 and 25 MPa. Due to its viscosity, the polymer network forms a thin layer at this pressure that effectively interacts with the fibre surface and penetrates into the fibre. Furthermore, the reduction in the homogenous coverage and wettability of fibres occurs by lowering the pressure to 15 MPa. The epoxy resin formed crystalline beads larger at 25 MPa than at 15 MPa, and infiltration was hindered by propagating carbonization of the fibres. The morphology of chopped kneaf/PLA composites fabricated by melt mixing method using SEM was studied by Pan et al. [163]. SEM micrographs of neat PLA and a composite of 30 wt.% kenaf fibre are shown in Fig. 12 [163]. Because of the brittleness of the resin, the fractured surface of neat PLA was uneven and rough. The interfacial adhesion between the fibre and matrix (shown by "A") was good, but many fibres were damaged during tensile testing as shown in Fig. 12. Some fibres in the fabricated composite (shown by "B" in Fig. 12) fractured in the matrix during tensile deformation, showing that the interfacial adhesion between the fibre and matrix further improved. Because of the rough surface of the kenaf fibre and high viscosity of PLA, agglomeration of kenaf fibres (shown by "C") and the presence of tiny voids (shown by "D") are also visible in Fig. 12. Pothan et al. [165] investigated the effect of the different fibre percentage on the morphology of chopped banana/polyester composite fabricated by compression moulding method through SEM. SEM micrographs of composites with different fibre content (10, 20, and 40 wt.%) are shown in Fig. 13a-c. The results revealed that fibre-matrix bonding was good in the composite with 40 wt.% fibre content, but fibre-matrix debonding was clearly visible in the composites with 10wt.% and 20wt.% fibre content. In addition, there was no voids and strong interfacial bonding between fibre and matrix in composite specimen (40 wt.% fibre content) was observed. However, when the fibre content was reduced, the accumulation efficiency of fibres was not high, which makes the interface area prone to bonding failure.

## Simulation and modelling of bio-composites used for automotive

### Analytical models

Due to different parameters, such as the type of resin and fibre used, the microstructure and composition of fibre, the fabricating method and the expected application, the modelling of the mechanical properties of bio-composites is considered a very complicated process [166]. The mechanical properties of bio-composites with chopped fibres have been predicated using six analytical models: rule of mixture, Hirsch model, Bowyer Bader model, series and parallel, Halpin–Tsai model, and shear model [167]. Micro-defects in the matrix and the fibre/matrix interface are not taken into account in these models. The prediction of the tensile strength and Young's modulus of unidirectional jute/epoxy composite fabricated by resin infusion moulding method using

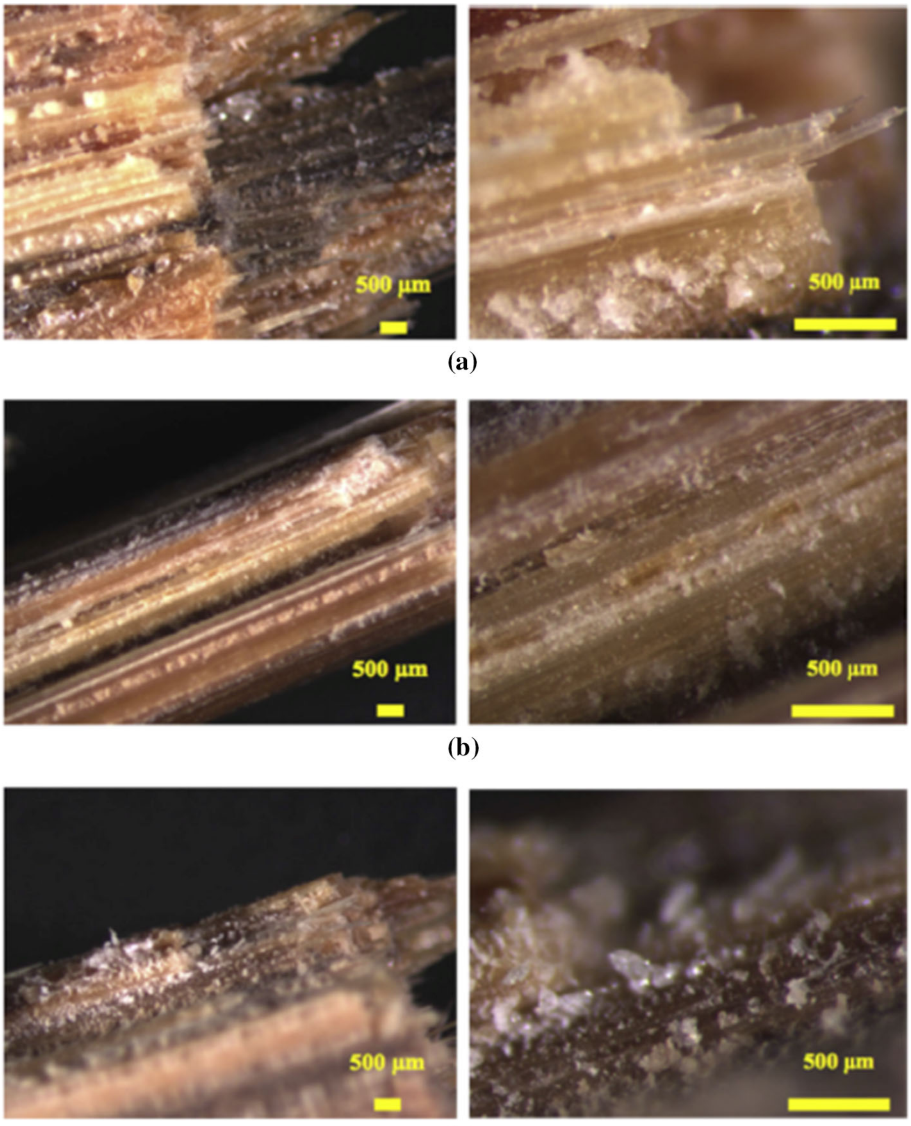


**Figure 11** Optical micrographs of the fractured surface of bamboo/epoxy composites fabricated at 100 °C and pressures of **a** 15, **b** 20, and **c** 25 MPa. Adapted with permission from [164]. Copyright 2014, Elsevier.

rule of mixture model was investigated by Virk et al. [168]. The author reported that measuring the cross-sectional area of fibres by linear measurement of fibre diameter and assuming a circular cross section of fibre would results in an overestimation of cross-sectional area and diminishing the mechanical properties of jute fibre was observed. The author suggested a fibre area correction factor (FACF) for predicting the composites tensile strength and Young's modulus accurately. Kalaprasad et al. [169] compared Hirsch, Halpin–Tsai, series and parallel, Bowyer–Bader, and shear lag models to predict tensile properties of chopped sisal/low-density polyethylene composites fabricated by injection moulding method. The author reported that except for the series and parallel model, all models exhibited good accord with experimental longitudinally chopped composite Young's modulus and tensile strength. In addition, Bowyer–Bader and Hirsch models were also shown to be in good accord with experimental results of chopped composites. Migneault et al. [170] used the Halpin–Tsai equation and the shear lag model to predict the Young's modulus of chopped pulp/high-density polyethylene composites fabricated by injection moulding method, and found that the predictions with an orientation factor in the modelling were in good accord with the experimental results. The prediction of the tensile strength of hemp/polypropylene composite fabricated by injection and extrusion moulding method using Bowyer–

