sustainability

Review

Trends and Challenges in Railway Sustainability: The State of the Art regarding Measures, Strategies, and Assessment Tools

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Abstract: Rail is expected to become the backbone of future mobility in the world as the cleanest and greenest high-volume transport. Rail generates the lowest CO_2 emissions and energy consumption when in operation, with respect to the other transportation modes, but during construction and maintenance phases, its environmental impacts are significant and need to be carefully assessed and properly mitigated. This paper, through an extensive analysis of the recent literature, aims to provide a comprehensive framework of trends and challenges in railway sustainability, with particular attention paid to track and related materials and components, maintenance strategies, and methods of assessment of sustainability. The followed approach takes into consideration the lifespan of the track and the related main stages. The results show that: (i) several innovative sustainable materials have been introduced with significant environmental performances and limitations, mainly due to the lack of knowledge of long-term mechanical behavior; (ii) appropriate strategies of maintenance, supported by effective monitoring of the track conditions, can reduce negative effects on the environment and society and contribute to making this transportation mode greener; (iii) many devices for the automated detection of the track defects allow increasingly widespread and effective monitoring of the track and are essential means in overcoming the challenge of "smart rails"; and (iv) life cycle assessment (LCA) and circularity metrics are effective and indispensable tools in the decision-making process, since they help to quantify the potential environmental enhancement of different materials and solutions.

Keywords: railway; track; sustainability; materials; maintenance; monitoring; circular economy; life cycle assessment

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1. Introduction

As it is well known, sustainability deals with "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. With growing concern for the environment, sustainable development has become one of the primary goals of all nations throughout the world.

Sustainable mobility and infrastructure are main global challenges and are important aspects of transport development. Rail transport is part of the solution to the challenge of sustainable transportation.

Railways play a structuring role in the European economy, as they facilitate the production and distribution of goods and economic services and form the basis for the provision of basic social services [2]. Indeed, rail transport is becoming increasingly important as part of the transportation system, and railway lines are an integral part of the countries' transport networks. In addition to their central role within the mobility system, some figures demonstrate the environmental performance of the railways well. Transport systems as a whole contribute about 21% of the total emission of carbon dioxide (CO_2) in the world. The main responsibility lies with road transport, which contributes about 74%, followed by aviation and marine transport, which both account for about 11%, and, lastly, rail comprises 4% [3]. Figures make clear that rail is the main pillar of transformative climate action in transport and the fastest and most cost-efficient way to decarbonize people's daily mobility and logistics chains. Two climate goals in the long term (2050) and in the transition term (until 2050) must be pursued: in the long term, zero direct emissions must be achieved, in parallel with the decarbonization of the energy sector; in the transition term, because Greenhouse gases GHG emissions persist in the atmosphere and contribute to climate change, we must minimize the cumulative to keep to the 1.5 °C target. Countries' developments need to follow paths toward these goals. As the cleanest and greenest high-volume transport, rail, representing 8% of global passenger and freight transport activity (in passenger per km, and tons per km), is expected to become the backbone of future sustainable mobility [4,5].

However, the evident sustainability of the rail does not exempt asset owners, researchers, or practitioners from continuing to make efforts to find solutions aimed at improving this mode of transport more and more, from the viewpoint of environmental sustainability. To this purpose, it is worthy to highlight that rail generates the lowest CO_2 emissions and energy consumption during operation, with respect to the other transportation modes, but during its construction and maintenance phases, CO_2 emission, energy consumption, and other environmental impacts are significant and need to be carefully assessed and properly mitigated [4,6,7]. This circumstance calls for research efforts aimed at improvements in specific aspects in all stages of railway lifespan [8], and particularly in construction and maintenance, where materials, practices, equipment, and strategies can be optimized with the aims of minimizing negative effects on the environment and society and making this transportation mode greener. In recent years, there has been a significant surge in research productivity on the environmental impact and sustainability of rail systems; however, this is very low in comparison to other topics and, therefore, further studies have been requested [9].

In railway operation, it is fundamental to guarantee the high quality of the service and provide a trip with efficiency, safety, and comfort. The quality of the track, ensured by adequate construction methods and materials and frequent maintenance activities, is essential to this purpose. Further, as several studies demonstrate, it is also important to analyze the effects of climate change on the vulnerability of the infrastructure [10–15]. In this context, the development and renewal of infrastructure are critical challenges [16–18]. Building new tracks or maintaining existing ones is a resource-intensive activity, resulting in environmental damages that must be reduced. In the literature, several papers, as will be discussed in the following sections, deal with the sustainability of the rail track, but they are limited to certain components and/or phases of the service life.

The objective of this work is to provide a comprehensive overview of the actions for sustainability in railways, with a special focus on track, and also to highlight challenges to overcome in the present and the future. The topics investigated include: (i) materials used in the construction and maintenance of track; (ii) maintenance strategies; (iii) devices for monitoring the state of the track; and (iv) methods of sustainability assessment.

The paper is articulated as follows. The Section 2 describes the methodology followed in addressing rail track sustainability. Section 3 reports the results of the study on the state of the art, based on the collected and analyzed publications belonging to the most recent literature. Finally, Section 4 reports the concluding remarks and outlines the future perspectives of the research.

2. Methods

The methodology used in this study to assess the actual trends regarding the environmental sustainability of rail track and to outline the future challenges takes into consideration the lifespan of the track and the related main stages, as shown in Figure 1.

Figure 1 explains that sustainability must be pursued from the track conception in the design phase, when the choice of suitable track system (ballasted or ballast-less) and its related materials and components requires the consideration of environmental concerns, as well as technical, functional, and economic aspects. In ballasted track, the rails are connected to the sleepers, which distributes the loads to the ballast layer. In the ballastless or slab track, the rails are supported by concrete slabs on the supporting layer. The construction features of these two systems result in different performances in service: the higher construction cost (30% to 50% higher than ballasted) and higher environmental impact (due to the cement production) of the slab track correspond with lower maintenance costs (20–30% of the cost for ballasted track), a higher service life (60 years instead of 40), and an overall lower life cycle cost, also considering the environmental costs, as demonstrated by several studies [19,20]. The traditional ballast system is, nevertheless, widespread all over the world; the ballast layer resists applied loads, providing adequate resilience and drainage, but its progressive degradation and the soiling of ballast are common problems and require a lot of maintenance.

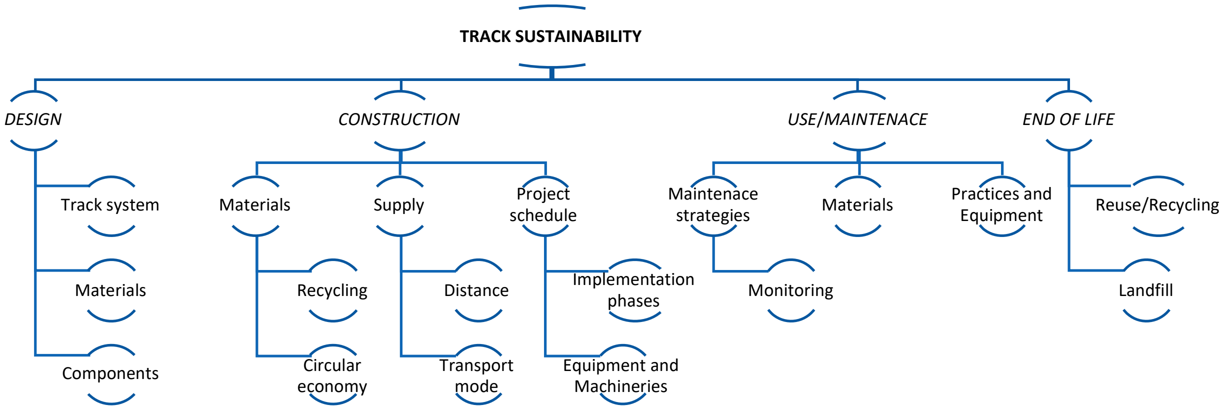


Figure 1. Areas of improvement of track sustainability in life cycle phases.

During construction, the mitigation of inevitable impacts and environmental sustainability arise from the choice of the materials, the supply mode, the supply distance of materials and components, and the construction schedule. As for the materials, their selection must focus on the circular economy and then on the use of recycled materials, which produce benefits for the environment, but it is also important to consider the supply mode (train or road vehicle) and the distance. Materials transportation is, in fact, one of the significant sources of air and noise emissions, which merits being careful when considering an environmental sustainability perspective. Impacts during constructions are usually temporary, and, therefore, the duration of the construction phase affects the disturbance produced by the activities and the acceptability of the negative burdens. The project schedule, the timetable that outlines start and end dates and milestones that must be met for the project to be completed on time, and adherence to these scheduled times, are crucial aspects in lowering the generated impacts. Another relevant topic to consider is related to the equipment and machineries: the number and type thereof contribute to the adherence of the timetable and the quality of the executed works, but they are usually diesel powered and therefore emissive [21]; thus, the choice of the type of machinery must be regarded as one of the actions required to achieve sustainability.

