Review Article

A Review of Natural Fibers Reinforced Composites for Railroad Applications

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Abstract
Composite materials are abundantly present in applications related to transportation industries, mainly due to their lightweight, good mechanical performance, and viable production costs. In this sector, weight reduction represents a two-fold advantage as fuel consumption can be reduced, as well as passenger (or load) capacity can be enhanced. The use of natural fiber composites is an excellent option considering weight reduction and source renewability, already being done in many automotive and aerospace utilities, but specifically in railroad applications, their choice seems to be eclipsed by synthetic fibers, such as glass and carbon fibers. The objective of this work is to analyze the current situation on composite applications in the railroad industry, deriving a discussion that includes the aspects that hinder the use of natural fibers and also indicates the current status of greener composites even if not including natural fibers. The production costs of these natural fiber-reinforced composites, when observed under a scalability scenario, associated with some specific properties of natural fibers (as flammability performance, for example) seem to be the reason for their rather infrequent consideration. Nevertheless, technology advancements related to production processes and innovative additives fabrication present an interesting prospect for future development in agreement with sustainability concerns.

Keywords: Composites, Natural fibers, Railroad, Transportation, Railtrack

1 Introduction

The amount of carbon dioxide (CO_2) emissions produced by countries is directly related to their population and their gross domestic product based on purchasing power parity (GDP-PPP). Thus, the more developed and populous countries are, the greater is their CO_2 generation [1]. Indeed, when analyzing countries' CO_2 production data related to transportation, this information is evidenced as shown in Figure 1 [2].

According to the US Environmental Protection Agency - EPA (2021), 14% of global greenhouse gas (GHG) emissions in 2010 were produced by the transportation sector [3]. It is noteworthy that there was a significant increase, and in 2019 the transport sector was responsible for 27% of global GHG emissions [4].

Transportation will figure among the largest contributions of a person's carbon footprint, especially in richer countries where the population travels more frequently. Figure 2 shows the carbon footprint (grams

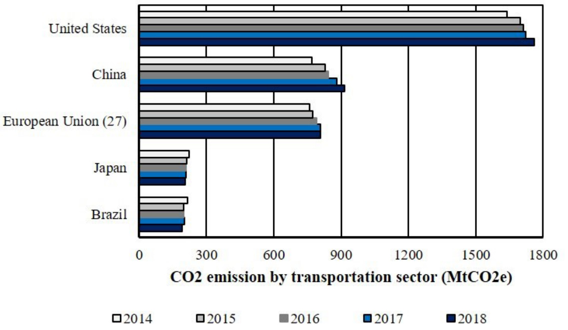

Figure 1: CO_2 emission by transportation sector ($MtCO_2e$). Elaborated by the authors based on information from CLIMATEWATCH [2].

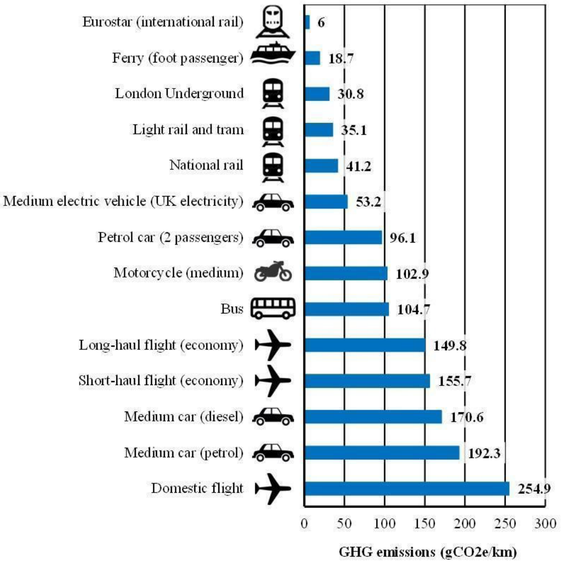

Figure 2: The carbon footprint of travel per kilometer, 2018. Elaborated by the authors based on information from Ritchie [5].

of carbon dioxide) per passenger taking into account different transport modes. Air transport and cars are ranked as the most impactful [5].