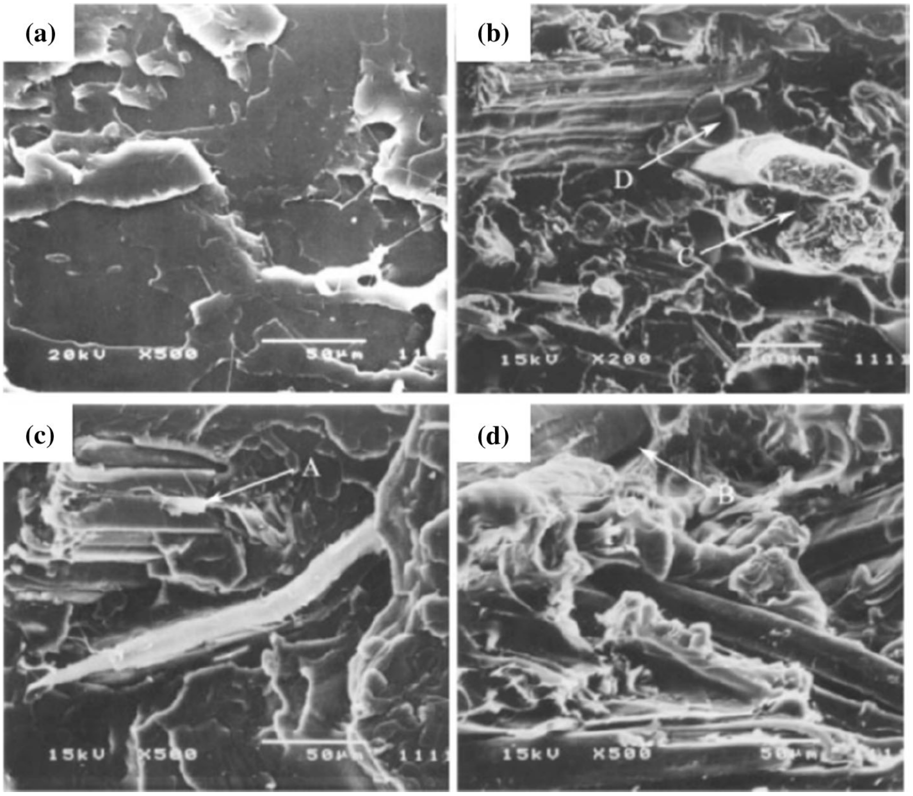


**Figure 12** SEM micrographs of fractured surface of neat PLA and chopped kneaf/PLA composite fabricated by melt mixing method with magnification of **a** 500x, **b** 200 × **c** 500x, and **d** 500x. Adapted with permission from [163]. Copyright 2007, John Wiley and Sons.

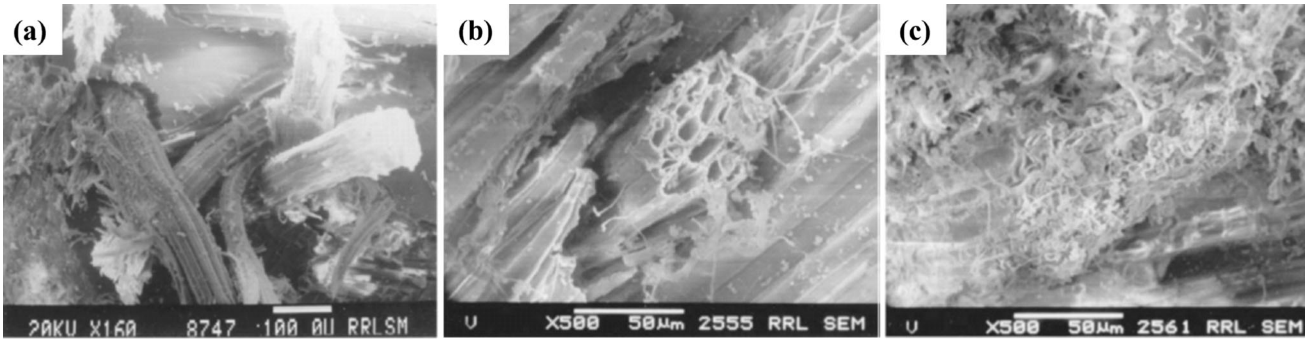


**Figure 13** SEM micrographs of chopped hemp/polyester composite fabricated by compression moulding method with fibre content of **a** 10 wt.%, **b** 20 wt.%, and **c** 40 wt.%. Adapted with permission from [165]. Copyright 2003, Elsevier.

Bader model was investigated by Beckermann and Pickering et al. [171]. The author reported that in predicting the mechanical properties of bio-composites, fibre aspect ratio (AR) and orientation are two key parameters to be considered. Facca et al. [172] used the Halpin–Tsai equation, rule of mixture, and the shear lag model to predict the Young's modulus of chopped hemp/HDPE composites fabricated by compression moulding method, and found that Halpin–Tsai model predicted Young's modulus more accurately than other models because the efficiency factor (EF) is generally derived from experimentally measurements of the material to be modelled in the Halpin–Tsai equation. Munde and Ingle et al. [173] compared Hirsch model, Bowyer–Bader, and Halpin–Tsai equation to predict Young's modulus and tensile strength of chopped coir/polypropylene composites fabricated by compression moulding method. The author reported that the Hirsch model predicted Young's modulus and tensile strength more accurately than other models.

## Simulation by finite element method (FEM)

The finite element analysis has been used to simulate the properties of bio-composites, because it can constructively investigate the influence of various parameters, such as the type of reinforcement, the fibre aspect ratio, volume fraction of fibre, and the fibre orientation on the performance of bio-composites [174]. Representative volume element (RVE) has been considered to predict the mechanical performance of composite materials as the most effective homogenization-based multi-scale approach for mechanical characterization of composites. To simulate bio-composites with chopped fibres, two RVE methods were used: orientation averaging and direct RVE. A single fibre is embedded in the matrix (as a unit cell) in the orientation averaging method, whereas the matrix is surrounded by number of fibres in the direct RVE approach. The mechanical properties of bio-composites with chopped fibres have been predicted using FEM approach in a few research. The prediction of the Young's modulus of flax/polypropylene composite fabricated by extrusion moulding method (shown in Fig. 14) using RVE orientation averaging approach was investigated by Modniks and Andersons et al. [175]. They used five loading nodes to obtain the composite's elastic constants, assuming that the unit cell is transversely isotropic. The results showed that the modelling approach were in a good accord with experimental results of chopped composites. Sliseris et al. [176] simulated the tensile properties of chopped flax/polypropylene composites with 3D RVE approach by considering the effect of voids, bundles, and fibre aspect ratio. PP matrix and flax fibre were modelled as nonlinear plastic material and linear isotropic elastic material, respectively. To analyse the effect of fibre defect in the simulation, they modelled (shown in Fig. 15) the interface between the fibres and the fibres using continuum damage mechanics approach.

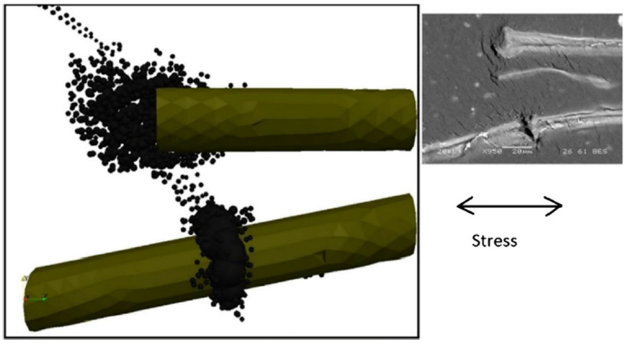


**Figure 15** Simulation of the tensile properties of chopped flax/PP composite using 3D RVE approach considering the plastic deformation starts at the end of the fibre and around the fibre defect. Adapted with permission from [176]. Copyright 2016, Elsevier.