The use phase is here discussed with regard to the maintenance needed during the service life. The sustainability issues of the operational phase of the railway are not the subject of this study. Maintenance strategies, materials, and practices and equipment are important themes in track sustainability. Ballasted track requires frequent interventions, aimed at ensuring geometric and structural quality, for the efficiency, safety, and regularity of train service.

Areas of enhancement of track sustainability in the end of life (EoL) stage are reuse/recycling, of the dismantled materials and components, and landfill, when recycling/reuse is partially or totally not allowed.

The significance of considering all the lifetime stages in the environmental sustainability assessment is suggested by several studies in the literature [20,22,23]. From studies, it can be derived that, in LCA with a midpoint approach, the main contribution to the impact of the life cycle is provided by the construction phase, including the production and transportation of materials and components, and by the maintenance phase. The EoL can have positive effects in some impact categories, depending on the approach used for recycling (i.e., a 100:100 approach or another). The focus on construction and maintenance appears therefore decisive. In addition, the contributions of track components to the different impact categories at various stages is of pivotal importance to establish strategies for improving sustainability.

From the analysis carried out, materials and maintenance strategies, supported by track monitoring, appear to be critical areas which researchers and practitioners must spotlight to increase sustainability. The methods for environmental assessments are crucial for qualitative and quantitative estimates of the benefits of alternative choices.

Table 1 synthetizes the main references analyzed in this work with the theme of sustainable measures, considering the quoted critical areas and related track components.

Table 1. Synthesis of the state of the art on track sustainability measures.

Topics	Track Component	References
Materials	Ballast	[24–45]
	Sub-ballast	[6,46,47]
	Sleepers	[48–53]
	Rail	[54–59]
	Fastening system	[60]
	Under sleeper pad	[61,62]
	Under ballast mat	[63]
Maintenance strategies	All	[64–77]
Monitoring	All	[78–83]
Environmental assessment	All	[84–98]

3. Results

3.1. Sustainable Track Materials and Components for Construction and Maintenance

To ensure efficiency and functionality over time, railway superstructures require both effective construction techniques and materials, and recurrent maintenance activities. The increases in traffic volumes, axle loads, and speed result in static and dynamic solicitations that increase wear and tear and the degradation of the track in all its components, such as rails, switches, sleepers, and subgrade, but particularly in the ballast layer [99]. The adequate quality of materials and mechanical properties of the track components are fundamental to counteract these phenomena and are essential to guarantee efficiency and safety during the service life of the track. In addition, increasingly pressing environmental issues require the evaluation of solutions which can offer an excellent environmental sustainability performance. In the following sub-sections, for all the track components, an analysis of the sustainable solutions is reported, highlighting potentialities and limitations.

3.1.1. Ballast

The ballast layer has the following functions [24]:

- Allows the resistance of sleepers against vertical, longitudinal, and lateral displacements, thus providing stable support for travelling trains.
- Transfers train forces to the subgrade, according to its bearing capacity, thus reducing compressive stresses on the subgrade.
- Keeps track geometry in the vertical and lateral directions.
- Provides elasticity to the railway track, achieving proper riding comfort.
- Provides effective drainage to the track and facilitates the absorption of noise and vibration.

The quality and mechanical characteristics of the ballast depend on the parent rock, petrography, size, and shape. The ballast is the weakest element of the superstructure because it is subject to the greatest deterioration; in fact, being an unbonded layer, the passage of vehicles, their speeds, and their vibrations cause geometric decay and the degeneration of the quality levels. This implies that the ballast requires more frequent maintenance interventions, specifically tamping, than other elements. The ballast quality directly influences not only track service life but also the tamping demand. Service life and tamping demand depend on loads, radii, ballast quality, and the subsoil and drainage, as demonstrated by Marschnig and Veit [25]. These reasons stimulated researchers to explore alternative materials and technologies for the construction and maintenance of the ballast layer, with the objective of increasing its stability and durability [26–30]. Some promising ballast technologies also focus their attention on environmental performance [31,32]. They include recycled crushed stone, asphalt materials, steel slag, and crushed stone bonding.

Various selection criteria for ballast materials and test methods for quantifying ballast quality have been applied [33–35]. Material properties affect the durability of the ballast layer and further the durability of the track itself.

As train speed and axle load increase, there are more demanding requirements for particles in the ballast layer, such as a tighter particle size distribution (PSD), higher particle strength, and higher particle densities. Note that the use of crushed stones as ballast material increases the difficulty of maintenance. Several studies have summarized the test methods for determining the mechanical, physical, environmental, and geometric properties of ballast materials. The two traditional and commonly used tests are the Los Angeles abrasion test (LAA) and the Micro-Deval abrasion test (MDA). The LAA test is performed only on dry ballast particles, while the MDA test can be performed on dry or impregnated particles. Based on the properties of the ballast and the corresponding tests, the quality of the ballast can be classified. It is inferred that the quality is classified according to degradation and weathering.

Other tests, more representative of the field condition, that are used to evaluate and measure the mechanical behavior of ballast are large scale triaxial and box tests. In particular, a large scale triaxial test allows for the understanding of properties like shear strength, angle of friction, shear stress–strain behavior, and volumetric change behavior under triaxial conditions; the box test instead simulates the behavior of ballast under a realistic field situation, like the vertical displacement of the fresh and fouled ballast under and away from the sleeper [35].

Considering the global strategy of low-carbon economies, it is important to maximize track life instead of replacing old/building new track. In addition, the principles of a circular economy must be even more so applied in the railway sector. To this purpose, traditional materials and solutions are joined to alternative materials, with the double aim of increasing durability and performance and guaranteeing environmental sustainability. For example, it has been shown that, by mixing a certain percentage of the ballast with the new ballast, the performance of the layer can still be maintained. Alternatively, it has been shown that waste ballast can be used to pave roads, when mixed with asphalt. Still, even waste products from industries can be recycled for use on railways.

Some alternative recycled materials, listed below, are proved to increase the lifetime and performance of the ballast, in addition to which, being recycled materials, they also make it possible to pursue economic and environmental benefits, according to the criteria of the circular economy [24]. In fact, the application of recycled waste materials in transport infrastructure developments is an efficient way to minimize waste accumulation in stockpiles.

- *Steel slag* as rail ballast exhibits interesting technical properties, such as a higher modulus of elasticity, lower vertical stress, and lower permanent deformation under high train loads. These observations imply that the use of steel slag ballast (SSB) can potentially reduce track maintenance costs, owing to its lower settlement and breakage, its ability to enhance the lateral resistance due to its higher density, and its ability to provide better riding comfort because of its higher resilient modulus [27,36]. Drawbacks of the use of this material include the following: its reliance on volume expansion; its leaching of heavy metals; signaling interference; incomplete standards of application; difficulties in quality control; the results of a heavy track; and high maintenance costs [24].

- *Steel slag and crushed rocks*: the mixture of crushed rocks with steel slag, by 50% (or lower), allow for the creation of a material that meets the standard for special class ballast, in terms of abrasion resistance, and improves the shear strength of the slag–rock ballast, compared to a pure steel slag ballast layer [37]. Based on laboratory tests, Esmaeili and Askari [38] found that the use of EAF (electric arc furnace) slag ballast (SB) increased the stiffness of the track by 35%, compared to rock ballast. They suggested a percentage of 75% of SB to balance the stiffness and damping ratio.
- *Steel slag and tire-derived aggregate (TDA)*: a study demonstrated that the settlement and damping ratio increased with an increase in the TDA percentage, whereas the breakage index and the stiffness of the ballast decreased. A TDA of 10% by weight (16.5% by volume) was selected as the optimum percentage for the mixture for a good balance between the dynamic stiffness and the damping ratio [30].
- *Crumb rubber (from end of life tires)*: a low percentage of this material (10%) brings significant improvements to the ballast's behavior, in terms of its settlement and deterioration, mechanical properties, capacity to dissipate energy, and contributions to extending the service life of a railway track [26,39]. The main disadvantages are drainage interference, potential contamination, low resilience, performance uncertainties due to limited use, interference in ballast–ballast contact, and uncertainty over movement in the ballast layer [24].
- *Asphalt*: the use of asphalt in the ballast layer improves the ballast layer's stiffness, by bonding the discrete ballast into a form of track between a slab track and a ballasted track. The asphalt can be recycled and decomposed after heating, making it easier to maintain and repair. Conversely, asphalt in ballast is costly and creates a high maintenance cost, producing maintenance difficulties, and is also subject to temperature deformation, posing the problem of long-term creep control [24].
- *Polyethylene fibers*: studies demonstrated that, when narrow fibers were used, the fiber-reinforced ballast significantly reduced the settlement, because the fibers in granular materials reduced the lateral expansion of the mixture (with smaller principal strains) and mobilized a higher stress ratio [40].
- *Polyurethane, cement, and geopolymer*: these binders act like asphalt; the differences entail with costs, working principles, and installation. Geopolymer is a promising material with a low carbon footprint but suffers with the problem of thermal expansion and contraction. A glued ballast layer is subject to rapid degradation, due to fouling in the ballast layer [41].
- *Bitumen-stabilized ballast (BSB)*: it represents an innovative solution, designed to increase ballast service life and reduce overall maintenance burdens. This technology, which can be used for new track beds, as well as for reinforcing existing ones, consists of the use of bitumen emulsion (BE) poured or sprayed at ambient temperatures onto the ballast. The main advantage resulting from the use of BSB is its long-term use (between 40 and 60 years) [42].
- *Geogrids*: several studies and experiments have shown how the inclusion of a geogrid in the ballast increases the service life of the track, improving the strength properties and, particularly, the resilient modulus of the railway ballast. Geogrids also reduce the extent of the dynamic amplification factor (DAF) [43,44].

