Circular Economy in Rail Track: Estimating the Environental Burdens of the Use of Recycled Material and EoL Processing Through Life Cycle Assessment

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Abstract. The paper focuses on the application of the principles of the circular economy (CE) to the rail track systems by considering two main aspects: the use of recycled materials for the construction and maintenance and the environmental items associated with the End-of-Life (EoL). CE is an alternative approach to the linear model, promoting reduced raw material consumption and encouraging waste reuse through recycling or the development of new products. However, the waste materials require some pre-treatments before their use for which it is necessary to estimate the environmental consequences to properly estimate the benefits of the application. On the other hand, the EoL of the tracks requires careful considerations on the destination of the decommissioned components. This is an aspect often not fully considered in previous studies. This research focuses on the application of the Life Cycle Assessment (LCA) methodology to the two critical phases of the rail track life cycle: material production and EoL. In the stage of material production, the study looks at a comparison of sourcing and processing of the recycled material into the track construction. For EoL phase, the environmental implication brought by reusing/recycling materials from old tracks versus land filling or incineration have been considered. The results show that, in construction, material recycling and re-use can significantly reduce the environmental burdens related to natural resource depletion, human health and ecosystem protection. The findings are strongly dependent on the quality and efficiency of the recycling processes and on the logistical challenges of reprocessing materials.

Keywords: Railways · Sustainability · LCA · Circular Economy · Recycled Materials

1 Introduction

Climate change requires an extensive application of the circular economy (CE) principles in the railway sector [1]. The conscious use of resources, the reduction of waste and the promotion of sustainable construction and maintenance practices can significantly lower emissions and energy consumption and contribute to a more environmental-friendly rail transportation network for future generations.

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In the European Union, the annual waste generated by construction and demolition (CDW) amounts to around 180 million tons, which equals more than 480 kg per person per year. Of this, approximately 75% is still landfilled. While Denmark, the Netherlands, and Belgium recycle about 80% of CDW, Italy, Spain, Portugal, and Greece recycle significantly less by comparison. [2, 3]. The great importance that material recycling has acquired nowadays, has prompted researchers to work on increasing and improving the recycling potential. In the railway sector, some studies have investigated the possibility of replacing natural aggregates (i.e., for ballast or sub ballast) with recycled ones, comparing their properties and assessing their impact on the final product [4–6]. Maintaining the track geometry produces ballast waste, which is important to reuse as much as possible. This can be done by sieving, cleaning and inserting back into new or renewed tracks the ballast particles with appropriate size (i.e. 30–63 mm). Usually, an average of 70% of removed ballast is suitable for reuse.

In recent years, interesting initiatives have been developed in response to the increasing demand for new construction and network renewal programs on the one hand, and the reduction in the use of virgin materials on the other. These factors have highlighted the need to explore methods for sourcing ballast from alternative materials such as steel slag [7, 8], tire-derived aggregate [9], crumb rubber, as well as innovative solutions to increase the service life of ballast layer including stabilization with bitumen [10], use of polyurethane, cement, and geopolymer [11, 12].

In particular, steel slag when used as railway ballast or blended with traditional crushed stone, provides a layer with excellent mechanical properties and lower permanent deformation under train loads. The slag is delivered as "waste" by the steel production cycle and is subjected to a specific recovery treatment in an authorized plant, from which are produced secondary raw materials (MPS) in different grain sizes, including ballast for railway use. Italy is the second-largest steel producer in Europe, with a 16% share of the entire EU production. In 2024, Italian steel mills produced 20 million tons of steel, generating about 2.6 million tons of black slag or steel slag—roughly 13% of the total production by weight. If this quantity were used to create the ballast layer at a rate of 50% of its total volume, it could support the construction of approximately 900 km of single track. This length could double if the proportion of black slag used were reduced to 25%.

The main steel mills in Italy are concentrated in the Northen Region, with a significant plant in Puglia, South Italy. Smaller plants are spread across the country. This uneven distribution raises concerns about the impact of transporting black slag for recycling in the railway industry, especially considering the distance from steel production hubs to construction sites.