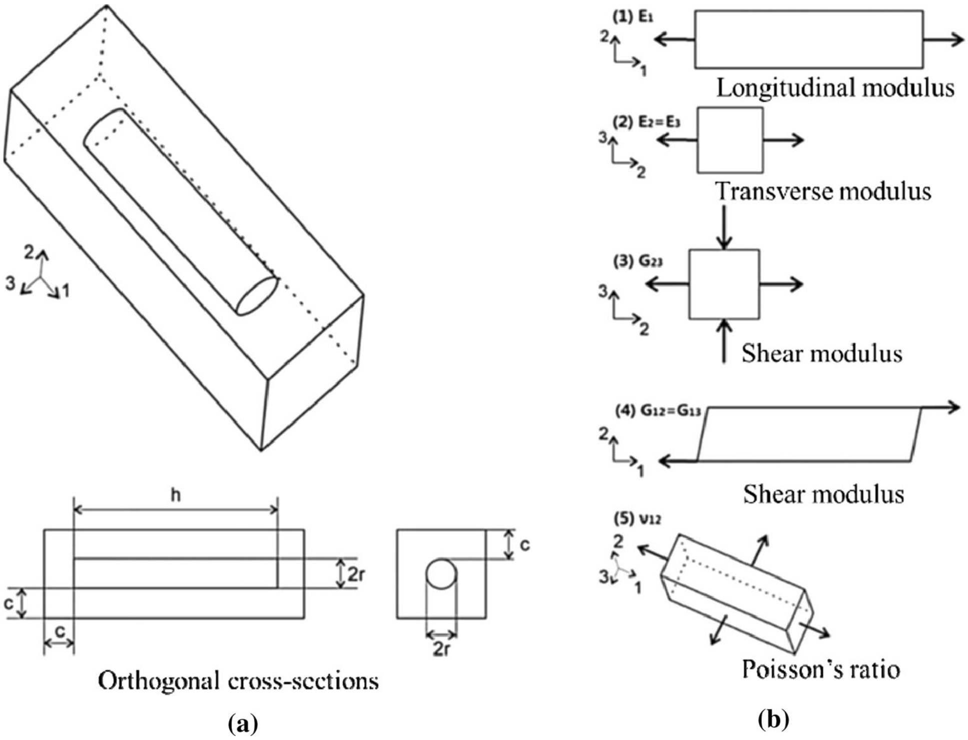


**Figure 14** Schematic diagram of **a** a single fibre is embedded in the matrix (as a unit cell) and **b** prediction the young's modulus using the RVE orientation averaging approach. Adapted with permission from [175]. Copyright 2010, Elsevier.

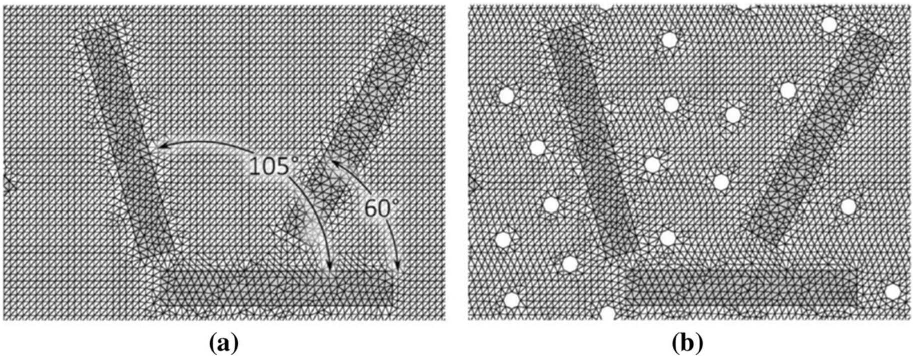


**Figure 16** In a 3D RVE approach, arbitrarily dispersion of fibres embedded in **a** solid PP and **b** PP containing micro-voids. Adapted with permission from [174]. Copyright 2016, Elsevier.

They reported that the plastic deformation of the composite material starts at the end of the fibre and around the fibre defect, which matched the experimental results. Kern et al. [174] simulated the tensile properties of chopped wheat/PP composites using 3D RVE approach (shown in Fig. 16) by considering the effect of micro-cellular voids. They reported that the void-filled composite had shorter fracture path than the void-free composite. Their predictions matched the experimental results. Gopalan et al. [177] investigated the dynamic behaviour of woven Flax/epoxy composite plates experimentally and numerically. It was reported that the structural behaviour of the fabricated composite showed a compromising one to some of the synthetic composite which were used in various dynamic load bearing structural applications. Furthermore, the numerical and experimental results were found to be in good agreement.

## Potential of natural fibres for automotive

One of the largest consumers of natural fibre-based polymeric composite is the automotive industry [178]. Natural fibre-based composites have superior specific mechanical properties, durable, sustainable, and environmentally friendly, which makes them captivate to the automotive industry. Initially, NFRC were used for interior components of a car due to their low weight [179]. The comparatively low cost of natural fibres (such as hemp, coir, sisal and jute) as compared to glass fibre, which makes them fascinate to the automotive industry [180]. The first car was made of hemp fibre-based composite by Henry Ford in 1940. Other manufacturers, Daimler-Benz (1994), Mercedes (1996), used composites in their cars, but the application of NFRC really started to play a dominant role in the automotive sector in 1998, when morassi fabricated seats made of coir fibre with latex for trucks [181]. Today, most car manufacturers, including Mercedes, Volkswagen, Daimler-Chrysler, Audi Group, Ford, BMW, Nissan, Opel, Toyota, and Mitsubishi, use natural fibre-based composites in several applications, as presented in Table 15. In 1994, Mercedes Benz used jute fibre-reinforced polymeric composites for the interior door panel of their E-Class variant [182, 183]. Flax, sisal/epoxy fibre mat reinforced composites were used to fabricate the door and reported 20% weight reduction. In 1999, Mercedes Benz used 65% blend of hemp, flax, and sisal fibre and 35% polyurethane (PU) for the inner door panel of their S-Class variant [184]. In 2000, flax/polyester-based composites were used in the engine encapsulations by Mercedes in their various bus brands; EvoBus, Trivago, Setra and Top-class and reported 5% weight reduction in the Setra series engine with the use of natural fibre-reinforced polymeric composites [185]. In 2003, Toyota used kenaf fibres reinforced in the PLA matrix to go green in their RAUM model spare tyre cover [186]. Mazda used kenaf/PP composites in their door trims, door scuff plates and other interior parts. Lexus CT200h models used PP/PLA composites in the door scuff plates, side trims, toolbox area, package trays, and floor finishing plates [187]. NFRC used primarily for interior parts such as cabin linings, door panels, dashboards, parcel shelves, backrests and seat cushions [79, 153]. Thus far, NFRC have found limited applications in exterior parts of the car due to their high hydrophilic behaviour. For instance, abaca fibre-reinforced composites were used underfloor panelling by the Mercedes A-class model. Flax fibres