However, according to Figueroa *et al.* [6], the cost of infrastructure installation for land transport, such as buses and cars, is 90% lower than the average investment for the installation of rail transport infrastructure, such as trains, for example. Nonetheless, considering the passenger transport capacity per hour, trains display a capacity 90% higher than cars and buses [6]. Therefore, regardless of the high infrastructure costs associated with rail transport, its superior passenger and cargo capacities render this modality economically feasible, and the infrastructure cost recovery can be attained with time. When evaluated along with its lower CO_2 emissions, as shown in Figure 2, rail transportation emerges as one of the most sustainable and environmentally friendly options.

Also in this context, an increase in the sustainability of rail transport can be achieved by replacing metallic materials, concrete, wood, for example, with plastic matrix biocomposites using vegetable-based fiber reinforcements [7]. These replacements can be proposed from station infrastructures to internal items of passenger cars, for example, interior of bathrooms, window frames, decorative, etc., thus reducing their weight [8].

The European Union has adopted actions to reduce the environmental impacts of the transport sector. Two examples are The Circular Economy Package and the Roadmap to a Single European Transport Area. The latter aims to reach a 60% reduction in transport emissions by 2050; in order to achieve this goal, innovation must be considered in parallel with new materials and design [9], [10]. FARBioTY has been investigating the replacement of lightweight fiberglass composite materials and seeking alternatives to new materials primarily using natural fibers [11]. Biocomposites can have high quality, in addition to reducing environmental impacts, for example, because they are more recyclable, biodegradable, and consume less energy during their production [12]. However, the potential of such materials has yet to be fully exploited, with combustibility being a particular concern.

The European Union's Life15 Program under grant agreement nº ENV/FR 000412 project aims to reduce the environmental footprint of the transport industry by increasing the volumes of flax fibers used for producing composite materials. Flax fiber adoption has the potential to reduce glass fiber production and the exploitation of raw materials (sand, petroleum-derived materials, and water). Flax is a natural and abundant resource, which can be sustainably managed to provide the natural fibers needed. However, in this research, they are mainly investigating the polyester thermoset matrix [13].

The scientific literature contains several research reports proposing the replacement of conventional materials by composites reinforced with glass and carbon fibers. One of the earliest adoptions was present in the 1950s, as described by Batchelor [14]; in the UK trains were using glass fiber reinforced composites indoors, with a 100% increase in fatigue resistance, cited also in Robinson *et al.* [15]. Another example is a comprehensive review on alternatives for timber sleepers published in 2010, in which several glass fiber reinforced materials are covered [16]. In contrast, very few authors propose the use of vegetable-based fibers for this kind of application [17], [18]. The automotive industry, on the other hand, has experienced significant development in designing products using natural fiber composites;, expressive companies such as Mercedes, Audi, Ford, among others, are already employing these materials in the production of vehicle parts - door and interior panels, fittings, linings and door boards [19]. According to Ning *et al.* [20] and Zwawi [21], the automotive and construction industries are the two most promising and important sectors for biocomposites. However, other literature reports also point to wide applications of natural fibers for the automotive and aircraft sectors [22]–[24]. The use of these materials for railway applications shows future potential and will be addressed in this work.

2 Overview of Natural Fibers Reinforced Composites

The demand for more sustainable materials has led to the development and replacement of composites reinforced with synthetic fibers - glass, carbon, etc. - by composites reinforced with natural fibers - vegetable, animal, or mineral based [11], [24]–[27]. The matrix can typically be a polymer, metal, or ceramic. Polymers can be classified into three classes: thermoplastic, thermoset, and elastomer [24]. Thermoplastic materials currently dominate as matrices for vegetable-based fibers addition; the most commonly used thermoplastics for this purpose are polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC); on the other hand, the most commonly used thermosetting matrices are phenolic, epoxy and polyester resins [28]–[30].