Another important and vulnerable component of the track is the sleeper, which is responsible for load bearing and load distribution. Various materials are used for sleepers, including timber, concrete, and steel. Currently, prestressed concrete sleepers have become one of the most common types of railway sleepers installed worldwide owing to their increased lifespan and strong structural performance. However, due to the larger quantities of CO_2 released in their manufacture, researchers are exploring alternative materials such as recycled plastics, recycled rubber, fiber-reinforced foamed urethane (FFU), epoxy polymer resin [13, 14]. The outcomes of the studies carried out

demonstrate that the use of recycled plastic and reinforced material can reduce overall environmental impacts of the sleepers in terms of carbon emissions and resource use.

Another area of improvement is related to the use of recycled aggregates for concrete sleeper manufacturing [15, 16]; this practice, while limited by the percentage of use of recycled material [17], exhibits high environmental performances.

All studies emphasized the importance of assessing environmental impacts across railway components to identify the most sustainable options and consider the entire life-cycle of the infrastructure. Several studies have been conducted to assess the environmental effect of the railway industry. They exhibit significant variety in methodological approaches, analytic periods, railway types, software, and datasets employed [18–21]. Few studies consider different rail track substructure solutions, and the environmental impacts associated with the design, construction, maintenance, and dismantlement of the track. Pons [22] examines and compares the potential environmental implications associated with the life cycle of three distinct track systems: ballasted track, cast-in sleeper track system, and embedded track system, revealing that ballasted tracks cause the lowest environmental impact for service lives of up to 75 years. Conversely, the embedded track beds generate the most significant environmental impacts, irrespective of their operational lifespan. The primary contributor to the impacts is steel manufacturing. The life-cycle energy consumption and global warming potential associated with ballasted and generic concrete track beds, including cast-in sleeper and embedded track systems were evaluated by [23] indicating that concrete slab track beds do not correlate with increased life-cycle energy consumption or global warming potential when compared to ballast track beds. The utilization of materials with elevated embodied energy in concrete systems is counterbalanced by their anticipated extended lifespan. Significant discrepancies exist between the lowest and highest embodied energy values provided for materials, such as aggregate, which undermines the conclusiveness of any comparisons.

This research focuses on two key track components, ballast and sleepers, and aims to assess the environmental impact associated with two specific life cycle phases: production and EoL. The appraisal was conducted by applying the Life Cycle Assessment methodology in accordance with [24]. The analysis of the production and EoL stages of these two components is crucial due to the growing demand for the expansion of railway transport, whether through the construction of new lines or the upgrading of existing ones. Additionally, these two components require frequent maintenance and replacement activities throughout the operational life of the railway track. This study introduces two main innovations with respect to the existing literature on railway infrastructure and life cycle assessment (LCA). First, it explicitly considers the upstream processes associated with the use of recycled materials, including the environmental impacts of collection, treatment, and preparation steps required prior to their integration into new production cycles, stages that are often neglected or only partially addressed in previous studies. Second, it provides a detailed examination of the EoL phase, hypothesizing scenarios in which both ballast and sleepers undergo recovery processes that enable their re-entry into the construction cycle as secondary raw materials. To identify sustainable pathways, the environmental impacts of using virgin materials were compared with those of using recycled materials, with particular emphasis on the pre-processing stages required for the latter. This comprehensive approach allows for a more accurate and holistic assessment

of the environmental trade-offs associated with material choices, thereby addressing critical gaps in traditional LCA studies that frequently overlook both upstream burdens and realistic circularity scenarios at end-of-life.

2 Life Cycle Assessment of Rail Track Components: Ballast and Sleepers

2.1 Description of Objectives, Product System, Boundaries and Functional Unit

Ballasted track (Fig. 1) is a layered structure composed mainly of rails and sleepers, which are supported by a crushed stone bed called ballast. This, in turn, rests on an underlying layer, called sub ballast, usually made of bituminous mixture that acts as a transition between the ballast and the underlying subgrade.