**Table 15** Applications of NFRC by various car manufacturers [79, 153, 159]

| Manufacturer | Car Model | Automotive components |
|---|---|---|
| BMW | 3, 5, 7 series | Headliner panel, door panels, moulded foot well linings, seatback, boot lining |
| Ford | Mondeo CD 162, Focus, Freestar | Floor trays, door panels, boot liner and B-pillar |
| Mercedes-Benz | A, E, C and S classes, 2004 Trucks, Mercedes | Instrument panel support, door panels, engine hood, sun visor, engine insulation,<br>interior insulation, trunk panel, bumper, wheel box and roof |
| Renault | Twingo, Clio | Rear parcel shelf |
| Lotus | Eco Elise | Body panels, Spoiler, seats and interior carpets |
| TOYOTA | Harrier, Brevis, Celsior, RAUM, ES3 | Seat backs, door panels, floor mats, pillar garnish and spare tire cover |
| Volvo | C70, V70 | Natural foams, seat padding and cargo floor tray |
| Opel | Zafira, Astra, Vectra | Door panels, headliner panel, instrument panel and pillar cover panel |
| Daimler/Chrysler | Travego bus, A, C, E, and S-Class, Stratus, EvoBus (exterior), Sebring convertible | Dashboard, door panels, instrumental panel, Pillar cover panel, windshield, business table |
| Peugeot | New model 406 | Seat backs and parcel shelf, door panels |
| Rover | Rover 2000 | rear storage shelf/panel and insulation |
| Volkswagen | Golf A4, Polo, Fox, Bora | Door panel, decklid finish panel, seat back and boot liner |
| Citroen | C5 | Interior door panel |
| Audi | A4 Avant, A2, A3, A4, A6, A6 Avant, A8 Roadster, Coupe | Seat backs, hat rack, spare tire lining, door panels and boot lining |
| Saturn | L3000 | Door panels and Package trays |
| Fiat | Brava, Marea, Alfa, Punto | Door panel |
| Honda | Pilot | Cargo area |

were also used in other exterior parts by Travego. Germany based car manufacturers like Audi, BMW, Volkswagen, Porsche and Mercedes are trying to make each component of their cars either biodegradable or recyclable [188]. AL Rahman et al. [189] studied pure micro-porous materials, used coir fibre and date palm fibres for sound insulation purposes, and results showed good acoustics properties at a low frequency, which showed a great potential to replace conventional materials counterpart. In 1980, bio-composites were used for the first time to fabricate automotive door panels [180]. Daimler A class used NFRC to fabricate boot lid, roof and bonnet of Bio Concept car [73]. The average usage of NFRC per vehicle is 11–13.2 kg in the automotive industry in Brazil. The natural fibre reinforcement is distributed in a vehicle, such as rear door liners (0.9–1.6 kg), front door liners (1.3–1.7 kg), boot liners (1.7–2.7 kg), sunroof interior shields (0.6 kg), headrests (2.3 kg) and parcel shelves (2.1 kg) [190]. In Europe, various automotive industries are using natural fibres to fabricate door panels in their C Segment cars, and 20% weight reduction was observed by the use of wood fibre in various models of sedans like Mercedes [191]. Flax, wood, hemp, kenaf, jute, coir and sisal fibres are being used nowadays as reinforcement for elastomers, thermosets and thermoplastics for the fabrication of several automotive components, such as pillars, door panels, instrument panels, seat panels and seat holsteries [73]. It was reported that 21% cost reduction and 32% weight reduction occurred by incorporating natural fibres into various components of the vehicle in the automotive industries. If the mass of the vehicle will be reduced, then it will consume less fuel and $CO_2$ emission will also be reduced. The European Union Commission set 'European Guidelines 2000/53/RG' for the automotive industries to set goals for automotive recyclability. Many countries, like Japan and the United States of America, are giving more emphasis on automotive recyclability [192]. In the automotive sector, NFRC are being used for dashboards and door

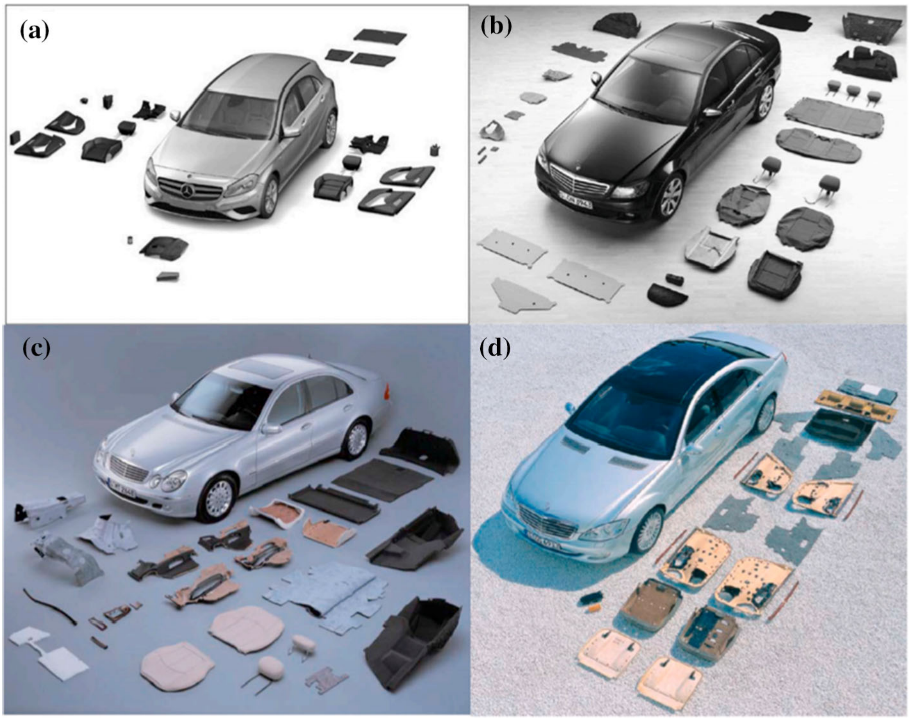


**Figure 17** Mercedes-Benz parts fabricated using different natural fibres (sisal, hemp, wool, flax, and others) of models **a** A-class, **b** C-class, **c** E-class, and **d** S-class. Adapted with permission from [193]. Copyright 2020, Elsevier.

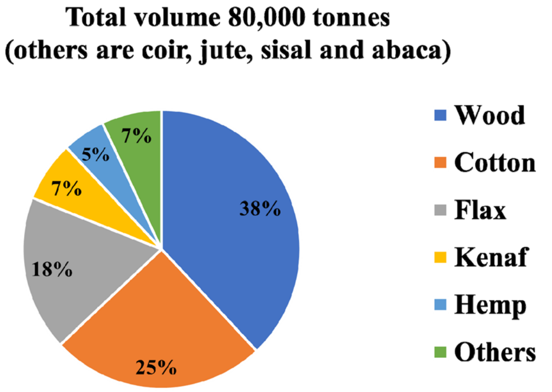


**Figure 18** Percentage of wood and natural fibres used for composite fabrication in the EU automotive sector in 2012 [194]. Re-drawn from [194].

panels. Wood-based composites are mainly used for spare wheels, trims for trunks, rear shelves, and interior trims for decklid. Different parts of various models of Mercedes-Benz (shown in Fig. 17) fabricated using different natural fibres (sisal, hemp, wool, flax, and others) [193]. In 2012, the total volume of natural fibres and wood used in the fabrication of composites for lorries and passenger vehicles in Europe was 80,000 t as shown in Fig. 18. Recycled waste cotton fibre-based composites were mostly used for cabins of the cars [194].