The main advantages and disadvantages of some thermoplastic matrices are:

- Polypropylene (PP): PP is widely used because it poses moderate dimensional stability, high temperature of thermal deformation, and flame resistance. Also, recovered PP from the recycling process can be used to develop new natural fibers reinforced composites [31]. PP has good mechanical properties at ambient temperature, is chemically stable, absorbs a low amount of water and maintains good insulating properties (even when moist), and is relatively cheap if compared with other polymers; however, its main disadvantages are ultraviolet (UV) irradiation sensitivity, low impact strength of some grades, poor creep behavior and low rigidity [32].
- Polyethylene (PE): This material has reasonable thermal and mechanical properties [31], associated with chemical inertness, good impact strength, low cost, and easiness of processing [32]. PE is a non-biodegradable polymer and is normally produced from a fossil source. However, it is possible to produce biobased-PE from sugar cane, sugar beet, starch plants, etc. [33]. Nevertheless, characteristics such as limited UV resistance, low rigidity, and high shrinkage during processing can be considered important drawbacks for its utilization [32].
- Polystyrene (PS): PS is a material with significant demand, mostly owing to interesting properties such as transparency, fluidity, good electrical insulation, low cost, rigidity, and dimensional stability [32], [34]. Also, PS matrix composites reinforced with vegetable fibers are less abrasive than traditional PS and can be reused instead of discarded, for example, it can have its calorific value recovered in a kiln or be composted [35], [36]. The main limitations of this material are its flammability and sensitivity to several conditions (UV irradiation, solvents, and heat, for example) [32].
- Polycarbonate (PC): Owing to its characteristics, this material is used in engineering applications that require superior mechanical properties, such as tensile strength, impact resistance, fatigue and creep behavior, with the added benefit of transparency; it is also easy to mold and thermoform and can be used in wide temperature ranges [31], [32]. Naturally, its production cost is higher, and other disadvantages are sensitivity to light and weather, as well as flammability [32].
- Polyvinyl chloride (PVC): In this case, the material exists in two conditions with different mechanical properties: rigid and flexible PVC. Composites usually are made with rigid variation, since it has low cost, good durability and resistance to termites, good chemical and flame resistance, dimensional stability, and good rigidity at ambient temperature; therefore, it shows suitable potential for use in building structures and construction works [31], [32]. Rigid PVC has also disadvantages, namely:

UV and heat sensitivity, low-temperature brittleness, higher density than other polymers, and it's also more difficult to inject [32].

Thermoset polymers can also be used as matrices in composites for structural applications subjected to lower mechanical stresses; also, these materials benefit from the fact that their processing methods are rather simple, due to the low viscosity of thermoset polymers. Fabrication processes include (but are not limited to) hand lay-up and spraying, compression, resin transfer, and injection. The main disadvantage pertaining to this class is their impossibility of further processing after curing, which renders them unrecyclable [31].

Biocomposites can be composed of a polymeric matrix reinforced with different vegetable-based fibers, such as bamboo, banana, coconut, cotton, flax, hemp, jute, kenaf, luffa, palm, pineapple, sisal, wood, etc. [22], [25], [28], [29]. Ideally, the use of a biodegradable renewable polymer as the matrix, such as natural rubber, polylactic acid, or polyhydroxybutyrate, in association with natural fibers represents a complete eco-friendly green composite, with significant interest from governments and private research agencies towards these materials [37].

Natural fibers in general display properties which are similar to those of artificial fibers, but their use in polymeric composites is hindered by characteristics such as water absorption and insufficient thermal properties [38]. The discussion of natural fibers' wide variety of properties is not the objective of this study; a comprehensive review of chemical composition, mechanical and physical properties of natural fibers was published by Madhu and coworkers in 2019 [39], and the reader is encouraged to refer to this work for further information.