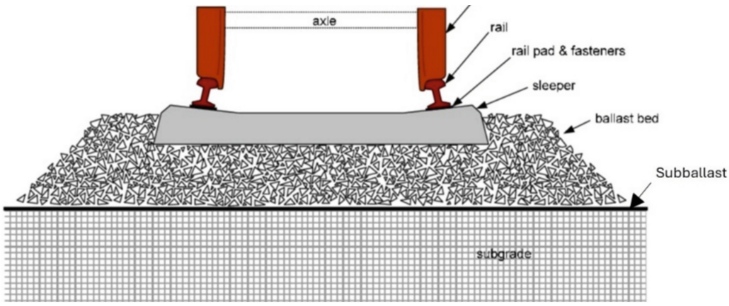


Fig. 1. Ballasted Track System

The purpose of this study is to compare the life cycle emissions of sleepers and ballast made from alternative recycled materials appropriately pre-treated with those of traditional components made from virgin materials. Attention is given to the environmental impacts arising from the pre-treatment processes necessary to make recycled materials suitable for use. This aspect is often underestimated or entirely overlooked in previous studies. By explicitly addressing it, the present approach seeks to evaluate whether the adoption of such alternative products is both environmentally justified and operationally feasible.

To achieve these goals, the specific objectives of this study are:

a. To conduct a life cycle assessment (LCA) on the emissions of sleepers and ballast made with virgin materials (base scenario) compared to those produced with recycled material.
b. To compare the results and determine whether the alternative ballast and sleepers are more environmentally friendly than the base scenario.

By adopting this approach, it is therefore possible to verify whether the application of the principles of CE in the railway sector allows for the reduction of global emissions from the system. The critical phases on which we will focus the most are the production phase of the elements and their end of life.

Two essential elements to define before proceeding with the system analysis are: the system boundaries and the functional unit (FU).

FU is a quantitative description of the service performance (the needs fulfilled) of the investigated product system(s). In the railway sector, FU is usually the length of the track expressed in kilometers (it is necessary to specify whether the track is single or double) [24, 25]. In this study the FU considered is 1 km of single-track line. The time boundaries in which the analysis is carried out correspond to a 30-year time frame.

The different life cycle system boundary models implemented are:

- *Cradle to gate,* this is a life cycle assessment that only considers the resource extraction phase up to the construction site.
- *End-of-life,* this is an assessment from dismantling to grave, where the EoL disposal phase coincides with a recycling process that makes the materials or components reusable for another product, thus allowing for the "closing of the loop".

2.2 Inventory

The inventory is a crucial phase of the LCA that refers to a quantitative analysis aimed at evaluating the resource use, energy consumption, and environmental emissions associated with a product, process, or activity throughout its entire life cycle. Data used are referred to a case study.

Ballast

In the subsequent analyses, three scenarios have been considered:

- Base Scenario B0: 100% virgin aggregate.
- Scenario B1: 50% virgin aggregate + 50% recycled aggregate.
- Scenario B2: 50% virgin aggregate + 25% recycled aggregate + 25% steel slag.

The data for the materials and energy used in the construction of the ballast layer in the different scenarios are shown in Table 1.

Table 1. Quantities and distances for ballast layer

Input	B0		B1		B2	
	t/FU	km	t/FU	km	t/FU	km
Virgin	13167	45	6583,5	45	6583,5	45
Recycled	-	-	6583,5	30	3291,8	30
Steel slag	-	-		-	3291,8	50
Energy Required for Primary Production (MJ)	5.18E + 04		3.28E + 04		3.50E + 04	

Embodied primary energy, expressed in MJ, includes all energy, direct and indirect, used to transform or transport raw materials into products, including inherent energy

contained in raw or feedstock materials that are also used as common energy sources. The database used for the estimate is Ecoinvent v3.10.

It was assumed that the distance between the quarry, where the virgin material is extracted, and the installation site is 45 km, and transport takes place via EURO5 trucks. Recycled material was analyzed by accounting for the fuel required for machinery to screen and wash particles from the EoL of the traditional ballast (70% of which is recoverable), while assuming a total transport distance of 30 km from the EoL ballast processing facility to the construction site. Transportation is modelled with reference to EURO5 lorries. So, the designing was based on an analysis of the energy required for processing the stone component that is removed from the life cycle, whether it be the ballast or the sleepers.

Steel slag was modelled with respect to the input flow referred to as "blast furnace slang," which encompasses the deposition of material (landfill of residuals from steel manufacturing). The modelling incorporates the fuel required for the machines to screen and clean the material, as well as the overall distance of 50 km from the slag treatment facility to the disposal location. Transport is modelled using a EURO5 vehicle, and the treatment system consumes 2000 kWh.