## Recent advancements in textile fibre-reinforced composites (TFRC)

### Natural-synthetic fibres reinforced hybrid composites for automotive structural components

In hybrid composites, one type of reinforcement is integrated with a mixture of two different matrices [195], or more than one reinforcing material are mixed in a single matrix phase [196], or both cases are combined together. The mechanical properties of hybrid composites depend on the AR (L/D) of fibres, the properties of discrete fibre, length of the discrete fibre, fibre-matrix interfacial bonding, the proportion of intermingling of fibres, failure strain of fibres, fibres arrangement, and also on the orientation of fibres [197]. In this section, application of hybrid composites in automotive structural parts (i.e., bumper beam, anti-roll bar and brake pads) is being discussed. The bumper beam is a structural part as it absorbs kinetic energy during a high impact crash and provides resistance to buckling in a low impact crash. In one study, mechanical properties of glass and jute fibres reinforced in polypropylene matrix were compared for the automotive car bumper beam by Olorunnishola et al. [198]. Hand lay-up technique was used to fabricate hybrid composites by laying the fibres on the bumper mould and the commercial-grade PP sprayed on it. The samples were cured for 20–24 h, and the surface was finished by grinding wheel operation. Three types of samples were prepared with 40 wt.% of jute fibre, 40 wt.% of glass fibre and 30 wt.% of jute fibre blended with 10 wt.% of glass fibre to make hybrid composites [198]. To enhance the adhesion across the interface of fibre and matrix, a maleated polypropylene coupling agent was used. The results revealed that hybrid composites showed the superior impact and hardness properties as compared to the non-hybridized composites and can efficiently substitute conventional materials used for bumper beams. In another study, thermo-mechanical properties of glass and flax fibres reinforced in methylene diphenyl diisocyanate (MDI) matrix were investigated by Hasan et al. [199]. The results revealed that the incorporation of glass fibre in composites showed satisfactory mechanical performance (tensile strength, tensile modulus, flexural strength, and flexural modulus). Furthermore, the thermal stability of glass/flax hybrid composites was also improved by the addition of glass fibre. However, with the addition of glass fibre in composites, the water absorption and moisture content began to fall. Figure 19 shows the schematic diagram of a typical structural bumper.

In another study, a kenaf/glass-based hybrid composite was fabricated for automotive structural car bumper beams with sheet moulding compound (SMC) to improve the desired mechanical properties. A specimen was tested and compared with automotive structural car bumper beam material known as glass mat thermoplastic (GMT). The result revealed that tensile strength, Young's modulus, flexural strength, and modulus were almost similar to GMT; however, impact strength was low. The researcher suggested optimization of design parameters to enhance the impact properties [201]. To design automotive structural components, replacement of iron and steel with natural fibre-reinforced hybrid composites was done because of high power consumption in fabricating metal structural components that influence the environment [202]. Hence, the researchers focused on natural fibre selection for hybrid composite materials to fabricate an automotive structural anti-roll bar (ARB) in order to evaluate the suitable natural fibre for hybrid composites that could satisfy both environmental and the customer requirements. This study was conducted using a fusion of the analytical hierarchy process (AHP) and environmental quality function deployment (EQFD). SolidWorks sustainability tool was used for life cycle assessment (LCA) of the developed hybrid composites to satisfy the expected environmental requirements. The results revealed that sugar palm fibre with 21.51% of the total score was the best fibre to fulfil the design requirements, followed by kenaf fibre, which obtained 20.19%. The selected sugar palm fibre reduced the production cost, making the sustainable rate of selected natural fibres comparable to the synthetic fibres used for the automotive structural ARB as shown in Fig. 20. Furthermore, the LCA was done for both the fibres and results revealed that sugar palm fibre exhibited 10% less effect on the environment because of its lower $CO_2$ footprints and lower energy consumption. Hence, sugar palm fibres were chosen as the prime material used in the hybrid fibre-reinforced polymeric composite for the automotive structural ARB [203].

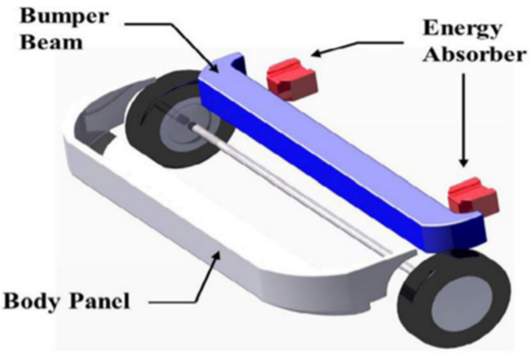


**Figure 19** Schematic of a bumper system. Adapted with permission from [200]. Copyright 2015, Elsevier.

Friction brake pads are safety–critical components of disc brakes used in the automotive. It is also known as friction linings which is used to stop or decelerate the vehicle by transforming the kinetic energy of the running vehicle into thermal energy through friction. Brake pad absorbs the maximum amount of heat; remaining heat is dissipated into the surrounding. Figure 21 shows the schematic arrangement of a typical brake pad. The friction material of brake pad consists of reinforcement in the

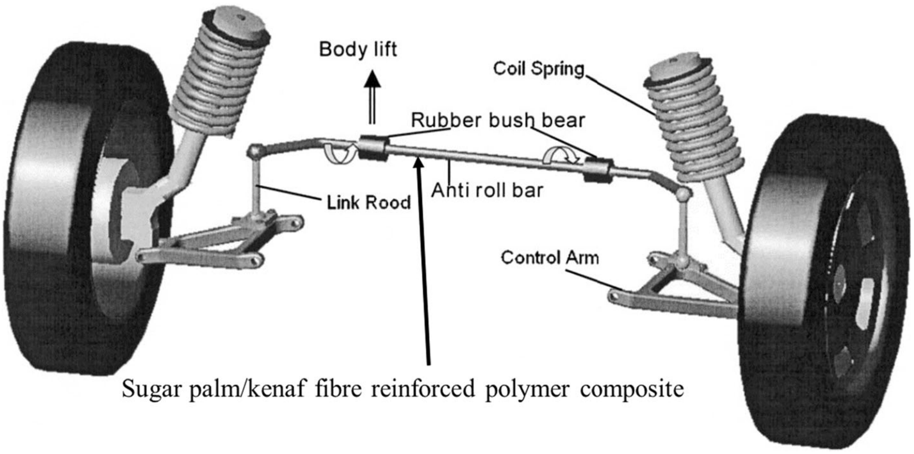


**Figure 20** Automotive structural ARB fabricated from hybrid natural fibre-reinforced polymeric composite. Adapted with permission from [204]. Copyright 2006, Elsevier.