For the application of new materials and technologies aimed at improving track response and durability, it is necessary to provide a set of recommendations and guidelines, distinguishing between design-based solutions and maintenance-based solutions. Design-based solutions include the use of elastic elements, the development of alternative elastic elements, the use of geogrids, and the use of bituminous layers. Maintenance-based solutions include conventional tamping, the use of stone blowing, and ballast stabilization, including polyurethane-based stabilization techniques [45]. Finally, it is worth highlighting that the limited application of these new ballast materials requires more deep evaluations, in order to report their maintainability with different tamping techniques and their degradation as a consequence of tamping and stabilization.

3.1.2. Sub-Ballast

Regarding the sub-ballast layer, the literature shows that sustainable solutions are related to the use of the following: non-conventional bituminous mixtures made with recycled materials [6], which are able to ensure great layer stability; and geocell-reinforced coal mine overburden waste materials [46], which have been proved to ensure a decrease in vertical settlements, lateral deformations, and subgrade stresses. A recent study [47] demonstrated that the use of recycled rubber products, such as CWRC mixtures (i.e., mixtures of coal wash (CW) and rubber crumbs (RC)) and SEAL mixtures (i.e., mixtures of steel furnace slag, CW and RC), to replace sub-ballast, tire cell reinforcements for sub-ballast and under-ballast mats increases the energy dissipation effect of the track, hence reducing the ballast degradation efficiently and increasing the track stability.

3.1.3. Sleepers

Another important component of the track is the sleeper. Several kinds of sleepers are in use: timber, steel, and concrete. Timber was the earliest material used, due to its excellent dynamic, electrical, and sound-insulating properties. The scarcity of timber and the growing environmental sensitivity, as well as problems related to timber rotting, splitting, insect attacks, and a limited service life (20 years), have led to the progressive disuse of this material.

Steel has been used as alternative material to timber. Steel sleepers are highly economical from the viewpoint of maintenance costs with respect to the concrete ones, and, in addition, the old ballast can remain in place, reducing new ballast requirements. The main drawbacks associated with their use are higher transportation costs, due to the heavy weight, being difficult to handle and requiring expensive and extensive equipment for installation, risk of corrosion, high electrical conductivity, fatigue cracking in the rail seat region, and difficulty of packing them within the ballast [48]. Mono-block pre-stressed concrete sleepers, since 1943, have been a widely used solution throughout the world in heavy haul and high-speed rail track constructions. This extensive application is due to their durability and lateral resistance [49]. Their main shortcomings can be summarized as the low impact resistance and susceptibility to chemical attack, together with the higher costs for transportation and handling due to the weight. A more lightweight solution is the bi-block sleeper, which consists of two lightly reinforced concrete elements held together by a steel tie rod, whose function is to guarantee the correct track gauge and to keep the adequate spacing among the aggregates in the casting. Compared to mono-block, bi-block sleepers, under certain conditions of ballast layer configuration, can ensure a greater resistance to lateral actions [50].

The mentioned timber, steel, and concrete sleepers generate several environmental concerns, due to the cutting down of the trees in the first case and the higher amount of CO_2 emitted in the production process of steel and concrete.

Research on sustainable solutions for this component has led to innovative projects based on the use of composites which, when engineered according to specific requirements, can ensure a high strength-to-weight ratio, excellent resistance against corrosion, moisture, and insects, and thermal and electrical non-conductivity. Different sleeper technologies have been developed with composites (Tietek, Axion, I-Plas, KLP, MPW, Wood core), mainly to replace the timber ones. Limits to the extensive use of these technologies are due to their low strength and stiffness properties, low anchorage capability, formation of material voids, creep deformation, and the high price of composites, especially for the use of fibers. In addition, the lack of information on their long-term performance under different loads and environmental conditions prevents technical and environmental evaluations on their use, from a life cycle perspective [48].

Another project which uses recycled materials is the Greenrail sleeper [51], which has an inner core of pre-stressed concrete and an outer shell made of a mix of rubber from old tires and recycled plastics. Rubber and plastic materials increase the average lifespan of a railway sleeper by reducing its maintenance needs and costs by two to two and a half times, compared to concrete. In fact, it reduces the ballast pulverization and provides greater resistance to the lateral displacement of rails and significant electrical isolation. Further, the outer shell creates less noise and fewer vibrations as the train passes over it, reducing noise pollution for nearby residents. Greenrail sleepers exhibit also greater resistance to fracturing problems caused by freezing and thawing. From an environmental standpoint, it is worth highlighting that the Greenrail sleepers needed for 1 km of a railway line contribute to the recovery of up to 35 tons of ELTs and plastic from urban waste [52].

With regard to the traditional pre-stressed concrete sleeper, a recent study [53] presented an innovative solution, called laminated CFRPU-reinforced green concrete railway sleepers (LCRG-type), in which reinforcements are made with laminated carbon-fiber-reinforced polyurethane (L-CFRPU), and concrete is produced with 30% lower cement and a dosage of 50% natural pozzolan. For the new sleeper, the CO_2 emission value is 54% less (on average) than conventional concrete sleepers, but compressive strength is almost halved.

Recently, recycled composite sleepers have been produced and applied on the weight-restricted Sherrington Viaduct, between Salisbury and Warminster, in the United Kingdom. These are expected to achieve the zero carbon 2050 target, due to at least a 40% reduction in greenhouse gas emissions from sleeper production and reusing recycled plastic within the track infrastructure for at least 50 years. Designed for over 50 years of use, when they are eventually replaced, they can be re-used, re-purposed, or recycled to make new sleepers or other composite products.

3.1.4. Rails

As for the rails, higher axle loads and speeds can lead to excessive wear, rolling contact fatigue (RCF), and ultimately fracture of the steel rails, depending on the type of steel. To withstand these phenomena and increase the rail service life, different strategies can be put into action. Higher strength steel grades have proven to be an optimal solution which significantly elongates the service life of the rails and reduces maintenance needs. Steel alloying and heat treatment are widely used to improve the lifespan of rails [54]. The use of harder steel poses the problem of wheel wear. In Europe, rail steels typically range in hardness from 260 to 440 Brinell hardness (HB), while wheel grades range in hardness from 225 HB to 255 HB. It has been demonstrated that, when the rail is harder than the wheel, there is no influence of increasing rail hardness on wheel wear [55]. Rail wear decreases with increasing hardness, and wheel wear remains unchanged, resulting in a reduction in overall system wear. Rail–wheel contact is a key aspect in the durability and service life of these two components. Lubrication has been extensively used on the gauge face of the high rail of sharp curves to reduce wear and RCF, by reducing the friction at the contact interface between the rail and the wheel [56]. However, RCF crack growth may increase, due to the pressurization of lubricant into the crack and/or because reduced wear means that cracks are truncated less [57]. With the aim of causing less damage to tracks, track-friendly running gears have been developed in recent years. However, to judge the track-friendliness of a running gear, both the track damage it causes over cumulative tonnage and the associated maintenance interventions must be considered [58]. One area of improvement in this component concerns the connection. Continuous welded rails (CWR) have increased consistently worldwide, thanks to their many advantages over the conventional jointed rail track, in terms of, for example, a reduction in maintenance costs or an increase in the life cycle of track components. A phenomenon to be controlled and tackled is track buckling, generated by the thermal dilatation of rails at hot temperatures, which, in extreme cases, can led to the interruption of rail services. Painting rails white is a current practice aimed at reducing the temperature of the rails and mitigating the risk of buckling. Some coatings are able to reduce the temperature of the rail by up to 10 degrees.

Since the production of steel is an emission process, increasing the durability and the service life of the rails and reducing the need for maintenance positively affects the rails' environmental sustainability. Further, it is worth noting that steel is a material that can be 100% endlessly recycled. Due to the high recyclability and relatively high value of scrap steel, this option often seems more attractive, as well as sustainable, and is in line with the principles of a circular economy. The reuse of these components poses the following technical challenges: a lack of standardization of components, uncertainty regarding the efficiency of reused components, lack of knowledge regarding fatigue history and product composition, and possibly inappropriate decomposition handling. The criteria for reuse are established as follows: if the components are "as good as new", they can be reinstalled in all lines; if they are "almost as good as new" they meet the criteria for less frequent lines and can be repurposed and used in secondary lines; if neither is possible the material is sold as scrap, used as fence posts or supports for railway equipment such as signals, or sold to produce designer furniture [59].