The modelling of the EoL of the ballast (Table 2) takes into consideration the following aspects:

i. Transport of the recovered ballast to the treatment site, via EURO 5 lorry for 40% of the distance and by train for the remaining 60%.
ii. Power supply for the machines necessary for the treatment of the ballast.

The equipment considered are:

- HOBCS (High Output Ballast Cleaner System) to sift the particles. The particular model used is RM-900-RT, with a flow rate of 900 m^3/h and power of 1500 kW.
- Ballast Washer for washing. The model adopted is the CLSB-24, with a flow rate of 125 m^3/h and power of 44 kW.

The distance from the processing site to the construction site is assumed to be equal to 100 km. The ballast recovered is 70% of the total dismantled.

All the scenarios have the same EoL.

Table 2. Quantities for ballast EoL

Input		All Scenarios
Transport (km)	lorry	40
	rail	60
Recovery (kW)	HOBCS	1500
	BW	44

Sleepers

Concerning the sleeper production, in Italy, sleepers are categorized according to a fundamental list established by RFI (Italian Railway Network), with RFI 260 being one of the types examined. The primary components of a sleeper cement (Portland, type 1), water, virgin aggregates, additives (this contribution includes various types of additives included in the basic bill of materials formulated by RFI, as ethylene vinyl acetate, carboxylates), and steel. The model incorporates transport from the production site to the construction site via EURO5 lorry over a distance of 20 km. This scenario is called Base Scenario S0.

The modified sleepers (Scenario S1) were constructed using recycled materials (from the EoL of the ballast or of the sleepers themselves), instead of virgin aggregates.

The data for the materials and energy used for construction of the sleepers are shown in Table 3.

Table 3. Quantities and distances for sleepers

Input	S0	S1
	t/FU	t/FU
Virgin aggregate	500	-
Recycled aggregate	-	500
Water	36,2	36,2
Cement	100	100
Steel	18,8	18,8
Additives	15	15
Transport (km)	20	20
Energy Required for Primary Production (MJ)	2,49E + 05	1,51E + 05

The EoL modeling (Table 4) of the sleepers takes into account two aspects:

i. Transport to the treatment site, with 40% of the distance covered by EURO 5 lorry and 60% by train.
ii. Power supply of the machine needed to treat the sleepers.

For the final treatment of the sleepers the use of M100 machine is considered [26]. This machine has a processing capacity of 400 sleepers/h and requires a power of 500 kW. The recycling of concrete railway sleepers is facilitated by the caterpillar conveyor belt. The machine gradually feeds the sleepers into the crusher, which crushes them into very small pieces in a short amount of time. These pieces are then separated by a system of conveyor belts. The long iron is expelled from the front end of the machine. On the left side of the machine, the fine-grained aggregate material is separated from the short iron (plates) and is possibly moistened through nozzles to prevent the formation of dust.

These recycled aggregates can have a second life, not only in the railway industry but also in other construction sectors, thereby reducing emissions associated with processing raw materials that would otherwise be used.

The distance from the sleeper treatment site to the construction site is assumed to be equal to 100 km.

Both base and modified sleepers have the same EoL.

Table 4. Quantities for sleepers EoL

Input		S0, S1
Transport (km)	lorry	40
	rail	60
Recovery (kW)	M-100	500

2.3 Life Cycle Impact Assessment and Interpretation

The impact assessment method used is the ReCiPe 2016 Endpoint (H) used within open-source software OpenLCA 10.2. The adoption of an endpoint methodology over a midpoint methodology provides a more comprehensive understanding of the overall effects on the environment. Endpoint assessments allow for the evaluation of environmental impacts in terms of their ultimate consequences on human health, ecosystem quality, and resource depletion, which can be more meaningful for stakeholders and decision-makers. Unit of measure for human health is DALYs (disability adjusted life years), that represents the years that are lost or that a person is disabled due to a disease or accident. The unit for ecosystem quality is the local species loss integrated over time (species year). The unit for resource scarcity is the USD 2013 (US dollars, base year 2013), which represents the extra costs involved for future mineral and fossil resource extraction [27]. By focusing on these broader outcomes, the authors aimed to illustrate the significance of their findings in a way that transcends specific environmental metrics.