The major problem identified with vegetable-based fibers is hydrophilic, and thermoplastic and thermosetting matrices are hydrophobic [31], [40]. The hydrophilic characteristic of vegetable-based fibers occurs because of the hydroxyl groups contained in the cellulose and hemicellulose molecular chains [41]. Therefore, the major problem is the chemical incompatibility between hydrophilic natural fibers and hydrophobic polymeric matrices. This incompatibility can be treated by coupling agents, such as Maleic Anhydride Grafted Polypropylene (PPgMA) to PP [32] and methyl methacrylate (MMA) for PS [42], [43]. Several surface treatments of natural fibers are conducted to improve their adhesion with different matrices. The main techniques are alkali treatment – mercerization, acetylation, benzylation, permanganate treatment, silane treatment, peroxide treatment, enzyme treatment, isocyanate treatment, plasma treatment, esterification, TDI treatment, corona treatment, and others [25], [31], [32], [44], [45]. In addition to enhancing fiber properties before the composite fabrication [46], fiber treatments promote better adhesion between natural fiber and polymeric matrix improving the mechanical properties of these composites [25], [45].

Reports of studies involving thermoplastic matrix composites in railroad applications seem to be less frequent than those regarding thermosetting polymers. In addition, according to Lee *et al.*, glass and carbon are the most common fibers used in composites bodies of railway rolling stock [47]. Carbon fiber is used because it has electrical and thermal conductivity, in addition to its low specific gravities, high strength, and high stiffness-weight ratio. Polyacrylonitrile (PAN), for example, is one of the types of carbon fiber used for this railway application. In Korea, epoxy resins are used as binders - to improve excellent adhesion properties, low shrinkage, resistance to high temperatures and numerous chemicals, moisture resistance, and excellent electrical properties - for carbon fiber reinforcing agents, making rail cars lighter - tipper trains. For this application, a combination of bisphenol A ($C_{15}H_{16}O_2$) and epichlorohydrin (C_3H_5ClO) is normally used [30].

Mistry *et al.* proposed the replacement of metallic components present in railroad transportation by fiber-reinforced polymer composite materials. In their work, the authors devised a methodology for ranking the most feasible parts to be replaced considering three steps: preliminary ranking, economic potential of composite replacement, and composite component evaluation. The authors defined a cantilevered seat bracket, luggage rack module, intermediate end structure, a body side structure, and roof structure as the components which could mostly take advantage of weight reduction if replaced by composites, also considering integration potential and commercial feasibility [48].

Based on the presented factors, biocomposites possess great potential to replace internal components of trains, stations, and railroad structures, aiming at higher transport capacity, material cost reduction, and environmental benefits. This is possible due to the very nature of composites, materials, which present a combination of the properties of their constituents, using a principle of combined action allowing for careful tailoring of specific characteristics [33]. The future suitability of biocomposites for outdoor railway applications relies on the development of novel adequate technologies, which is an ongoing trend to other applications of these materials [49].

3 Railroad Applications

Requirements and restrictions are specific to each application, and materials selection must consider the range of properties of each possible material when designing a project. In these topics, we present an approach to the challenges of materials and their specific applications in the railway sector, as well as related manuscripts in literature concerning the use of composite structures or materials.

3.1 *Infrastructure*

The railway infrastructure includes all structures, buildings, land, and equipment to support the railway lines [50]. The components of the rail fastening system have the main function to prevent the movement of the lateral and horizontal steel rail. These components are rail clip, railroad spike, rail bolt, rail tie plate, rail pad, washer, plastic dowel, rail insulator, rail shoulder, etc. [51]–[53].

Fire risk scenarios are a possibility to be considered in railroad transportation applications, thus being of interest when it comes to composite materials since their fire resistance is dependent on matrix and fiber types [54]. While thermosetting polymers usually maintain their geometry while burning, thermoplastics will mostly deform, flow, and possibly drip when subjected to fire [55].