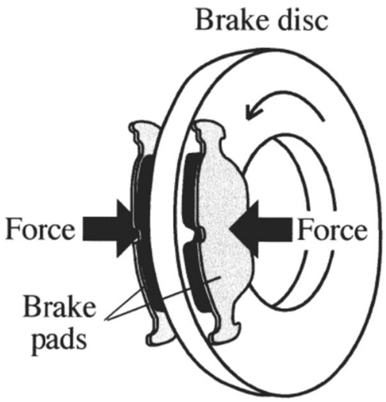


**Figure 21** Schematic of an automotive brake pad. Adapted with permission from [209]. Copyright 2000, Elsevier.

form of fibres, friction modifier, binders, and fillers. Asbestos fibres as a reinforcement incorporated in the polymeric matrix have been a supreme choice among brake pad manufacturers because of its excellent mechanical and thermal properties. However, due to stringent environmental concerns and its carcinogenic nature, the scientific community is trying to find suitable alternate materials to replace asbestos. In one study, sisal, nettle and Grewia optiva fibres in mat form reinforced PLA matrix and their tribological properties were evaluated. Hot compression moulding technique was used to fabricate hybrid composites. The results revealed that wear properties were enhanced substantially because of the inclusion of hybrid fibres [205]. Another study, the effect of banana fibres on tribological and mechanical properties of the friction brake pad was investigated by Zhen-Yu et al. [206]. The results revealed that as fibre percentage increased, wear rate, compressibility and water absorption were increased. However, the hardness of the composite decreased as the fibre percentage increased. Furthermore, higher frictional and brake pad performance was observed when the banana fibre content used was less than 10 wt.% [206]. Choosri et al. [207] investigated the compressive, hardness, wear and friction properties at room temperature and high temperature (100 °C-150°C) of S-glass/phenolic composites containing the bagasse ash and industrial waste fly ash as secondary abrasive (0–12 wt.%) for replacing primary abrasives (alumina and silica). Composite was fabricated by a compression moulding technique. The results revealed that composite with 4 wt.% natural abrasives showed an optimum performance and a great potential to replace primary abrasives (alumina and silica) counterparts. Furthermore, compressive strength of bagasse based phenolic composites was enhanced as compared to the natural fly ash based phenolic composites for a given load. In addition, lower wear resistance and higher coefficient of friction of phenolic based composites was observed at 100 °C and 150 °C. In another study, jute fibres combined with pulverized hazelnut shells as biodegradable natural fillers used for non-asbestos organic friction brake pad composites was studied. Two combinations of samples, jute fibres combined with graphite solid lubricant and jute fibres combined with hazelnut shells were prepared. According to SAE J661 standard using CHASE tester, friction and wear properties of the prepared composites were evaluated. The results revealed that jute-graphite based composites exhibited fade phenomenon if the temperature increased above 300 °C. At the same time, jute-hazelnut shell-based composites exhibited better resistance to fade phenomenon even if the temperature exceeded 300 °C. Furthermore, for 14 vol.% natural and biodegradable components, a combination of jute fibres (5.6 vol.%) with pulverized hazelnut shells (8.4 vol.%) possessed better frictional performance, whereas for 30 vol.% natural and biodegradable components, a combination of jute fibres (23.6 vol.%) with pulverized hazelnut shells (6.3 vol.%) has shown allowable stability of frictional coefficient [208].

## Natural filler reinforced polymer nanocomposites

Nanocomposites are those materials in which nano-sized filler particles are incorporated into the matrix, resulting in an improvement in mechanical properties, electrical and thermal conductivity. Generally, nanocomposite materials are a multiphase solid material in which at least one phase has a dimension lower than 100 nm [210]. Nowadays, this technology is growing at a rapid pace in the manufacturing of various automotive components such as sensors, windows, batteries, fuel cells, paints, nano-filters, and tires due to its higher AR (L/D) and larger surface area with fascinating properties. In nanocomposites materials, nanofillers are key components and can be composed of inorganic/organic, inorganic/inorganic, or organic/organic sources. There are various types of bio-based filler materials available in nature, such as ramie, kenaf, jute, coir, hemp rice husk, and bamboo [211]. When the size of fillers is reduced from micrometers to nanometers, various characteristics, such as a larger surface area to volume ratio, excellent mechanical properties (tensile modulus and strength), and flexibility in surface functionalities, tend to appear as compared to any other conformation of material [212]. A wide range of polymeric nanocomposite materials has been developed for several applications by integrating various polymer matrices, nanostructured materials, and nanofabrication techniques. To improve the performance (mechanical strength, optical, thermal, and electrical properties) of PMC, nanomaterials can be incorporated with both the matrix and fibre. The diameter of cellulose nanofibre is less than 0.5 µm and has high stiffness and strength compared to micro-natural fibres. Solution spinning, melt blown, electrospinning, melt spinning, and electrospinning techniques are used to process nanofibres [213]. Similar to surface modification treatments of natural fibres, nanofibres are also given various modification treatments, which result, improvement in mechanical properties, thermal properties, and physico-chemical properties of nanofibres [214]. Recognizing the mechanical and morphological advantages of nanofillers, the scientific community produced nanocomposite materials by using different reinforcing fibres and polymeric matrix by a wide variety of clays, which showed better properties. Reported work on nanocomposite materials as recited in Table 16. Nanocomposite materials showed improvement in electrical, mechanical, and thermal properties over conventional composites. In addition, a notable reduction in flammability of the polymer matrix was observed by using nanoparticles [52, 215].

**Table 16** Nanocomposite materials from various polymer matrix with nano filler/natural fibre [216–223]

| Polymeric matrix | Nano Filler/Natural Fibre |
|---|---|
| Polyamide 11 (PA-11) | Nano clay |
| PP | Nano clays |
| e-Caprolactam | Organo clay |
| Polyurethanes (PU) | Carbon nanotubes |
| Epoxy resin | Coir fibre nano filler |
| PS | Carbon nanotube |
| Poly (ether ether ketone) (PEEK) | Organo-alkoxysilanes |

## Textile structural reinforced polymeric 3-D composites

TSRPC are composites reinforced by textile structures committed for load-bearing applications. These TSC must have textile structure (act as a preform for composites), matrix, ceramic, or metal component and must have the potential to withstand primary and secondary load in automotive. The principal objective of TSC envisions the utilization of textile fibre-based structures in composite fabrication to achieve lightweight composites, load-bearing composites, and advanced composites. And the prime advantage of textile structural reinforced polymeric 3D composites is to take advantages of textile structure (preform) inclusion to textile-based materials in structural composites to achieve high strength/weight ratio, structural anisotropy, high impact resistance, withstand multidirectional mechanical stress, thermally stable, numerous shape and

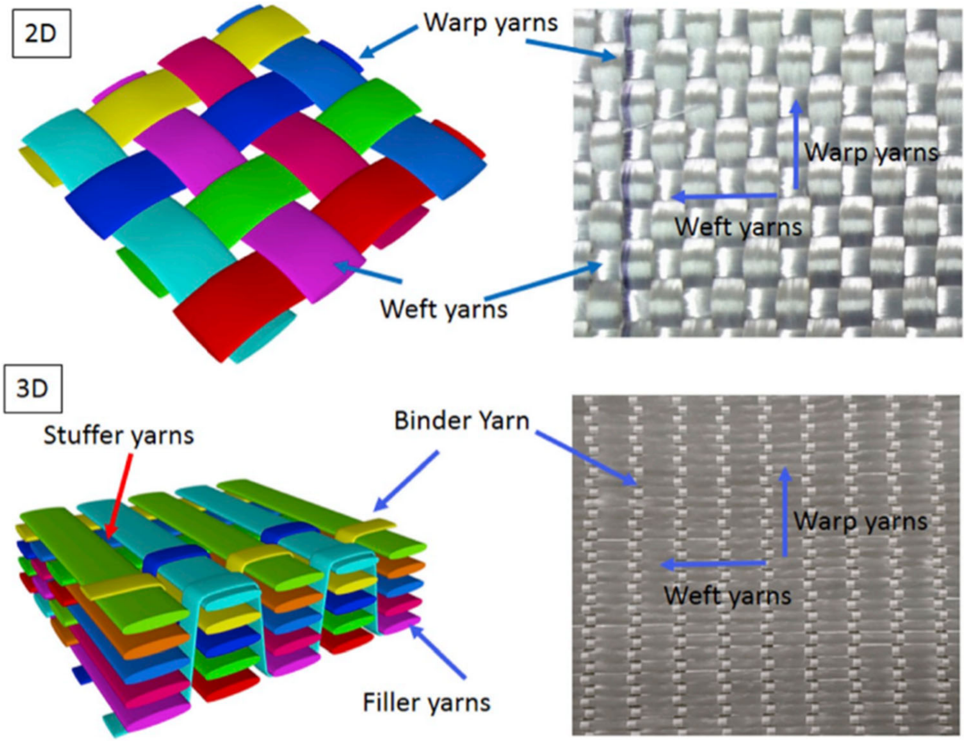


**Figure 22** Schematic of 2D and 3D textile structures. Adapted with permission from [227]. Copyright 2020, Elsevier.

geometry, endless textile structures like knitted, woven, braided, etc. and existing textile manufacturing technologies.