Ballast

Figure 2 illustrates the environmental impact in the area of protection of natural resources, human health and ecosystem of ballast production and transport across the different scenarios.

Concerning ballast production, for all Scenarios, the more consistent environmental impacts are ascribed at the area of protection of naturals resources. It suggests that the extraction of raw materials significantly affects natural landscapes and environmental raw systems. Additionally, high energy consumption during production, often sourced from non-renewable resources, further depletes natural resources and emphasizes the impact in the area of the natural resources.

The impact on the category of natural resources is significantly influenced by the choice between using virgin (B0) or recycled materials (B1, B2) in ballast production.

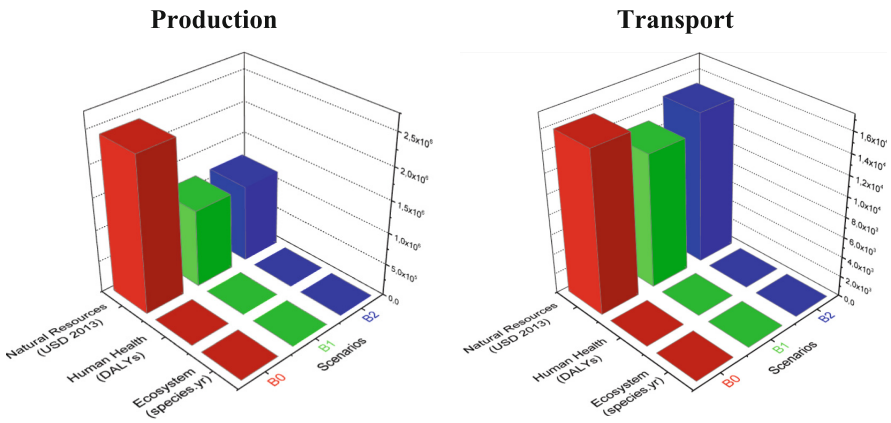


Fig. 2. Environmental impact for alternative types of ballast in production and transport phases

Utilizing virgin materials typically entails higher environmental costs due to the extraction processes, which can lead to habitat destruction and resource depletion. In contrast, incorporating recycled materials can mitigate these impacts by reducing the demand for new resources and minimizing waste.

In the transport phase of ballast, a similar pattern emerges regarding environmental impacts. Just as with the production phase, the choice of materials can significantly influence the area of protection of natural resources. Transporting virgin materials typically entails higher energy consumption and associated emissions, which contribute to the depletion of natural resources and overall ecological impact. On the other hand, using recycled materials can lead to reduced transportation distances and lower energy requirements, thereby minimizing emissions and resource use. This shift underscores the importance of sustainability not only in material selection but also in logistical considerations.

The comparison between the production and transport phases (Fig. 3) regarding the areas of protection for human health reveals that the contributions from both phases are comparable. Each phase plays a significant role in influencing environmental impacts, and their effects on human health and transportation safety are similarly significant.

In scenarios (B1, B2) where recycled materials are used, the transport phase tends to have a more significant impact on environmental outcomes.

Since the production phase in scenarios B1 and B2 presents lower contributions due to the lower exploitation and demand for raw materials which reduces natural resources, necessarily, from a percentage and not an absolute point of view, transport, compared to total emissions, will present a more significant impact in the alternative scenarios.

In the assessment of impacts of the EoL of ballast for all areas of protection valued, the transport process exhibits greater value (95 $\pm$ 5%) with respect recovery ballast process due to a range of factors associated with logistics and the processes involved in both activities.