3.1.5. Fastening System

The fastening system is a key component of track structures, because it fixes the rail to sleepers and retains it in the required position, whilst permitting any necessary vertical, lateral, and longitudinal movements. An additional key function is reducing the noise related to high-speed trains and track structures. Fastening systems include a variety of components such as clips, bolts, screws, and plates. There are various type of fastenings: with and without plate, elastic, tree screw with plates, Pandrol E-clip, and Pandrol Fastclip, etc. Different types present different elasticities and suitability for timber sleepers, concrete sleepers, and slabs. Given the important function they perform, understanding the external and internal mechanisms of rail fastener failures and the potential detrimental consequences to railway operation safety is very important. A recent study investigated the suitability of the combined use of image processing and deep learning algorithms for detecting missing clamps within a rail fastening system [60].

3.1.6. Resilient Components

Under sleeper pads (USPs) and under ballast mats (UBMs) are two important resilient components in tracks.

USPs, usually made of polyurethane elastomer with a foam structure including air voids, are installed underneath sleepers to provide additional track resiliency between the sleepers and ballast. The main objectives for using USPs are to moderate track stiffness, to reduce ground-borne vibrations, and to reduce ballast breakage. The stiffness is a key aspect of this component, because it affects the degradation speed of the infrastructure. In fact, high pad stiffness could increase the dynamic loads and stresses on the substructure, whereas a low stiffness could cause damages in the rail track, increasing their stress state even more. Engineering properties in recent years have been merged with environmental concerns, and the suitability of rail pads with recycled polymers and crumb rubber has been studied [61,62]. The use of plastics and crumb rubber allow mats to enact different solutions and can reduce the stiffness more than 50%, even if softer solutions lead to higher plastic deformations during fatigue tests, reducing their durability, in comparison to the pads made from high-density polyethylene. From an environmental standpoint, plastics offer a reduced carbon footprint, compared to conventional pads.

UBMs, usually made with elastomeric materials like polyurethane or rubber, are used in ballasted track to reduce rail vibrations and protect the ballast against fast degradation generated by the abrasion and breakage of its particles. Also, for this component, recent studies demonstrated the suitability of the use of rubber from end-of-life tires, with the double benefits of reducing both the cost and environmental impacts [63].

3.2. Maintenance Strategies: Environment-Related Effects

Maintenance is constantly required in ballasted track to ensure the efficiency, reliability, availability, functionality, and safety of the railways. The replacement of the components and renewal of the track are needed at the end of the service life (Table 2). An efficient maintenance and repair (M&R) operation would ensure the optimization of resources, leading to smarter and more sustainable infrastructure.

Table 2. Service life of ballasted track components.

Component	Service Life [Years]
Rail replacement	28
Sleepers' replacement	40
Fastenings replacement	40
Ballast recovery	30
Tamping/levelling	1–5

The component towards which maintenance is mainly addressed is the ballast, which needs periodic interventions to maintain its alignment and restore its geometry to an acceptable condition [64,65].

Maintenance activities include renewal and re-construction, as well as ballast cleaning, resurfacing, rail-head grinding, and re-railing. From an environmental standpoint, all these activities require the use of resources and diesel power machineries, such as: tamping machines (which have a diesel engine), used for packing, lifting, and lining the track bed; ballast regulators, used for replenishing ballast and rebuilding shoulder profiles; and dynamic stabilizers, which, when passing through the track, consolidate the ballast aggregate to a uniform fit, ensuring a good interlocking between the crushed aggregates. All these operations have the aim of extending the track's life, reducing riding discomfort, and improving train–track interaction and the functionality of the infrastructure. CO_2 emissions from railway maintenance equipment are significant, as demonstrated by several studies [21,66,67]. Some authors [21,68] found that track geometry restoration is peaked by ballast-cleaning activity, followed by ballast tamping and regulating and stabilizing. The formation/rehabilitation and ballast-cleaning machines have the highest impact per kilometer by far, but tamping produces the highest annual emissions, due to the fact that it is the most frequent work performed on the track. An improvement in productivity, achievable using parallel multiple tamping heads/units, can considerably reduce life cycle CO_2 emissions. Regarding the construction and maintenance machines, the mitigation of CO_2 emissions can arise from the use of alternative drives, with the aim of achieving zero direct emissions. Zeiner et al. [68] identified battery technology and hydrogen fuel cells as suitable solutions for energy demands lower than 300 kWh per construction shift and higher than 800 kWh, respectively. For energy requirements between these amounts, enhancements in battery technology are necessary and desirable in the coming years.

Few studies deal with the prediction of the effect of climate change on the maintenance of railway networks. Dépoues [69] addressed the need to proactively consider climate change as an external constraint in the early stages of planning and decision-making. Palin et al. [70] studied the effect of increasing temperatures during the summertime and extreme weather on track components in Great Britain. They found that the increasing temperature during the summer could result in track buckling, the postponement of maintenance operations, and the exposure of workers to heat stress during outdoor maintenance.

The environmental aspects of maintenance cannot be underestimated, with respect to cost-effective issues. The optimization of maintenance activity from technical, economic, and environmental standpoints requires the awareness that this is a critical activity in managing railway infrastructure assets. Maintenance management covers a wide range of themes [71]:

- Maintenance policy: preventive maintenance, corrective maintenance, or improvement;

- Maintenance operation: activities and equipment;
- Degree of maintenance: perfect, imperfect, or minimal;
- Decision-making level: strategical, tactical, or operational;
- Maintenance planning: action intervention and prioritization, intervention timing, and inspection interval planning;
- Maintenance scheduling: possession time of the track for maintenance, maintenance sequencing, vehicle routing, and crew scheduling.

Another important theme is related to the decision-making process. In this sense, track degradation modelling is the basis for estimating the appropriate time for condition-based maintenance interventions in railway track maintenance. The literature on this topic has been gathered and deeply analyzed. Track degradation behavior is affected by uncertainties about heterogeneous influencing factors, such as weather conditions, train axle loads, track-bed settlements, and construction materials [72].

Researchers classify degradation models into mechanistic or physics-based, empirical or data-driven, and hybrid models, considering both physics-based and data-driven models [73,74].

In recent years, AI-based models have become popular, as they can overcome the deficiencies of current mechanistic models in predictions of rail track degradation. AI models involve activities and developments relating to human-like intelligence reproduced by computer applications. For this purpose, they exploit computer techniques or reasoning algorithms that attempt to automate intelligent functions [75,76]. AI models can be categorized into different sub-categories, including artificial neural networks (ANNs), adaptive neuro-fuzzy inference systems (ANFIS), decision support systems (DSSs), and machine learning models.

The efficiency of the railway network system can be improved through a higher control of the maintenance processes and application timing. It increases the overall quality level of the track-bed, reduces the discomfort experienced by users, decreases the environmental impacts [77], and promotes a better allocation of the commonly large amount of economic resources needed for maintenance and renewal [72].

3.3. Devices for Monitoring the State of the Track

Monitoring the state of the track is a core activity for implementing the correct maintenance strategies in terms of sites, time, and modes of interventions. Intervening on the track at the correct time and in the correct mode allows for an increase in its lifetime and, therefore, a reduction of the need for reconstruction/rehabilitation that results in significant environmental impacts.

Research carried out on the devices for monitoring showed that there are several devices that enable European railroad companies to perform track diagnostics to support maintenance activities. The main geometric parameters monitored are as follows: gauge, alignment, longitudinal level, transverse level, and twist. Various other parameters related to the track components can be monitored with manual devices (e.g., hand-driven trolley measuring systems) or with equipment mounted on the board of vehicles (e.g., track recording vehicles) [78]. The first type of inspection is labor-intensive, prone to human error, time-consuming, expensive for railroad companies, and also poses safety issues for maintenance staff. Further, it is not suitable for long-term and large-scale development projects. Automated inspection systems, based on machine vision, are widely used for the inspection of the track and its components. Moving towards autonomous visual inspection will facilitate a reduction in resource consumption arising due to manual labor, thus making the railway sector more sustainable. Various techniques have been developed to allow measurements to be made continuously or at fixed points.

These include:

- RSMV, rolling stiffness measuring vehicle, is a technique used in Sweden that is based on measurements of track stiffness. It is used to identify areas where action is needed.