Although the composite flammability is more related to the polymeric matrix of choice, fibers can still influence fire resistance behavior and safety performance. The most common fibers applied to railroad transportation, namely glass fiber, and carbon fiber, tend to reduce the heat release in fire situations [13]. In comparison, carbon fiber is combustible in opposition to glass fiber, in addition to being thermally conductive, but even so, do not contribute significantly to total heat release [54]. On the other hand, cellulosic fibers are readily burned when exposed to flames and can decrease flammability performance [55], a possible reason for their less frequent use in railroad applications. However, when associated with flame retardants, these fibers can do something that neither glass nor carbon fibers can: act as additional char sources in intumescent formulations, effectively contributing to fire protection [56].

3.1.1 Train structure

In the last few years, composites, in general, have been used in rail vehicles mostly in components where their easiness of production is an advantage - for example, in complicated three-dimensional parts associated with excellent stiffness and low density [15]. Historically, in the United Kingdom, the 1970s witnessed the first adoptions of composites in train cab ends; laminated glass-reinforced fiber facings were used as exterior components of a sandwich composite structure, which also contained polyurethane foam in its interior [14]. More recent examples are:

- Italian ETR 460: this high-speed train’s front cab is composed of aramid fabric, high silica glass fiber, flame retardant polyester resin, and polyurethane foam [57]; although being more expensive than the corresponding metal component, the composite’s easiness of assembly and shape improvement compensate for choice making;
- Le Shuttle power cars: in this case, the operation conditions (mostly underground) required attendance to fire safety restrictions; a phenolic resin granted fire resistance, leading to the creation of front ends among the largest hand-laid phenolic products to date [15];
- C20 Stockholm Metro: in Sweden, the intricate geometry of the driver’s cab acted (in practice) as a restriction for materials selection, since composite manufacturing was the only feasible option; the 15 m^2 moulding is hand-laminated in one piece [15].

The train roof structure can also benefit from composite materials. Grasso *et al.* described the performance of three proposed sandwich composite configurations, basically using polyurethane foam core and external aluminium faces, to replace traditional metallic train car roof structures. According to the authors, the widespread use of composites in other transportation methods had not reached trains because of production costs. Indeed, their proposed configuration did result in properties comparable with aluminium counterparts but representing significant weight saving [58].

A trend, which may represent an important approach to greener rail components is the use of recycled biomaterials in association with carbon fiber, as in the example related by Nickels [59]. In this report, a panel door leaf composed of a recycled foam core and carbon fiber in sandwich configuration showed satisfactory properties in terms of mechanical and fire resistance performance, with a 35% weight saving. The resin matrix system used, based on Polyfurfuryl Alcohol derived from a by-product of sugar refinement, presents no toxicity and does not use volatile organic solvents.

3.1.2 Railroad tracks

Railroad tracks are conventionally built on compacted ballast and structural fill layers that are placed above the natural foundation (subgrade). One schematic diagram of this structure is given in Figure 3.

In railway structures, vibration represents an important factor to consider since train car transit will necessarily cause the underlying structure to vibrate. Considering polymer types, elastomers and thermosetting resin-based polymers present better damping properties due to their more elastic character when compared to thermoplastics [33]. However, given the complex nature of forces and other phenomena present in railroad systems, damping performance must be accompanied by a set of properties which usually is only feasible with composite materials. For example, the rail cars' bogies - frame structures, which generally carry the wheelset - are components, which take advantage of fiber-reinforced polymer composites (FRPs) combination of lightweight, high specific and fatigue strengths, corrosion resistance, and structural damping properties [15].

Track deterioration occurs progressively during train operations due to ballast degradation, reducing the load-bearing capacity of the system and leading to the need for more frequent maintenance. Several developments were carried out by Indraratna *et al.*, including numerical modeling of geogrids. The use of plastic and rubber elements in rails for energy absorption (e.g., rubber crumbs, tire cell residues, and rubber mats) was shown to be very promising. Performance tests evidenced that the addition of rubber materials can efficiently improve the energy absorption of the structural layer, in addition to reducing ballast breakage [62].