One of the primary reasons is that transportation emissions, which largely stem from fuel consumption, generate significant greenhouse gas emissions and air pollutants. The

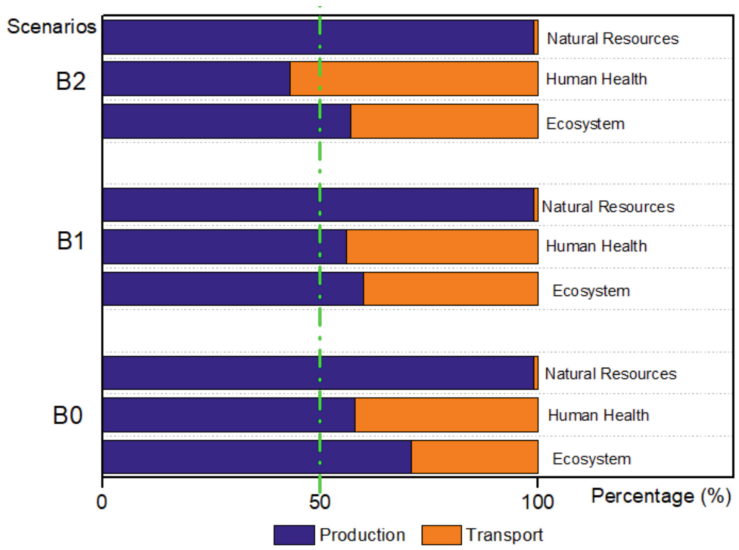


Fig. 3. Comparison of percentage emissions for different types of ballast in production and transport phases

impact of these emissions increases sharply with the distance traveled, meaning that transporting heavy materials like ballast over long distances can lead to a substantial cumulative environmental impact.

In contrast, the recovery of ballast, which typically involves processes such as cleaning, sorting, and reusing of existing materials, is generally less energy intensive. This means that the associated emissions from recovery processes are usually lower than those from transportation.

Recovery minimizes the need for the extraction and processing of new materials, making it a more sustainable option for managing ballast waste.

At the end of their useful life, recovered materials can often be repurposed or recycled, further mitigating environmental impacts by extending the lifespan of existing resources.

Moreover, transportation can also contribute to infrastructure impacts, such as road wear and maintenance, increased traffic congestion, and potential disruption to local habitats and ecosystems.

The logistical requirements for moving heavy materials not only involve high fuel consumption but also can lead to additional environmental consequences related to land use and habitat degradation.

These logistical challenges translate into higher operational costs and broader environmental impacts, compounding the overall impacts associated with transport.

Sleepers

Figure 4 illustrates the environmental impact of production and transport of sleepers in the area of protection of natural resources, human health, and ecosystem, across the scenario that considers the use of virgin materials (S0) and its with recycled aggregates (S1).

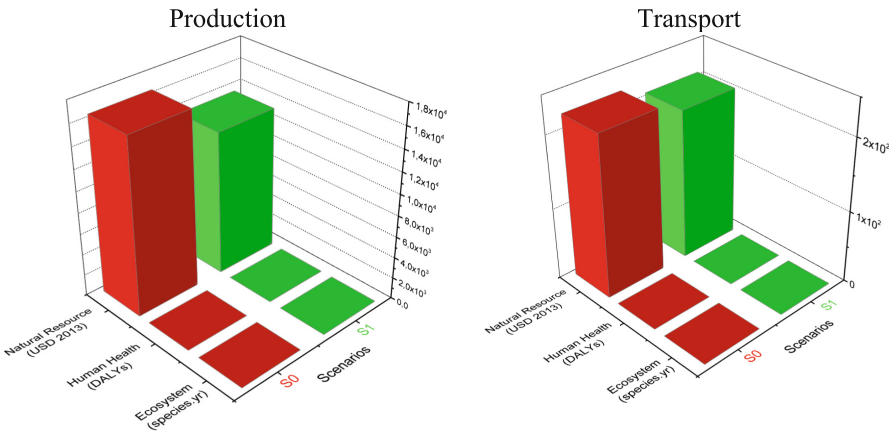


Fig. 4. Environmental impact for two types of sleepers in production and transport phases

In the production and transport of sleepers, the higher impacts related to natural resources compared to human health and ecosystem factors can be attributed to several key reasons. The extraction and processing of raw materials often lead to significant resource depletion which directly affects the environment. Moreover, while human health and ecosystem impacts are important, they may be less immediately apparent in the context of production and transport compared to the visible effects on natural resources. The comparison between the production and transport for all areas of protection and in all scenarios reveals that the production phase of sleepers exerts an impact of over $98 \pm 2\%$ compared to transportation, which highlights the critical role that materials play in this context. This significant influence is primarily due to the resource-intensive processes involved in manufacturing sleepers, where materials such as cement, steel, and various additives require substantial energy and raw materials. The extraction, processing, and transformation of these materials not only generate considerable greenhouse gas emissions but also lead to environmental degradation.