- FWD, falling weight deflectometer, is a non-destructive test (NDT) used in the United Kingdom. The data obtained, after the test is carried out, allow the elastic modulus of the lower zone of the track to be calculated.
- GPR, ground-penetrating radar, is a tool that allows for fast, non-destructive inspection to estimate the integrity of the railway substructure. It provides continuous measurements of the thicknesses of the layers of ballast, sub-ballast, and subgrade. The measurements are sensitive to water content and material density. It is also capable of distinguishing dirty ballast from clean ballast.
- Acoustics, electromagnetics, and machine vision are NDTs for rail. Each of these tests has advantages and limitations. Acoustic tests, and particularly ultrasonic tests, and electromagnetic tests are suitable for detecting the internal defects of the rail but cannot accurately detect the surface damage; on the contrary, visual inspection is suitable for the detection of cracks, deformation, and corrosion on the rail surface but cannot detect internal damage. Combined NDT techniques allow personnel to overcome these limitations and reach a greater accuracy in defect detection [79].
- The Archimede train is the most important diagnostic tool in Italy. It consists of a locomotive, four coaches, and a driving trailer. It can simultaneously measure 119 primary parameters and more than 200 derived parameters at 200 km/h. The on-board equipment comprises 57 computers, capable of globally processing data, which are designed to be able to withstand electromagnetic interference. An innovative positioning system enables the accurate localization of each measurement at a specific point on the network. This train, which has the ability to measure track, ride quality, overhead line, signaling, and telecommunications conditions, has made it possible to:
  - Make measurements that were not possible before its introduction (2003);
  - Carry out line monitoring without interruption;
  - Increase the frequency of visiting operations;
  - Carry out different measurements simultaneously;
  - Increase the maximum diagnostic speed from 160 to 200 km/h.
- ETR500Y2 Dia.man.te (acronym for diagnostics, maintenance and technology) is an innovative train used in Italy to periodically monitor the conditions of the infrastructure, track, contact lines, signaling equipment, and telecommunications facilities of high-speed high-capacity railway lines. It consists of two driving trailers and height coaches, where 16 diagnostic systems, with 98 cameras and over 200 sensors, are installed on board. These are placed on the roof rail, in the underbody, and on the trolleys near the wheels, to monitor data and values aimed at analyzing the conditions of the railway infrastructure, such as, for example, the geometry and wear of the track, the interaction between the wheel and the rail, the quality of energy collection from the overhead power line, signaling, and telecommunications. The train is able to measure 500 parameters at 300 Km/h.

Furthermore, different types of sensors are used today [80–83]. The inclusion of sensors in railway track components permits the automated and real-time monitoring of track behavior and traffic conditions, which is necessary for adopting preventive maintenance strategies. Various types of accelerometer, piezoresistive, and piezoelectric sensors were evaluated, to determine their viability for smart rail pads. The piezoelectric sensor presented the highest implementation potential for this application, considering its low cost and clear ability to monitor variations in traffic and/or track state. Some of these sensors are as follows:

- Fiber optic sensors: in the last two decades, a significant number of innovative sensing technologies, based on fiber optic sensors (FOS), have been utilized for structural health monitoring (SHM) due to their inherent distinctive advantages, such as their small size, light weight, immunity to electromagnetic interference (EMI) and corrosion, and embedding capability. Fiber optic-based monitoring systems use quasi-distributed and continuously distributed sensing techniques for the real-time measurement and long-term assessment of structural properties. This allows for early stage damage detection and characterization, leading to timely remediation and the prevention of catastrophic failure.

- Force sensing resistors (FSR), or piezoelectric sheets, work by measuring voltage changes due to variations in the stress levels to which they are subjected.

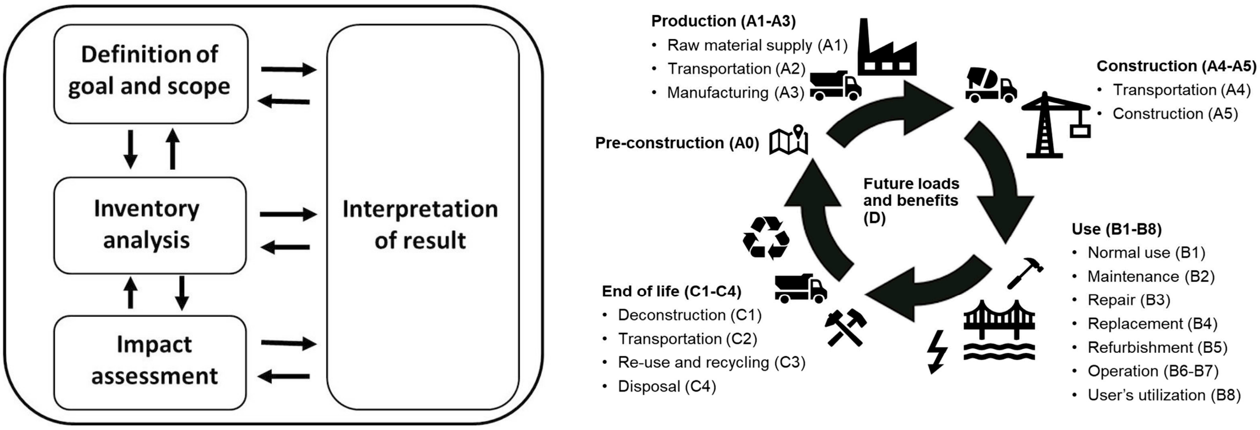
Based on monitoring data, there are specific tools that help to manage maintenance tasks. For example, Timon is a computer application that is being used in France to visualize track defect development and provide information on actions (i.e., tamping and grinding) and future analysis to be performed; another example is Defrail, a digital application for describing rail defects.

3.4. Sustainablity Assessment Methods

The assessment of the real performance of alternative materials and technical solutions, and the awareness to mitigate the environmental negative burdens, call for the consideration of many classes of impacts, and for methods able to perform sound analyses referring to the life cycle of a railway track. Different methods can be used for this purpose. Below, the applicability of life cycle assessment and circularity metrics are discussed.

3.4.1. Life Cycle Assessment

Life cycle assessment (LCA) is a methodology defined by ISO 14040, 2006 a, b [84,85], and applied to evaluate the environmental impacts of a product/material over its entire life cycle. A LCA aims to analyze the "environmental profile" of a rail infrastructure project or construction process, and it is a useful operational tool for integrating sustainability into project development and for measuring the environmental and energy loads. The LCA framework encompasses four stages: (i) goal and scope definition; (ii) life cycle inventory analysis (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation, as shown in Figure 2a.



(**a**) (**b**)

Figure 2. (**a**) The phases of the LCA, ISO 14040, 2006a; (**b**) schematic illustration of the life cycle stages of a civil engineering works project and their classification in modules, ISO 21931-2.

According to the current ISO 21931-2 [86] framework for methods of assessment of the environmental and sustainability performance of construction works, LCA is able to evaluate the impacts occurring during modules A1 (raw material extraction), A2 (the transport of raw materials to a construction material manufacturing factory), A3 (construction material manufacturing at the factory), A4 (the transport of materials to the road construction site), and A5 (all processes during construction of the road), as well as B1–B5 (road maintenance), B6–B8 (the use stage, relating to the operation of the road), C1–C5 (the end-of-life stage and relandscaping), and module D (the net benefits from reuse, recycling, and energy recovery beyond the system boundary), as shown in Figure 2b.

However, it is not always possible or necessary to include all modules (analysis from cradle to grave), as often the analyses conducted, as can be seen from the literature, are partial, and refer only to some phases of the life cycle (i.e., from cradle to gate).

Recently, several studies applied the LCA method to assess the environmental impacts of railways [20,23,87–90]. The LCA may need to fulfil different requirements in different decision contexts. Some key aspects to be addressed in LCA applications are [91]:

- Determining the length of the period of analysis.
- Estimating the maintenance frequency.
- Including the effects of climate change on infrastructure performance.

The period of analysis is commonly determined based on the infrastructure's service life. The maintenance frequency is estimated based on current practices, laboratory tests, modelling, or scenarios. The effects of climate change are considered, i.e., by comparing results in a control case (i.e., under the actual temperature regime) and in a changed climate (i.e., under a forecasted variation of temperature regime).

3.4.2. Circularity Metrics

Considering the quantity of the materials in the construction and maintenance of the rail track, one of the strategies for sustainability deals with reducing, reusing, and recycling materials and extending a product's useful life through maintenance and repair. This is the concept of the circular economy (CE), intended in sensu stricto, and focusing on the technological cycle of resources and, therefore, on slowing (for the extended period of utilization) and closing (for the circular flow) resource loops [92,93]. There is another definition of CE, in sensu latu, which refers to a sustainable economic system where economic growth is decoupled from resource use. According to this broad concept, CE "is an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being" [94,95]. The transition to a circular economy, as stated by the European Commission [96], "is a tremendous opportunity to transform our economy and make it more sustainable, contribute to climate goals and the preservation of the world's resources, create local jobs and generate competitive advantages for Europe in a world that is undergoing profound changes".