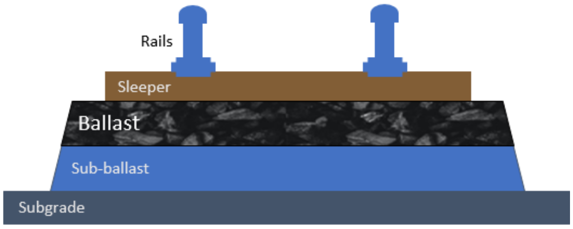

Figure 3: Schematic drawing of a ballasted rail track. Elaborated by the authors, based on Lee *et al.* [60] and Zeng *et al.* [61].

A life cycle assessment (LCA) on a railway beacon shell has been performed. This analysis shows that bio-composites formulated by natural fiber (flax) and the polyester matrix is more efficient than the fiberglass-based solution, more or less depending on the application method and the resin used [11].

In a similar context, Zeng *et al.* aimed to reduce vibration in ballasted tracks (one class of rail tracks) using rubber composite sleepers as an alternative for concrete sleepers. These components are responsible for transferring and distributing wheel loads from the trains to the underlying ballast and are susceptible to vibrations possibly causing early deterioration in addition to environmental damage. The authors demonstrate that the proposed composite sleepers, which were tested in full indoor models, showed a significant reduction in the vibration characteristics of the system, such as vibration acceleration energy, velocity, and duration [61].

Lee *et al.* reported an application of a thermosetting polymer and a ceramic-based material as infilling components to strengthen existing ballasted tracks. Even if this study does not consider natural fibers, it is yet another example of how composite structures (in this case, proposed materials as matrices and aggregates as reinforcement) are interesting candidates for railroad applications [60].

The longevity of a railroad track is strongly affected by the wear characteristics of wheel-track interface. Naturally, the development of technologies aimed at reducing track wear is ongoing and can also benefit from composite structures. Vélez *et al.* (2020) proposed a composite friction modifier made of vinyl ester matrix and two reinforcements: molybdenum sulfide and carbon nanotubes. The composite's performance was compared to that of a commercial lubricant, and results indicated lower values for the coefficient of traction and mass loss for the composite, which used lower additive content than the commercial product used in the comparison [63].

3.1.3 Railway bridges

Railway bridges figure as important components of railroad transportation and are structurally much different than ground tracks. In Korea, for example, several bridges are constructed with plain concrete piers, in an open-steel-plate-girder (OSPG) configuration [64]. Lateral loading and overturning of the pier are real failure possibilities in these bridges; to tackle this problem, Choi *et al.* [64] proposed the use of composites uniting fiber-reinforced polymer and steel plates. Push-over tests conducted by the authors demonstrated the feasibility of applying this solution to retrofit existing bridges.

According to the extensive literature review by Ali *et al*. there are scarce literature reports that bring knowledge about the recent development of bridges made of fiber-reinforced polymers [65]. In line with Telang, most bridges are commonly made using carbon, glass, aramid, and basalt fiber reinforcements, which can be made continuously (roving and woven) or discontinuously (chopped strand) [66]. This subject becomes even more scarce or non-existent when looking for polymers reinforced with natural fibers. For this reason, more research and development need to be done to develop cost-effective, flexible, and automated manufacturing solutions in addition to green composites, made from natural fibers and recyclable plastics, to provide more sustainable bridges [65].

3.1.4 Rail brakes

The braking performance of rail vehicles is based on friction [67], and thus binder polymeric resins present interesting characteristics for this end since these materials rely on desirable friction/wear properties: heat resistance, processing capability, dimensional stability, and endurance [68].

Haddadi *et al.*, in a study regarding wear and thermal effects of components in polymeric-based friction material, showed that the low-modulus polymeric materials considered in the study presented higher wear resistance in comparison to cast iron friction materials. They conclude that temperature increase during friction can be minimized by large contact areas, which demands a relative softness achievable using low modulus polymers such as resins [69].