Textile reinforcement structures may be classified on the basis of continuity and discontinuity of fibres, reinforcement axis (uniaxial, biaxial, triaxial, and multiaxial), structural integrity (integrated or laminated), dimensions (UD, 2D, or 3D), and manufacturing techniques (non-woven, woven, braided, and knitted), etc. All the fibres are arranged in one direction in unidirectional (UD) preforms and fibres are arranged in two directions (warp and weft) in bidirectional (2D) preform, whereas in 3D preforms all fibres are arranged in three directions [224]. Figure 22 represents 2D and 3D textile structures (preforms) used for composite reinforcement. In 3D structures, constituent yarns are arranged in such a manner that they make a right angle to each other in three mutually perpendicular planes, in which two yarns (i.e., warp and weft) are positioned in X and Y directions, whereas the third yarn binds the weft and warp yarns in Z direction which provides better structural integrity, having substantial thickness higher than yarn diameter, higher fibre volume fraction (45–50%) without any crimp in the yarns [11]. On the other side, in 2D structures, constituent yarns are arranged in such a manner that both yarns in warp and weft directions make a right angle to each other in a single plane. The thickness of 2D structures is small; high thickness can be attained only by sewing and laminating. 2D fabrics are generally poor in plane resistance to shear, anisotropic in nature and comparably low modulus than fibre due to crimp presence. Basic difference between 2 and 3D structures is shown in Table 17. However, the performance of composites was influenced by fibre architecture, and it can contribute up to 90% of composite strength if its construction and design parameters are selected properly. The mechanical behaviour of natural fibre-based 3D woven structural composites for automotive applications was investigated. UD, 2D,

**Table 17** Difference in 2D and 3D textile structures [11]

| 2D structure | 3D structure |
|---|---|
| Low thickness | High thickness |
| Delamination occurs | No delamination |
| Poor resistance to impact load | High resistance to impact load |
| High crimp | Zero or very low crimp |
| Low production speed | High production speed |
| Single pick in a cycle | Multiple pic in a cycle |

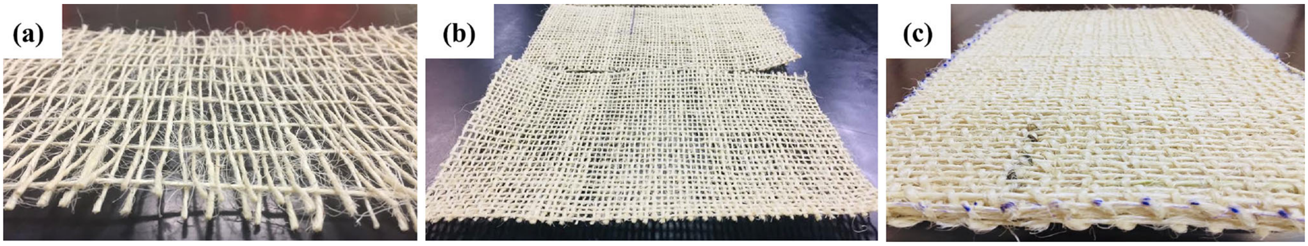


**Figure 23** Various textile structure developed **a** UD Tows **b** 2D preform **c** 3D woven orthogonal structures.

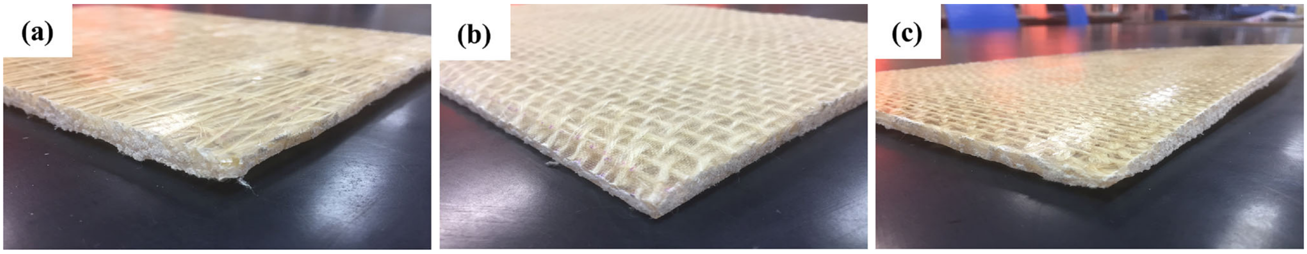


**Figure 24** Developed natural fibre-reinforced polymeric composites from various textile structures (preforms) **a** UD **b** 2D **c** 3D.

and 3D textile structures (shown in Fig. 23) were fabricated using sisal yarn at a 3D customized weaving machine. These preforms were reinforced in epoxy resin to fabricate various composites (shown in Fig. 24) by VARTM technique. The results revealed that specific tensile strength and specific flexural strength of sisal/epoxy composite were found lower than the metallic counterpart, but the izod impact strength of 3D sisal/epoxy composite was found to be higher in comparison with the metallic counterpart [Unpublished]. It was concluded that the structural parameters of 3D woven solid structure could further be optimized to achieve better results. In another study, thermomechanical properties of flax woven fabric reinforced in PLA and PP matrices were investigated by Hasan et al. [225]. The results revealed that the mechanical performance (tensile and flexural) and physical properties (thickness swelling and water absorbency) imparted significant results for the performance of the fabricated bio-composites. Furthermore, the thermal stability of the fabricated bio-composites was also improved. Krishnasamy et al. [226] investigated the vibration and wear behaviour of aloe vera/flax/hemp woven fabric epoxy composite reinforced with wire mesh and $BaSO_4$. The results revealed that the incorporation of wire mesh and $BaSO_4$ reinforcement in the fabricated composite enhanced the wear property and mechanical performance (tensile and compressive strength by 8.68% and 10.72%, respectively) compared to the other composites. Furthermore, the addition of filler enhanced the specific stiffness, which further increased the natural frequency of the beam.

## Textile fibre-reinforced aluminium metal matrix composites

TFRAMMC are composites reinforced by textile fibre in aluminium matrix committed for lightweight and load-bearing applications. These composites must have textile fibre (acting as reinforcement) and aluminium matrix; they must have the potential to withstand primary and secondary load in automotive. Aluminium-based metal matrix composites reinforced with textile fibre in the aluminium matrix have many advantages such as superior strength to weight ratio, high modulus, resistance to creep, wear and fatigue properties. Aluminium-based composite materials have high potential application in the automotive sector (piston rod, valve train, piston pin, crankshaft, cylinder head, cylinder blocks, and engine blocks). Today, most car manufacturers, including Volkswagen, Daimler-Chrysler, Honda, Toyota, Nissan, and GM, use aluminium metal matrix-based composites in various applications, as presented in Table 18. A very little effort has been put up so far towards TFRAMMC by the scientific community. Arab et al. [228] fabricated TFRAMMC using milled and chopped E-glass, S-glass, and carbon fibres as reinforcement, and then friction stir processing (FSP) was employed to disperse the textile fibres into the aluminium matrix to improve the