Circularity metrics and tools help to assess the impacts or benefits generated by circular strategies. Several circularity indices and tools can be found in the literature, according to the two quoted definitions of the CE [93,95,97,98]. Circularity indices express the circularity of a system and are mainly based on the quantity, in percent, of recirculated materials in a product or component. The percentage of recirculated material expresses the circularity degree. Circularity indices focus, therefore, on the preservation of materials and the reduction in the extraction of virgin materials. In this view, the contribution of recycled materials to the demand of raw materials can be represented by two indicators, as follows:

a. The end-of-life recycling input rate (EOL-RIR) measures, for a given raw material, how much of its input into the production system comes from the recycling of "old scrap".

b. The circular material use rate (CMU rate) is defined as the ratio of the circular use of materials (U) to the overall material use (M) [59].

Tools for circularity assessment analyze the contribution of circular strategies to an environmental impact or to an impact on economics and society. They can be categorized as assessment frameworks and assessment indicators. Methods belonging to the first group are based on life cycle assessment, material flow analysis, and input output analysis, and they provide several indicators assessing different aspects of the circularity of a system. The second group of tools gives such an assessment through only one indicator. Both types of tools can provide burden-based indicators (e.g., CO_2 eq), and/or value-based indicators (e.g., EUR or years).

4. Concluding Remarks and Future Perspectives of Research

The literature review carried out provides in-depth perspectives on the research area and helps to identify gaps in the literature that must be bridged with future research. From the analysis carried out, the themes to be developed in research and the challenges to be faced in the future, with regard to rail track sustainability, are mainly the reduction in the environmental impact of railway activities, through reducing waste and pollution.

- As for materials, different alternative materials, most of which come from recycling/reuse enabled by a circular economy perspective, have been proven to be capable for use in track components. Many questions merit tackling in the sustainability assessment of different alternatives: availability and supply distance, circularity index, impacts of the recycling processes, and the quantitative assessment of environmental benefits. Performance uncertainties, due to the limited use of some solutions (i.e., new sleepers or the maintainability of ballast with new materials) represent gaps to be bridged, through extensive monitoring of the behavior in service.
- Concerning maintenance strategies and their effects on the environment, regular inspections and preventative repairs are essential to address the challenges of the sustainable maintenance of rail track. New technologies enable more accurate and frequent monitoring of track conditions. Drones and specialized camera systems can survey large sections of the railroad to spot potential issues proactively. The application of sensors in critical points of the railway superstructure, such as joints and welds, allows for the acquisition of information of a different nature, with the aim of making the indication more robust and better able follow the evolution over time. In this way, it is possible to create "sensory nodes", which, with a self-powering capacity, are able to collect and transmit data to a collection point, for the formation of a database with which workers can remotely carry out diagnostic activities and anticipate and plan substitution activities on a singular point. Machine learning is a valid approach for automatically analyzing track imagery and/or data from sensors, in order to identify maintenance needs. Future research paths include the setting-up of track degradation models, to formulate appropriate and specific evaluations on maintenance requirements, while also considering new materials.
- The assessment of environmental performance, by means of an LCA, needs to be more extended in the railway sector and should address the quantification of environmental benefits arising from the use of innovative materials, components, and construction and maintenance techniques. To this purpose, a gap to bridge is the lack of knowledge regarding long-term performance, which can negatively affect the assessment of impacts in the life cycle. From the viewpoint of the wide application of the principles of the circular economy in the design and maintenance of the track, the setting-up of appropriate circularity metrics is a crucial aspect.

The future challenges of climate change require the adaptation of both new railways and the existing ones. In the first case, climate resilience can be ensured by locating, designing, and operating assets with the current and future climates in mind. The existing infrastructures can be made more climate-resilient by retrofitting them and/or ensuring that maintenance regimes incorporate resilience to the impacts of climate change over the lifetime of an asset.

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References

1. Brundtland, G.; Khalid, M.; Agnelli, S.; Al-Athel, S.; Chidzero, B.; Fadika, L.; Singh, M. *Our Common Future 'Brundt-Land Report'*; Oxford University Press: Oxford, UK, 1987.
2. European Commission. *Adapting Infrastructures to Climate Change*; The European Commission: Brussels, Belgium, 2013.
3. Ritchie, H. Cars, Planes, Trains: Where Do CO_2 Emissions from Transport Come from? 2020. Available online: https://ourworldindata.org/co2-emissions-from-transport (accessed on 26 October 2023).
4. Lawrence, M.; Bullock, R. *The Role of Rail in Decarbonizing Transport in Developing Countries*; Mobility and Transport Connectivity Series; World Bank: Washington, DC, USA, 2022. Available online: http://hdl.handle.net/10986/38214 (accessed on 26 October 2023).
5. Köllő, S.A.; Faur, A.; Köllő, G.; Puskás, A. Environmental Impacts of Railway Transportation Systems. *Earth Sci. Hum. Constr.* **2021**, *1*, 1–5. [CrossRef]
6. Bressi, S.; Santos, J.; Giunta, M.; Pistonesi, L.; Lo Presti, D. A comparative life cycle assessment of asphalt mixtures for railway sub-ballast containing alternative materials. *Resour. Conserv. Recycl.* **2018**, *137*, 76–88. [CrossRef]
7. Olugbenga, O.; Kalyviotis, N.; Shoshanna Saxe, S. Embodied emissions in rail infrastructure: A critical literature review. *Environ. Res. Lett.* **2019**, *14*, 123002. [CrossRef]
8. Milewicz, J.; Mokrzan, D.; Szymanski, G.M. Environmental Impact Evaluation as a Key Element in Ensuring Sustainable Development of Rail Transport. *Sustainability* **2023**, *15*, 13754. [CrossRef]
9. Da Fonseca-Soares, D.; Galvinicio, J.D.; Eliziário, S.A.; Ramos-Ridao, A.F. A Bibliometric Analysis of the Trends and Characteristics of Railway Research. *Sustainability* **2022**, *14*, 13956. [CrossRef]
10. UIC. *ARISCC-Adaptation of Railway Infrastructure to Climate Change*; Final Report; Nolte, R., Ed.; IZT: Berlin, Germany, 2011.
11. EEA. *Adaptation of Transport to Climate Change in Europe: Challenges and Options across Transport Modes and Stakeholders*; Publications Office of the European Union: Luxembourg, 2014.
12. Baker, C.J.; Chapman, L.; Quinn, A.; Dobney, K. Climate change and the railway industry: A review. *Proc. Inst. Mech. Eng. J. Mech. Eng. Sci.* **2010**, *224*, 519–528. [CrossRef]
13. Nemry, F.; Demirel, F. *Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures*; JRC Working Papers; Directorate Growth & Innovation and JRC-Seville, Joint Research Centre; Publications Office of the European Union: Luxembourg, 2012.
14. Armstrong, J.; Preston, J.; Hood, I. Adapting railways to provide resilience and sustainability. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2016**, *170*, 225–234. [CrossRef]
15. Giunta, M. Sustainability and resilience in the rehabilitation of road infrastructures after an extreme event: An integrated approach. *Balt. J. Road Bridge Eng.* **2017**, *12*, 154–160. [CrossRef]
16. Climate ADAPT. Operation and Construction Measures for Ensuring Climate-Resilient Railway Infrastructure. 2019. Available online: https://climate-adapt.eea.europa.eu/metadata/adaptation-options/operation-and-construction-measures-for-ensuring-climate-resilient-railway-infrastructure (accessed on 27 October 2023).
17. Wang, T.; Qu, Z.; Yang, Z.; Nichol, T.; Clarke, G.; Ge, Y.-E. Climate change research on transportation systems: Climate risks, adaptation and planning. *Transp. Res. Part D* **2020**, *88*, 102553. [CrossRef]
18. Blackwood, L.; Renaud, F.G.; Gillespie, S. Nature-based solutions as climate change adaptation measures for rail infrastructure. *Nat.-Based Solut.* **2022**, *2*, 100013. [CrossRef]
19. Praticò, F.G.; Giunta, M. LCC-based appraisal of ballasted and slab tracks: Limits and potential. *Balt. J. Road Bridge Eng.* **2018**, *13*, 475–499. [CrossRef]
20. Pons, J.J.; Villalba Sanchis, I.; Insa Franco, R.; Yepes, V. Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks. *Environ. Impact Assess. Rev.* **2020**, *85*, 106444. [CrossRef]
21. Krezo, S.; Mirza, O.; Kaewunruen, S.; Sussman, J.M. Evaluation of CO_2 emissions from railway resurfacing maintenance activities. *Transp. Res. Part D Transp. Environ.* **2018**, *65*, 458–465. [CrossRef]
22. Landgraf, M.; Marschnig, S. Towards a sustainable railway infrastructure. In Proceedings of the 12th World Congress on Railway Research, Tokyo, Japan, 28 October–1 November 2019.
23. de Bortoli, A.; Bouhaya, L.; Feraille, A. A life cycle model for high-speed rail infrastructure: Environmental inventories and assessment of the Tours-Bordeaux railway in France. *Int. J. Life Cycle Assess.* **2020**, *25*, 814–830. [CrossRef]
24. Guo, Y.; Xie, J.; Fan, Z.; Markine, V.; Connolly, D.P.; Jing, G. Railway ballast material selection and evaluation: A review. *Constr. Build. Mater.* **2022**, *344*, 128218. [CrossRef]
25. Marschnig, S.; Veit, P. Assessing Average Maintenance Frequencies and Service Lives of Railway Tracks: The Standard Element Approach. In *New Research on Railway Engineering and Transport*; IntechOpen: Rijeka, Croatia, 2023. [CrossRef]
26. Sol-Sanchez, M.; Thom, N.H.; Moreno-Navarro, F.; Rubio-Gamez, M.C.; Airey, G.D. A study into the use of crumb rubber in railway ballast. *Constr. Build. Mater.* **2015**, *75*, 19–24. [CrossRef]
27. Guimaraes Delgado, B.; Viana da Fonseca, A.; Fortunato, E.; Maia, P. Mechanical behavior of inert steel slag ballast for heavy haul rail track: Laboratory evaluation. *Transp. Geotech.* **2019**, *20*, 100243. [CrossRef]
28. Sahay, J.; Nagpal, O.; Prasad, S. Waste management of steel slag. *Steel Times Int.* **2000**, *24*, 38.
29. Jia, W.; Markine, V.L.; Jing, G. Analysis of furnace slag in railway sub-ballast based on experimental tests and DEM simulations. *Constr. Build. Mater.* **2021**, *288*, 123114. [CrossRef]

