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Low-carbon solid waste materials for railway sub-ballast layers: a review of mechanical performance, sustainability and regulatory gaps

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Abstract

Purpose – This paper presents a comprehensive systematic review of low-carbon solid waste materials applied in railway sub-ballast layers, aiming to critically assess their mechanical performance, durability, environmental benefits and regulatory readiness. The study addresses the growing need to decarbonize rail infrastructure while reducing dependence on natural aggregates, positioning sub-ballast as a strategic layer for circular economy implementation in ballasted track systems.

Design/methodology/approach – A PRISMA-based systematic review methodology was adopted to identify, screen and analyses peer-reviewed studies published between 2000 and 2025. The final database comprises experimental, numerical and field investigations covering mining residues, steel slags, construction and demolition waste, rubberized composites, alkali-activated materials and other industrial by-products applied to railway sub-ballast. Mechanical behavior under cyclic loading, resilient modulus, permanent deformation, hydraulic performance, durability and environmental indicators were extracted and synthesized. In parallel, an international regulatory analysis was conducted to compare sub-ballast specifications across Europe, North America, Asia-Pacific and Brazil, enabling identification of performance-regulation gaps and barriers to implementation.

Findings – The review demonstrates that several low-carbon waste-derived materials exhibit mechanical performance comparable to or exceeding that of conventional granular sub-ballast, particularly in terms of stiffness retention, resistance to permanent deformation and degradation under repeated loading. Steel slags, recycled concrete aggregates, slate waste and rubber-modified blends consistently show favorable resilient behavior and enhanced damping capacity, while certain mining residues and alkali-activated granular systems present promising strength and durability characteristics. Life-cycle evidence indicates substantial reductions in embodied carbon and natural aggregate consumption when these materials are adopted. However, current railway standards remain largely prescriptive and index-based, rarely incorporating cyclic performance criteria or carbon metrics, creating a structural disconnect between scientific evidence and regulatory acceptance. This gap significantly limits large-scale implementation despite growing technical maturity.

Originality/value – This study provides the first integrated synthesis focused exclusively on low-carbon solid waste materials for railway sub-ballast, combining mechanical performance, environmental assessment and international regulatory comparison within a unified analytical framework. By explicitly linking laboratory evidence to policy and standardization challenges, the paper advances performance-based pathways for

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sustainable railway substructure design. The findings offer actionable guidance for infrastructure managers, regulators and researchers seeking to accelerate the transition toward circular, low-carbon rail systems through sub-ballast innovation.

Keywords Railway sub-ballast, Low-carbon materials, Solid waste valorization, Cyclic mechanical performance, Life-cycle assessment, Performance-based standards

Paper type Literature review

1. Introduction

Railway transport is frequently promoted as a cornerstone of sustainable mobility due to its comparatively low operational greenhouse gas emissions, particularly in electrified systems (Chester & Horvath, 2009; Rozycki, Koeser, & Schwarz, 2003). However, life-cycle assessments (LCAs) have demonstrated that infrastructure construction, maintenance and material production constitute a significant share of the overall environmental footprint of railway systems (Celauro, Cardella, & Guerrieri, 2023; Kiani, Parry, & Ceney, 2008; Stripple & Uppenberg, 2010). The extraction, processing and transportation of mineral aggregates for ballast and sub-ballast layers represent dominant contributors to embodied carbon and resource depletion.

In parallel, industrial production, mining activities and urban demolition generate large volumes of solid waste streams, including steel slags, recycled concrete aggregates (RCA), construction and demolition waste (CDW), mining residues and rubber-based materials. These streams are often landfilled or stockpiled despite possessing geotechnical characteristics suitable for infrastructure applications (Motz & Geiseler, 2001; Proctor *et al.*, 2000; Vieira & Pereira, 2015; Wang *et al.*, 2022). Circular economy frameworks increasingly advocate their valorization in civil engineering, yet railway adoption remains cautious and fragmented.