In contrast, transportation, while important, generally has a lower impact in comparison because it constitutes a smaller fraction of the overall life cycle emissions associated with the production of sleepers.

The demand for resources in the production, like concrete, steel and all materials included, create different pressures on the areas of the protection (see Fig. 5).

Considering the natural resources in both scenarios, the significant contribution of additives, specifically polyurethane, ethylene vinyl acetate, and polycarboxylate, reflects the resource-intensive processes involved in their production. Polyurethane, commonly used for its durability and flexibility, is derived from petroleum-based resources, which inherently require extensive fossil fuel extraction and processing.

Similarly, ethylene vinyl acetate (EVA) is produced through the polymerization of ethylene, a byproduct of crude oil refining. The production of EVA necessitates significant energy input, further straining natural resources and contributing to environmental impacts related to fossil fuel extraction. The high demand for energy and raw materials

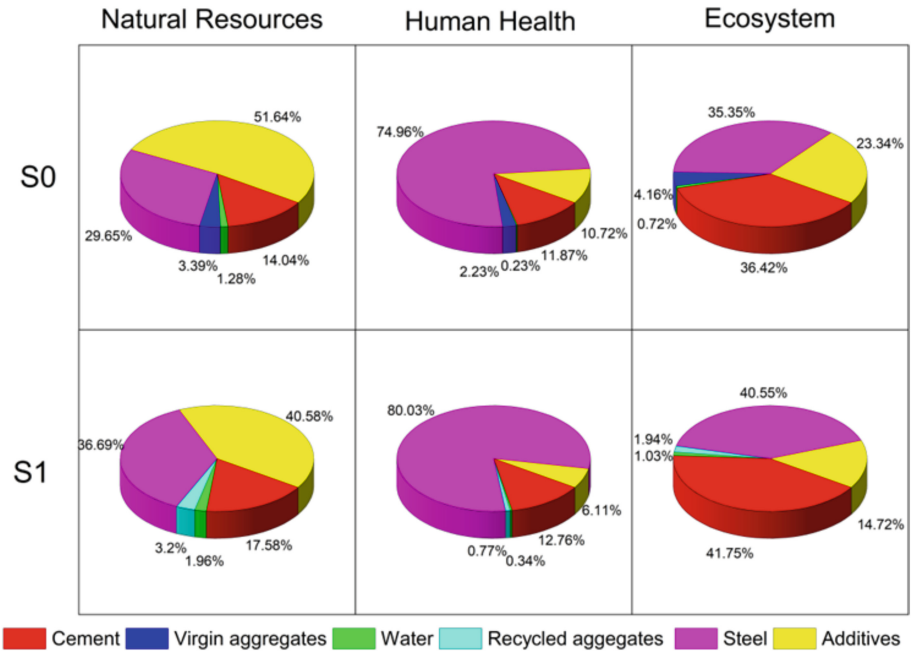


Fig. 5. Analysis of material contributions for two types of sleepers

during the manufacturing process of these plastics can lead to increased greenhouse gas emissions, which exacerbate climate change.

Polycarboxylate, often used as a superplasticizer in concrete and other construction materials, also has a considerable environmental footprint. Its production involves chemical processes that may involve additional energy-intensive steps and the use of non-renewable resources, contributing further to the overall impact on natural resources.

For the area of protection of Human Health, the major contributor is steel.

The steel industry significantly impacts human health due to several interrelated factors. Firstly, the production process generates various pollutants, including particulate matter and nitrogen oxides, which can adversely affect respiratory health for those living near steel plants. Additionally, the release of toxic substances, such as heavy metals, can contaminate surrounding environments and water supplies, exposing local communities to health risks. The resource-intensive nature of steel production often relies on unsustainable energy sources, contributing to pollution and climate change, which further threaten public health. Moreover, workers in the steel industry face direct occupational hazards, including exposure to harmful chemicals and physically demanding conditions. Together, these elements highlight the multifaceted ways in which steel production impacts human health.