The understanding of the thermal conductive properties of composites is interesting in developing new brake materials for railroad applications. Shojaei *et al.* described the influence of adding different thermally conductive fillers to a commercial railroad friction material, including aluminum, brass, and talc. One important conclusion from this research is that factors such as filler shape and size can influence the material's thermal conductivity, in addition to composition. The authors also developed a semi-empirical model for multiphase systems, aimed at estimating the thermal conductivity of proposed formulations [67].

About mechanical and tribological properties, adding different fiber types can produce varied results. Specifically working with a copper/phenolic-based friction material, Ho *et al.* demonstrated that cellulose and carbon fiber addition resulted in lower compressive strengths as opposed to copper and brass fiber-reinforced composites, which presented higher performance. An important conclusion is that the average coefficient of friction calculated for the composites is higher than the material without fibers, except for cellulose fiber addition which reduced this property. This fact is an indication of why natural fibers are not as frequently used as synthetic fibers in reinforcement roles regarding wear properties [17].

3.2 *Internal and finishing*

The internal components of train cars have incorporated composites more extensively than structural counterparts. For a specific train model, the interCity passenger coach, fiber reinforced polymers represent almost 10% of its overall weight [15]. Because of the versatility of production processes, such as cold pressing, spraying, and hand-laying, the combination of glass fibers and polyester resin have been successfully used for the fabrication of components such as toilet modules, end of roof canopies, vestibule panels and window trim surrounds [15].

One example of a more recent application of natural fibers for rail applications is the work of Sachin *et al.* [70]. The authors demonstrate that composite materials fabricated from polylactic acid (PLA) reinforced with neem fibers can be used as a substitute for conventional plywood for furniture, building infrastructure and interior components for the automobile, aircraft and railway sectors, since they displayed higher performance in tensile, flexural and impact tests than the control sample.

Fiber hybridization can represent an interesting option for wider adoption of natural fibers in the railroad industry. Kaliappan *et al.* [71] developed biocomposites reinforced with combinations of processed neem fibers, abaca fiber, and glass fiber in an epoxy matrix, in a work aiming to determine the influence of fiber hybridization and orientation on the mechanical performance of composites.

The association of recycled PP, sisal fiber, and nanoclay was reported [18] in a study regarding the South African rail car industry prospect. A clear influence of fiber treatment, nanoparticles, and increase in fiber content was demonstrated on the mechanical properties and thermal stability of the composites, which are considered in the manuscript as feasible for seats, backrests, and other interior parts of passenger trains.

Biocomposites are also being researched as potential materials for printed circuit boards (PCBs), which undoubtedly are necessary for the electronic components of technologically advanced rail vehicles. Bharath *et al.* [72] reported a novel proposal for the production of a bio-based composite made of rice husk and an epoxy resin. PCBs usually employ petroleum-based resins such as polyester and polytetrafluoroethylene, in addition to often requiring processes that involve carcinogenic materials to obtain desirable flame retardancy properties. In this research, no chemical solvent was used in the process, thus representing an additional ecological factor of interest for these biodegradable PCBs [72].

4 Conclusions

Natural fiber-reinforced composite materials are already a reality in transportation sectors, such as aerospace and automotive. In the railroad industry, however, synthetic fibers respond for the majority of applications, mainly due to escalated production costs and specific natural fibers characteristics, such as flammability performance, but the current reports indicate that natural fiber composites seem more appropriate for train cars internal components rather than structural parts. Nevertheless, a recent growth trend in this application is noted in literature in consonance with technology development responsible for cost reduction and new chemical additives to tackle natural fibers disadvantages. Also, fiber hybridization seems to be an interesting choice for broadening the inclusion of natural fibers in this specific sector. Future research in this area is expected to increase sustainability, environmental gains and reduce GHG emissions.

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