Within the ballasted track system, the sub-ballast layer plays a critical mechanical and hydraulic role. Positioned between ballast and formation soil, it distributes stresses, provides drainage, limits fine migration and protects the subgrade against cyclic degradation (Esveld, 2022; Selig & Waters, 2007). Compared to ballast, sub-ballast experiences lower impact stresses but remains subjected to high-frequency cyclic loading transmitted through sleepers and ballast contacts (Indraratna, Lackenby, & Christie, 2005; Sun, Indraratna, & Nimbalkar, 2016). Its structural demand profile makes it particularly suitable for the integration of engineered low-carbon materials, provided that resilient modulus, permanent deformation and hydraulic conductivity requirements are satisfied.

Despite this potential, research on waste-derived materials in railways has historically focused on ballast or sleeper components (Ferdous & Manalo, 2014; Hussain & Hussaini, 2022; Safari, Rezaie, Esmaeili, & Habibnejad Korayem, 2025). Dedicated analyses targeting sub-ballast layers remain comparatively scarce. Recent investigations have begun to evaluate recycled concrete blends, steel slags and rubber inclusions in substructure applications (Castro *et al.*, 2024; Ferreira & Teixeira, 2012; Naeini, Mohammadinia, Arulrajah, Horpibulsuk, & Leong, 2019; Santos, Rodrigues, Leiva, & Pereira, 2025), yet a consolidated synthesis integrating engineering performance, environmental impacts and regulatory constraints is lacking.

Furthermore, international railway standards largely rely on prescriptive grading envelopes and index tests, such as Los Angeles abrasion and plasticity limits, while cyclic stiffness, durability under repeated loading and life-cycle carbon performance are seldom incorporated into formal acceptance criteria (Guo *et al.*, 2022; Sorança, Couto, Marques, & Mendes, 2026). This regulatory conservatism may inhibit the deployment of technically viable low-carbon alternatives.

Against this backdrop, this study provides a comprehensive systematic review focused exclusively on low-carbon solid waste materials applied in railway sub-ballast layers. The review integrates five interconnected domains:

(1) Material characterization and processing pathways;

(2) Cyclic mechanical performance and degradation behavior;

(3) Hydraulic functionality and durability;

(4) Life-cycle environmental assessment;

(5) International regulatory frameworks and policy implications.

By consolidating current knowledge and identifying structural barriers, the paper aims to clarify the technical readiness of waste-derived sub-ballast systems and to propose pathways toward performance-based implementation in railway infrastructure.

2. Structural function and performance requirements of railway sub-ballast

2.1 Role within the ballasted track system

The conventional ballasted track structure comprises rails, sleepers, ballast, sub-ballast and formation soil. Load transfer initiates at the rail-wheel interface and propagates through sleepers into ballast, where stresses concentrate at particle contacts (Abadi, Le Pen, Zervos, & Powrie, 2015; Aursudkij, McDowell, & Collop, 2009). The sub-ballast layer acts as a transitional granular stratum that redistributes these stresses, reduces shear stresses at the formation interface and enhances drainage (Esveld, 2022; Selig & Waters, 2007).

Numerical modeling has shown that stress attenuation through granular layers is strongly dependent on stiffness contrast and particle interlock (Suiker & de Borst, 2003; Zhai, Wang, & Lin, 2004). Insufficient sub-ballast stiffness can increase subgrade strain accumulation, accelerating settlement and maintenance frequency (Dahlberg, 2001; Priest & Powrie, 2009).

2.2 Cyclic loading and degradation mechanisms

Under repeated axle loading, granular layers experience stress-dependent deformation characterized by resilient (recoverable) strain and permanent (plastic) strain accumulation (Indraratna *et al.*, 2005; Sun *et al.*, 2016). Particle breakage and rearrangement contribute to stiffness degradation and fouling generation (Indraratna, Sun, & Nimbalkar, 2016; Rak, Klosok-Bazan, Zimoch, & Machnik-Slomka, 2022).

Although ballast degradation has been extensively studied (Guo *et al.*, 2022; Indraratna, Salim, & Rujikiatkamjorn, 2018), sub-ballast degradation mechanisms differ due to smaller particle size distribution and confinement conditions. Permanent deformation in sub-ballast typically evolves under lower stress amplitude but can become critical when drainage is impaired or material stiffness is insufficient (Castro *et al.*, 2024; Ferreira & Teixeira, 2012).