**Table 18** Applications of aluminium metal matrix composites by various car manufacturer [236]

| Manufacturer | Component | Composite |
|---|---|---|
| Nissan | Connecting rods | Al/SiCw |
| Toyota | Piston rings | Al/$Al_2O_3$ |
| Daimler-Chrysler | Connecting rods | Al/$Al_2O_3$ |
| Honda | Engine blocks | Al/$Al_2O_3$-Cf |
| Volkswagen | Brake rotors | Al/SiCp |
| GM | Engine cradle, driveshaft, rear brake drum | Al/SiCp |

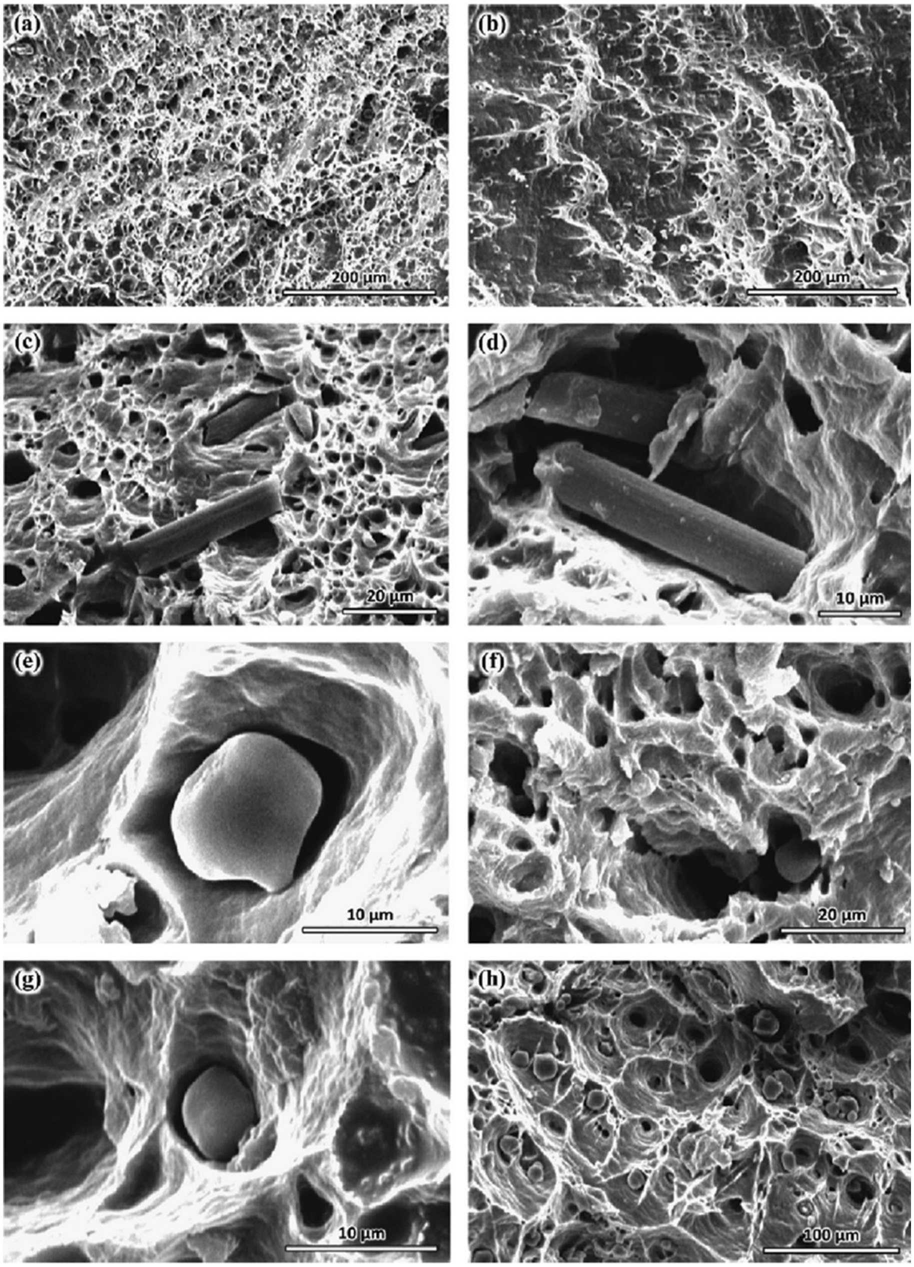


**Figure 25** **a** Aluminium matrix **b** Non-reinforced FSPed, and reinforced with **c** milled carbon fibres **d** chopped carbon fibres **e** milled E-glass fibres **f** chopped E-glass fibres **g** milled S-glass fibres **h** chopped S-glass fibres. Adapted with permission from [228]. Copyright 2015, Elsevier.

mechanical properties. The results revealed that tensile strength, micro-hardness, toughness, and ductility were improved for all the processed samples. Appropriate distribution of the reinforcements in the aluminium matrix was observed by scanning electron micrographs, as shown in Fig. 25. The synergetic effects by reinforcing the fibre into the aluminium matrix and severe plastic deformation (SPD) improved mechanical properties compared to base aluminium. No other studies have been reported on glass or carbon fibres reinforced aluminium metal matrix composites (GFRAMMC or CFRAMMC) fabricated by FSP. These fibres are easy to use and more economical than other conventional reinforcing phases, such as carbon nanotubes [229, 230]. Mertens et al. [231] investigated the mechanical properties of FSPed Mg-Carbon fibre composites, and the results revealed that the yield strength of the composite was increased by 15%-25% as compared to the as-received Mg alloys. It is concluded from the above discussion that FSP has been proven to be a viable approach to homogeneously disperse the textile fibres in the metal matrix [232–235]. Therefore, more studies will still be needed to explore more advanced technical concepts to fabricate the glass and carbon fibres reinforced aluminium metal matrix composites with better distribution of fibres and improved bonding across the interface, which further explores to clarify the further mechanism for the enhanced properties.

## Conclusion

The usage of natural fibre-based composites in automotive industries has gained investment and great focus by the scientific community due to the necessity for eco-friendly, lightweight, and renewable materials with improved properties. In these circumstances, fuel-saving could be achieved through light-weight materials, which results in a reduction of $CO_2$ emission on a large scale. Apart from lightweight multi-material design (MMD) options and metallic alloys, emerging trends in textile fibre-reinforced composite structures provide a feasible solution to develop lightweight vehicles. For long-term sustainability, easy availability, low cost, low density, good acoustic and thermal insulation, environmentally friendly, renewability, recyclability, and adequate mechanical properties make NFRC a substitute for conventional synthetic fibre-based composites. However, their disadvantages, such as moisture absorption, poor interfacial bonding between the natural fibres and matrix, low impact strength, low durability, and poor fire resistance, have restricted them from being considered as an alternative material for traditional composites. Water degradation is the biggest challenge associated with NFCs. It is clear from the assessment of review articles that desired mechanical properties needed for the automotive sector cannot be obtained by natural fibre itself. Although it fulfills the condition of lightweight biodegradability, it delivers minimal adverse impact on the environment due to its carbon neutrality and eco-friendliness. This paper evaluates the several chemical treatment methods which are used to lower the moisture absorption content of natural fibres and enhance their mechanical properties, which makes them an alternative for obtaining lightweight and more environment-friendly materials for the automotive sector. In addition, the concept of vehicle weight reduction, recent advancements in TFRC such as natural-high performance fibre-reinforced hybrid composites, natural filler reinforced polymer nanocomposites, textile structural reinforced polymeric 3D composites, and TFRAMMC have been explored. This paper will assist researchers to initiate further technical advancements in the field of textile fibre-reinforced composites for the automotive industry.

## Declarations

**Conflict of interest** All the authors declare that they have no conflict of interest.

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