In the ecosystem category, cement, additives, and steel contribute similarly to environmental impacts due to their resource-intensive production processes and the associated ecological consequences. Cement production is notorious for its high carbon dioxide emissions and significant energy consumption, leading to habitat loss and degradation

of natural environments. Similarly, the manufacturing of additives, such as polyurethane and ethylene vinyl acetate, often entails chemical processes that can lead to pollution and disruption of local ecosystems.

Steel production also shares these challenges, involving resource extraction that can cause habitat destruction, and emissions that contribute to air and water pollution. The entire supply chain for these materials—including extraction, processing, and transportation—exerts cumulative pressure on ecosystems, contributing to biodiversity loss and ecosystem imbalance.

Moreover, all three materials can have lasting effects on soil and water quality, impacting the flora and fauna that depend on these resources.

The environmental assessment of the end-of-life management of sleepers reveals a significant challenge, with transport accounting for $88 \pm 5\%$ of the total impact across all areas of protection, including natural resources, human health, and ecosystems. This overwhelming contribution from transport underscores the substantial emissions and resource consumption associated with moving heavy materials. Such a high percentage indicates that logistics play a crucial role in the overall environmental impacts of sleepers.

The remaining $12 \pm 5\%$ attributable to recovery and recycling processes highlights that, while these efforts are valuable, they currently account for only a small fraction of the total impact. This suggests there is considerable room for improvement in enhancing recovery practices and increasing the efficiency of recycling processes.

3 Discussion and Conclusion

This life cycle assessment (LCA) provides a comprehensive evaluation of the environmental impacts associated with the production and end-of-life management of railway ballast and sleepers. The analysis reveals a complex interplay of factors influencing various impact categories, highlighting the need for a holistic approach to sustainable railway infrastructure development.

The study demonstrates that material selection significantly affects the overall environmental performance. While utilizing recycled materials offers considerable advantages in reducing the depletion of virgin resources, it also introduces trade-offs, primarily impacting other environmental aspects. This underscores the importance of carefully considering the full environmental profile of both virgin and recycled materials and optimizing their processing to minimize negative consequences. Simply substituting one material for another without a thorough assessment of the entire life cycle can lead to unintended shifts in environmental burdens.

Transportation emerges as a critical factor impacting the overall environmental footprint, consistently ranking as a major contributor across all life cycle stages for both ballast and sleepers. This emphasizes the need for optimizing logistics, exploring alternative transportation modes, and potentially redesigning supply chains to minimize transportation distances and emissions. The substantial influence of transport highlights the interconnectedness of environmental impacts and the importance of considering the broader context beyond material choices alone.

The analysis also reveals that the manufacturing processes themselves, particularly for key components like cement and steel in sleeper production, contribute significantly

to various environmental impacts. This indicates the potential for further improvements through technological advancements and the adoption of more environmentally friendly production methods. Investing in research and development to reduce the environmental impacts of manufacturing processes is crucial for advancing sustainable railway practices.

Finally, end-of-life management significantly impacts on the overall environmental performance. A comprehensive strategy for managing the end-of-life phases of both ballast and sleepers is essential for minimizing environmental burdens. This requires not only efficient recycling and disposal methods but also innovative solutions to minimize transportation needs during this phase. The integration of end-of-life considerations into the design and production phases is vital for achieving truly sustainable railway infrastructure.

The limitations of this work are primarily related to the use of a case study, with parameters specific to that context; nonetheless, the results remain valid as they offer meaningful insights and highlight key trends that are broadly applicable to similar scenarios.

In conclusion, achieving truly sustainable railway infrastructure requires a holistic approach that integrates material selection, manufacturing processes, transportation optimization, and efficient end-of-life management strategies. The findings of this LCA highlight the complex trade-offs involved and the need for continuous innovation and improvement across all stages of the life cycle to minimize environmental impacts and build a more sustainable future for the railway industry. Furthermore, there is an interesting outlook for the transition to a more circular economy in the rail track systems, basically due to the recycling of materials instead of landfilling, as it will decrease the general environmental impact while pursuing sustainability within the railway infrastructure industry.

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