2.3 Hydraulic performance and moisture sensitivity

Effective drainage is fundamental to preserving track stiffness. Sub-ballast layers must exhibit adequate hydraulic conductivity to prevent pore pressure build-up and subgrade softening (Paiva, Ferreira, & Ferreira, 2015). Excess fines generation or clogging may reduce permeability and accelerate settlement (Saussine & Gautier, 2009). Waste-derived materials must therefore be evaluated not only for mechanical strength but also for gradation stability and long-term hydraulic behavior.

2.4 Sustainability context

Life-cycle analyses of railway infrastructure have consistently shown that aggregate production and transport contribute substantially to embodied emissions (Celauro *et al.*, 2023; Kiani *et al.*, 2008; Pons, Sanchis, Franco, & Yepes, 2020). Substituting virgin aggregates with industrial by-products may reduce both carbon intensity and natural resource extraction (Motz & Geiseler, 2001;

Tossavainen *et al.*, 2007). However, environmental benefits must be balanced against durability and maintenance implications.

3. Methodology

3.1 Review design and scope delimitation

This study was structured as a systematic review focused specifically on the engineering and sustainability performance of low-carbon solid waste materials applied to railway sub-ballast layers. The review protocol followed the PRISMA 2020 reporting framework for systematic reviews (Page *et al.*, 2021), ensuring transparency, reproducibility and methodological rigor throughout the evidence synthesis process.

The methodological workflow comprised six sequential stages: (1) formulation of research questions tailored to sub-ballast applications, (2) database searching and record management, (3) screening and eligibility assessment, (4) structured data extraction, (5) qualitative synthesis by waste category and performance domain and (6) comparative analysis integrating mechanical behavior, environmental indicators and regulatory compliance pathways. This integrated approach allowed the review to bridge traditional railway geotechnics with emerging low-carbon infrastructure paradigms.

Unlike previous railway waste reviews that aggregate multiple track components, the present study deliberately isolates the sub-ballast layer, recognizing its critical structural and hydraulic role and its strategic potential as a high-volume sink for low-carbon secondary materials.

3.2 Research questions

The review was guided by the following research questions (RQs):

RQ1. Which categories of solid waste materials have been investigated for application in railway sub-ballast layers, and how are they processed or engineered?

RQ2. How do waste-derived sub-ballast materials perform in terms of stiffness, permanent deformation, drainage capacity and durability under cyclic loading?

RQ3. What environmental benefits, particularly in terms of embodied carbon reduction and resource conservation, are reported for these materials?

RQ4. To what extent do existing international railway and geotechnical standards accommodate low-carbon waste-based sub-ballast systems?

RQ5. What technical, environmental and regulatory barriers currently limit large-scale implementation?

These questions were designed to capture not only laboratory performance but also system-level readiness, thereby supporting translational pathways from research to practice.

3.3 Search strategy

The Scopus and the Web of Science Core Collection bibliographic databases were selected to ensure comprehensive coverage of engineering, materials science and transportation journals. The search window spanned January 2000 to December 2025, capturing both early experimental studies and the rapid expansion of low-carbon infrastructure research over the last decade. Backward and forward snowballing were additionally applied to the reference lists and citation networks of the most relevant studies.

A representative search string applied to titles, abstracts and keywords was:

> (“railway” OR “railroad” OR “rail track”) AND (“sub-ballast” OR “subballast” OR “capping” OR “formation layer”) AND (“waste” OR “recycled” OR “by-product” OR “slag” OR “rubber” OR “plastic” OR “tailings” OR “glass” OR “circular economy” OR “life cycle” OR “LCA”).

3.4 Eligibility criteria

Eligibility criteria were explicitly formulated to ensure direct relevance to railway sub-ballast applications and low-carbon material pathways.