30. Mehran Khoshoei, S.; Mortazavi Bak, H.; Mahdi Abtahi, S.; Mahdi Hejazi, S.; Shahbodagh, B. Experimental Investigation of the Cyclic Behavior of Steel-Slag Ballast Mixed with Tire-Derived Aggregate. *J. Mater. Civ. Eng.* **2021**, *33*, 04020468. [CrossRef]
31. Ghanbari, M.; Abbasi, A.M.; Ravanshadnia, M. Production of natural and recycled aggregates: The environmental impacts of energy consumption and CO_2 emissions. *J. Mater. Cycles Waste Manag.* **2017**, *20*, 810–822. [CrossRef]
32. Pradhan, S.; Tiwari, B.R.; Kumar, S.; Barai, S.V. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *J. Clean. Prod.* **2019**, *228*, 679–691. [CrossRef]
33. Nalsund, R. Railway Ballast Characteristics, Selection Criterion and Performance. Ph.D. Thesis, Norwegian University of Science and Technology, Department of Civil and Transport Engineering, Trondheim, Norway, 2014.
34. Indraratna, B. 1st Proctor Lecture of ISSMGE: Railroad performance with special reference to ballast and substructure characteristics. *Transp. Geotech.* **2016**, *7*, 74–114. [CrossRef]
35. Alabbasi, Y.; Hussein, M. Large-scale triaxial and box testing on railroad ballast: A review. *SN Appl. Sci.* **2019**, *1*, 1592. [CrossRef]
36. Hussain, A.; Hussaini, S.K.K. Use of steel slag as railway ballast: A review. *Transp. Geotech.* **2022**, *35*, 100779. [CrossRef]
37. Jing, G.; Wang, J.; Wang, H.; Siahkouhi, M. Numerical investigation of the behavior of stone ballast mixed by steel slag in ballasted railway track. *Constr. Build. Mater.* **2020**, *262*, 120015. [CrossRef]
38. Esmaeili, M.; Askari, A. Laboratory investigation of the cyclic behavior of rock ballast mixed with slag ballast for use in railway tracks. *Constr. Build. Mater.* **2023**, *365*, 130136. [CrossRef]
39. Fathali, M.; Nejad, F.M.; Esmaeili, M. Influence of Tire-Derived Aggregates on the Properties of Railway Ballast Material. *J. Mater. Civ. Eng.* **2017**, *29*, 04016177. [CrossRef]
40. Ajayi, O.; Le Pen, L.; Zervos, A.; Powrie, V. Feasibility Study of Random Fibre Reinforced Railway Ballast. In Proceedings of the 23rd European Young Geotechnical Engineers Conference, Barcelona, Spain, 2–5 September 2014.
41. Jing, G.; Qie, L.; Markine, V.L.; Jia, W. Polyurethane reinforced ballasted track: Review, innovation and challenge. *Constr. Build. Mater.* **2019**, *208*, 734–774. [CrossRef]
42. D'Angelo, G.; Bressi, S.; Giunta, M.; Presti, D.; Thom, N. Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast. *Constr. Build. Mater.* **2018**, *161*, 1–8. [CrossRef]
43. Sweta, K.; Hussaini, S.K.K. Effect of geogrid on deformation response and resilient modulus of railroad ballast under cyclic loading. *Constr. Build. Mater.* **2020**, *264*, 120690. [CrossRef]
44. Leonardi, G. Analysis of railway tracks reinforced with geogrids. *ARPN J. Eng. Appl. Sci.* **2021**, *16*, 2722–2728.
45. Sol-Sanchez, M.; D'Angelo, G. Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks. *Constr. Build. Mater.* **2017**, *157*, 402–415. [CrossRef]
46. Banerjee, L.; Chawla, S.; Kumar Dash, S. Application of geocell reinforced coal mine overburden waste as subballast in railway tracks on weak subgrade. *Constr. Build. Mater.* **2020**, *265*, 120774. [CrossRef]
47. Indraratna, B.; Qi, Y.; Sai Malisetty, R.; Navaratnarajah, S.K.; Fatima Mehmood, F.; Tawk Rail, M. Recycled materials in railroad substructure: An energy perspective. *Rail. Eng. Sci.* **2022**, *30*, 304–322. [CrossRef]
48. Ferdous, W.; Manalo, A.; Van Erp, G.; Aravinthan, T.; Kaewunruen, S.; Remennikov, A. Composite railway sleepers—Recent developments, challenges and future prospects. *Compos. Struct.* **2015**, *134*, 158–168. [CrossRef]
49. Mansouri, P.; Zakeri, J.-A.; Esmaeili, M.; Ghahremani, S. Discrete element method analysis of lateral resistance of different sleepers under different support conditions. *Constr. Build. Mater.* **2022**, *327*, 126915. [CrossRef]
50. Jing, G.; Aela, P.; Fu, H.; Esmaeili, M. Numerical and Experimental Analysis of Lateral Resistance of Biblock Sleeper on Ballasted Tracks. *Int. J. Geomech.* **2020**, *20*, 04020051. [CrossRef]
51. Greenrail, Innovative and Sustainable Railway Sleepers: The Greener Solution for Railway Sector. Available online: https://cordis.europa.eu/project/id/738373 (accessed on 30 October 2023).
52. Dolci, G.; Rigamonti, L.; Grosso, M. Potential for improving the environmental performance of railway sleepers with an outer shell made of recycled materials. *Transp. Res. Interdiscip. Perspect.* **2020**, *6*, 100160. [CrossRef]
53. Çeçen, F.; Aktaş, B.; Ozbayrak, A. Decarbonization of the concrete railway sleeper production: Bringing the low-dosage pozzolanic cement usage in the sleeper production via novel laminated CFRPU reinforcement technique. *Mater. Today Sustain.* **2023**, *23*, 100455. [CrossRef]
54. Babachenko, O.I.; Kononenko, H.A.; Podolskyi, R.V.; Safronova, O.A. Steel for railroad rails with improved operating properties. *Mater. Sci.* **2021**, *56*, 814–819. [CrossRef]
55. Tuzik, J. Steel Hardness and Wear at the Wheel/Rail Interface: Perception vs Reality. *Interface J. Wheel/Rail Interact.* 2023. Available online: https://interfacejournal.com/archives/21462 (accessed on 30 October 2023).
56. Liu, J.-H.; Yu, P.-J.; Zhou, Y.-J.; Xu, Z.-B.; Li, Y.-J.; Li, P.; Zhao, Z.; He, C.-G.; Shen, M.-X. New insight on wheel flange/rail gauge lubrication: Effect of lasered microtexture shapes on the wear and fatigue behaviour of wheel/rail steels. *Wear* **2022**, *498–499*, 204310. [CrossRef]
57. Wang, W.J.; Lewis, R.; Evans, M.D.; Liu, Q.Y. Influence of Different Application of Lubricants on Wear and Pre-existing Rolling Contact Fatigue Cracks of Rail Materials. *Tribol. Lett.* **2017**, *65*, 58. [CrossRef]
58. Six, K.; Mihalj, T.; Trummer, G.; Marte, C.; Krishna, V.; Hossein-Nia, S.; Stichel, S. Assessment of running gear performance in relation to rolling contact fatigue of wheels and rails based on stochastic simulations. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **2020**, *234*, 405–416. [CrossRef]