3.4.1 Inclusion criteria. Studies were included if they:

(1) Addressed railway sub-ballast or formation layers directly;

(2) Investigated solid waste materials, including industrial by-products (e.g. steel slags), recycled aggregates, polymers/rubber wastes, mining or quarry residues, glass wastes or engineered multi-waste blends;

(3) Reported at least one quantitative performance indicator (e.g. resilient modulus, permanent deformation, permeability, degradation);

(4) Were peer-reviewed journal articles or high-quality conference papers with explicit experimental or modeling methods;

(5) Included environmental indicators such as LCA, energy demand or greenhouse gas emissions, where available.

3.4.2 Exclusion criteria. Studies were excluded if they:

(1) Focused exclusively on road pavements, slab track systems or non-rail applications;

(2) Addressed ballast or sleepers without transferable sub-ballast implications;

(3) Discussed waste management policy without material incorporation;

(4) Were editorials or non-technical notes;

(5) Were published in languages other than English.

These criteria ensured that the final dataset reflected engineering-grade evidence specific to sub-ballast performance.

3.5 Study selection process

Records were exported to a reference manager and deduplicated prior to screening. Title and abstract screening were followed by full-text assessment of potentially relevant studies.

The selection workflow is summarized in the PRISMA flow diagram (Figure 1), consistent with PRISMA 2020 recommendations. Following database searching in Scopus and Web of Science, duplicate removal, title and abstract screening, and full-text eligibility assessment, a final dataset of 56 peer-reviewed studies directly focused on waste-based railway sub-ballast systems was obtained. This curated database formed the empirical foundation of the review and included laboratory investigations, field-oriented studies, environmental assessments and numerical modeling contributions relevant to the structural and sustainability performance of railway sub-ballast.

3.6 Data extraction and coding framework

A structured extraction template was developed to enable consistent coding across studies. For each included publication, the following attributes were recorded:

(1) Bibliographic descriptors: authors, year, journal, country.

(2) Waste category: industrial by-products (e.g. BOF/EAF slags), recycled aggregates (CDW, recycled ballast), polymers/rubber, mining and quarry residues, glass wastes and multi-waste blends.

(3) Sub-ballast configuration: untreated granular replacement, blended systems or stabilized composites.

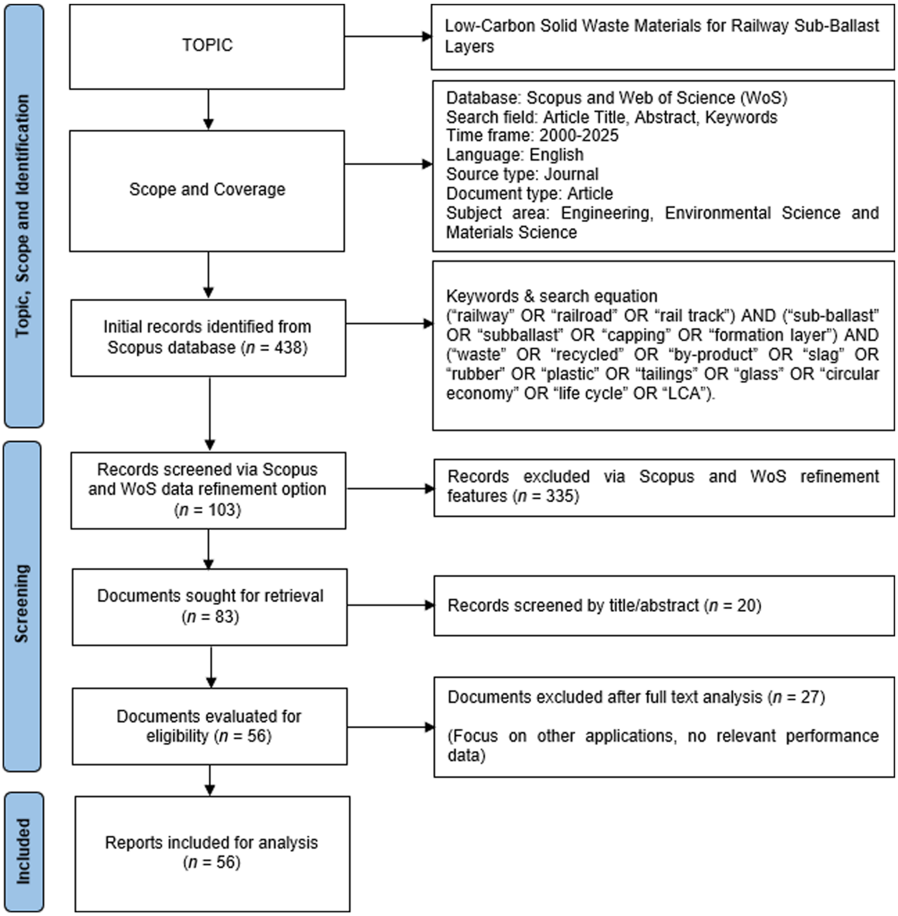

Figure 1. PRISMA 2020 flow diagram illustrating the study selection process for low-carbon solid waste materials applied to railway sub-ballast layers

(4) Performance indicators: resilient modulus, permanent deformation, hydraulic conductivity, particle degradation, vibration attenuation and durability.

(5) Sustainability indicators: embodied energy, CO_2 emissions, LCA boundaries (cradle-to-gate or cradle-to-grave) and life-cycle costs were reported.

4. Classification of low-carbon waste materials for railway sub-ballast applications

The classification of low-carbon solid waste materials for railway sub-ballast applications requires an engineering-oriented framework that goes beyond origin-based categorization. While waste streams are traditionally grouped according to industrial sector or source, their suitability for sub-ballast layers is governed primarily by functional performance, including load distribution capacity, resistance to cyclic degradation, drainage behavior and long-term durability under coupled mechanical and environmental actions.

Accordingly, this review adopts a performance-informed classification scheme that integrates material origin with key geotechnical attributes relevant to railway substructures.

The identified waste-derived materials were grouped into five main families: (1) industrial by-products, (2) recycled construction materials, (3) mining and quarry residues, (4) polymeric and rubber wastes and (5) engineered multi-waste systems. Each family exhibits distinct mechanical signatures, environmental profiles and implementation challenges when applied to railway sub-ballast.

Industrial by-products, particularly steel slags from basic oxygen furnace (BOF), electric arc furnace (EAF) and blast furnace (BF) processes, represent the most mature category in terms of mechanical performance. These materials are characterized by high angularity, rough surface texture and elevated crushing resistance, resulting in enhanced interparticle friction and stiffness. When appropriately aged or stabilized, steel slags exhibit resilient modulus values comparable to or exceeding those of conventional crushed rock, coupled with low permanent deformation under cyclic loading. Their dense mineralogy and inherent strength make them especially attractive for heavy-haul corridors, where high axle loads demand robust stress diffusion into the formation layers.

Recycled construction and demolition materials constitute a second major family, encompassing RCA, reclaimed ballast and mixed CDW blends. These materials display greater heterogeneity due to variable source composition and residual cementitious phases. While RCA-based sub-ballast systems generally exhibit lower initial stiffness than steel slags, their performance can be substantially improved through grading optimization, blending with natural aggregates or incorporation of glass and plastic fractions. However, their higher porosity and susceptibility to particle breakage during compaction require stricter quality control to preserve drainage capacity and limit fines generation.

Mining and quarry residues, including slate waste, phosphate rock and quarry fines, represent an emerging class of low-carbon sub-ballast materials with favorable mechanical stability and minimal processing requirements. These materials often exhibit crystalline mineral structures and angular particle morphologies that promote interlocking behavior and resistance to cyclic degradation. Their growing availability in proximity to railway corridors offers additional environmental benefits through reduced transportation distances and direct valorization of extractive by-products.

Polymeric and rubber wastes, primarily derived from end-of-life tires, introduce viscoelastic behavior into granular matrices. When incorporated into sub-ballast blends, rubber particles enhance energy dissipation and vibration attenuation but typically reduce overall stiffness. As a result, rubber-modified systems are rarely deployed as full-depth sub-ballast replacements. Instead, they are more commonly applied in hybrid configurations or transition zones, where damping properties complement structural support provided by stiffer aggregates.

Finally, engineered multi-waste systems combine two or more waste streams to achieve synergistic performance. Typical examples include slag–rubber composites, RCA-glass blends and alkali-activated granular mixtures. These systems aim to balance stiffness, deformation resistance and durability while maximizing environmental benefits. Although still largely confined to laboratory-scale investigations, multi-waste approaches represent a promising pathway toward tailored sub-ballast materials designed explicitly for cyclic railway loading conditions.