59. International Union of Railway. UIC SUSTAINABILITY Circular Practices in the Railway and Ways Forward REUSE Project Final Report 2021. Available online: https://uic.org/IMG/pdf/reuse_project_final_report.pdf (accessed on 31 October 2023).
60. Chandran, P.; Asber, J.; Thiery, F.; Odelius, J.; Rantatalo, M. An Investigation of Railway Fastener Detection Using Image Processing and Augmented Deep Learning. *Sustainability* **2021**, *13*, 12051. [CrossRef]
61. Sol-Sanchez, M.; Moreno-Navarro, F.; Rubio-Gamez, M.C. The use of deconstructed tire rail pads in railroad tracks: Impact of pad thickness. *Mater. Des.* **2014**, *58*, 198–203. [CrossRef]
62. Castillo-Mingorance, J.M.; Sol-Sanchez, M.; Mattinzioli, T.; Moreno-Navarro, F.; Rubio-Gamez, M.C. Development of rail pads from recycled polymers for ballasted railway tracks. *Constr. Build. Mater.* **2022**, *337*, 127479. [CrossRef]
63. Kraskiewicz, C.; Zbiciak, A.; Pełczynski, J.; Al Sabouni-Zawadzka, A. Experimental and numerical testing of prototypical under ballast mats (UBMs) produced from deconstructed tires—The effect of mat thickness. *Constr. Build. Mater.* **2023**, *369*, 130559. [CrossRef]
64. Giunta, M.; Praticò, F.G. Design and maintenance of high-speed rail tracks: A comparison between ballasted and ballast-less solutions based on Life Cycle Cost Analysis. In Proceedings of the International Congress on Transport Infrastructure and System, Rome, Italy, 10–12 April 2017.
65. Italferr. *LCA Life Cycle Assessment, Line Guida per la Valutazione LCA di Infrastrutture Ferroviarie*; Italferr: Rome, Italy, 2019.
66. Milford, R.L.; Allwood, J.M. Assessing the CO_2 impact of current and future rail track in the UK. *Transp. Res. Part D Transp. Environ.* **2010**, *15*, 61–72. [CrossRef]
67. Kiani, M.; Parry, T.; Ceney, H. Environmental life-cycle assessment of railway track beds. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2008**, *161*, 135–142. [CrossRef]
68. Zeiner, M.; Landgraf, M.; Knabl, D.; Antony, B.; Barrena Cárdenas, V.; Koczwara, C. Assessment and Recommendations for a Fossil Free Future for Track Work Machinery. *Sustainability* **2021**, *13*, 11444. [CrossRef]
69. Dépoues, V. Organisational uptake of scientific information about climate change by infrastructure managers: The case of adaptation of the French railway company. *Clim Chang.* **2017**, *143*, 473–486. [CrossRef]
70. Palin, E.J.; Thornton, H.E.; Mathison, C.T.; McCarthy, R.E.; Clark, R.T.; Dora, J. Future projections of temperature-related climate change impacts on the railway network of Great Britain. *Clim. Chang.* **2013**, *120*, 71–93. [CrossRef]
71. Sedghi, M.; Kauppila, O.; Bergquista, B.; Vanhataloa, E.; Kulahcia, M. A taxonomy of railway track maintenance planning and scheduling: A review and research trends. *Reliab. Eng. Syst. Saf.* **2021**, *215*, 107827. [CrossRef]
72. Bressi, S.; Santos, J.; Losa, M. Optimization of maintenance strategies for railway track-bed considering probabilistic degradation models and different reliability levels. *Reliab. Eng. Syst. Saf.* **2021**, *207*, 107359. [CrossRef]
73. Soleimanmeigouni, I.; Ahmadi, A.; Kumar, U. Track geometry degradation and maintenance modelling: A review. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **2018**, *232*, 73–102. [CrossRef]
74. Elkhoury, N.; Hitihamillage, L.; Moridpour, S.; Robert, D. Degradation prediction of rail tracks: A review of the existing literature. *Open Transp. J.* **2018**, *12*, 88–104. [CrossRef]
75. Khajehei, H.; Ahmadi, A.; Soleimanmeigouni, I.; Haddadzade, M.; Nissen, A.; Javad Latifi Jebelli, M. Prediction of track geometry degradation using artificial neural network: A case study. *Int. J. Rail Transp.* **2022**, *10*, 24–43. [CrossRef]
76. Jovanovic, S.; Guler, H.; Coko, B. Track degradation analysis in the scope of railway infrastructure maintenance management systems. *Gradjevinar* **2015**, *67*, 247–258.
77. Bressi, S.; D'Angelo, G.; Santos, J.; Giunta, M. Environmental performance analysis of bitumen stabilized ballast for railway track-bed using life-cycle assessment. *Constr. Build. Mater.* **2018**, *188*, 1050–1064. [CrossRef]
78. Kostrzewski, M.; Melnik, R. Condition Monitoring of Rail Transport Systems: A Bibliometric Performance Analysis and Systematic Literature Review. *Sensors* **2021**, *21*, 4710. [CrossRef] [PubMed]
79. Gong, W.; Akbar, M.F.; Jawad, G.N.; Mohamed, M.F.P.; Wahab, M.N.A. Nondestructive Testing Technologies for Rail Inspection: A Review. *Coatings* **2022**, *12*, 1790. [CrossRef]
80. Du, C.; Dutta, S.; Kurup, P.; Yu, T.; Wang, X. A review of railway infrastructure monitoring using fiber optic sensors. *Sens. Actuators A* **2020**, *303*, 111728. [CrossRef]
81. Sol-Sanchez, M.; Castillo-Mingorance, J.M.; Moreno-Navarro, F.; Rubio-Gamez, M.C. Smart rail pads for the continuous monitoring of sensored railway tracks: Sensors analysis. *Autom. Constr.* **2021**, *132*, 103950. [CrossRef]
82. Sol-Sanchez, M.; Castillo-Mingorance, J.M.; Moreno-Navarro, F.; Mattinzioli, T.; Rubio-Gamez, M.C. Piezoelectric-sensored sustainable pads for smart railway traffic and track state monitoring: Full-scale laboratory tests. *Constr. Build. Mater.* **2021**, *301*, 124324. [CrossRef]
83. Antognoli, M.; Marinacci, C.; Ricci, S.; Rizzetto, L. Requirement specifications for track measuring and monitoring systems. *Ing. Ferrov.* **2020**, *11*, 841–864.
84. *ISO 14040*; Environmental Management—Life-Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
85. *ISO 14044*; Environmental Management—Life-Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
86. *ISO 21931-2*; Sustainability in Buildings and Civil Engineering Works Framework for Methods of Assessment of the Environmental, Social and Economic Performance of Construction Works as a Basis for Sustainability Assessment. Part 2: Civil Engineering Works. International Organization for Standardization: Geneva, Switzerland, 2019.

87. Fathali, M.; Chalabii, J.; Astaraki, F.; Esmaeili, M. A new degradation model for life cycle assessment of railway ballast materials. *Constr. Build. Mater.* **2021**, *270*, 121437. [CrossRef]
88. Landgraf, M.; Zeiner, M.; Knabl, D.; Corman, F. Environmental impacts and associated costs of railway turnouts based on Austrian data. *Transp. Res. Part D Transp. Environ.* **2022**, *103*, 103168. [CrossRef]
89. Celauro, C.; Cardella, A.; Guerrieri, M. LCA of Different Construction Choices for a Double-Track Railway Line for Sustainability Evaluations. *Sustainability* **2023**, *15*, 5066. [CrossRef]
90. Gulcimen, S.; Aydogan, E.K.; Uzal, N. Life cycle sustainability assessment of a light rail transit system: Integration of environmental, economic, and social impacts. *Integr. Environ. Assess. Manag.* **2021**, *17*, 1070–1082. [CrossRef]
91. Liljenstrom, C.; Bjorklund, A.; Toller, S. Including maintenance in life cycle assessment of road and rail infrastructure-a literature review. *Int. J. Life Cycle Assess.* **2022**, *27*, 316–334. [CrossRef]
92. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product design and business model strategies for a circular economy. *J. Ind. Prod. Eng.* **2016**, *33*, 308–320. [CrossRef]
93. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van Acker, K.; de Meester, S.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef] [PubMed]
94. Murray, A.; Skene, K.; Haynes, K. The circular economy: An interdisciplinary exploration of the concept and application in a global context. *J. Bus. Ethics* **2017**, *140*, 369–380. [CrossRef]
95. Corona, B.; Shen, L.; Reike, D.; Rosales Carreón, J.; Worrell, E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resour. Conserv. Recycl.* **2019**, *151*, 104498. [CrossRef]
96. European Commission. *A Monitoring Framework for the Circular Economy, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*; European Commission: Brussels, Belgium, 2018.
97. Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F.; Kendall, A. A taxonomy of circular economy indicators. *J. Clean. Prod.* **2019**, *207*, 542–559. [CrossRef]
98. De Pascale, A.; Arbolino, R.; Szopik-Depczynska, K.; Limosani, M.; Giuseppe Ioppolo, G. A systematic review for measuring circular economy: The 61 indicators. *J. Clean. Prod.* **2021**, *281*, 124942. [CrossRef]
99. Giannakos, K.S. Control of the Geometry of a Railway Track: Measurements of Defects and Theoretical Simulation. *Int. J. Appl. Phys. Eng.* **2022**, *1*, 102–115. [CrossRef]