Taken together, the material families identified in this section already suggest distinct performance domains. Steel slags and selected mining residues are generally associated with high stiffness and low permanent strain, as reported by Delgado, da Fonseca, Fortunato, Paixão, and Alves (2021), Inabi *et al.* (2025) and Santos *et al.* (2025), whereas RCA and CDW blends exhibit a broader response spectrum controlled by source heterogeneity, adhered mortar, gradation evolution and moisture sensitivity, as shown by Naeini *et al.* (2019, 2021), Ferreira, Vieira, Lopes, and Lopes (2024) and Sindi, Carraro, and Lawrence (2025). Rubber-modified blends occupy a different functional domain, in which damping enhancement is obtained at the expense of stiffness, as discussed by Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, and Airey (2015), Koohmishi and Azarhoosh (2021) and Qiang, Jing, Connolly, and Aela (2023).

Beyond material origin, the reviewed studies highlight that sub-ballast functionality depends critically on grading continuity, particle morphology and moisture sensitivity. Materials exhibiting high angularity and broad particle size distributions generally demonstrate superior load transfer and reduced settlement accumulation. Conversely, excessive fines content or weak residual binder phases accelerate fabric collapse and compromise hydraulic performance. These observations reinforce the necessity of performance-based classification frameworks that prioritize cyclic mechanical behavior and durability rather than solely compositional descriptors.

Table 1 synthesizes the principal waste families, representative materials, typical processing routes and reported sub-ballast applications identified in the literature. This classification also establishes the functional basis for the subsequent performance synthesis, allowing direct interpretation of how each material family relates to the mechanical, hydraulic, durability and regulatory domains discussed in the following sections.

5. Mechanical performance of low-carbon materials in railway sub-ballast layers

Mechanical performance governs the structural viability of any alternative material proposed for railway sub-ballast layers. Unlike pavement foundations, railway sub-ballast operates under high-frequency cyclic loading transmitted through discrete sleeper-ballast contact zones, resulting in complex stress paths characterized by repeated deviatoric loading combined with relatively low mean effective stresses. This loading regime promotes progressive fabric rearrangement, particle degradation and accumulation of permanent deformation, even when peak stress levels remain well below monotonic strength thresholds.

Consequently, the suitability of waste-derived sub-ballast materials cannot be assessed solely through conventional index properties or monotonic strength parameters. Instead, cyclic stiffness evolution, permanent strain accumulation and degradation mechanisms must be evaluated in an integrated manner.

Table 1. Classification and key properties of waste-derived materials for railway sub-ballast

Material category	Source	Typical particle size	Key mechanical properties	Environmental aspects	Representative studies
Steel slags (BOF, EAF, BF)	Steel industry by-products	0–63 mm	High angularity, high friction angle, high stiffness	Potential leaching of metals (requires assessment)	Motz and Geiseler (2001), Tossavainen *et al.* (2007), Delgado *et al.* (2021), Hussain and Hussaini (2022)
Recycled concrete aggregates	Demolished concrete structures	0–50 mm	Moderate stiffness, higher absorption	Carbonation benefits, potential fine content	Vieira and Pereira (2015), Naeini *et al.* (2019), Sindi *et al.* (2025)
CDW blends	Mixed construction waste	Variable	Variable strength, gradation-dependent	Requires sorting and contamination control	Ferreira *et al.* (2024), Morata and Saborido (2017)
Mining residues	Phosphate, slate, quarry waste	0–75 mm	Mineral-specific stiffness	Environmental screening needed	Inabi *et al.* (2025), Santos *et al.* (2025)
Rubber-modified blends	Crumb rubber + granular	0–30 mm	Increased damping, reduced stiffness	Potential microplastic concerns	Sol-Sánchez *et al.* (2015), Koohmishi and Azarhoosh (2021), Qiang *et al.* (2023)

Experimental and numerical studies consistently demonstrate that track settlement is governed by the interaction between resilient response and irreversible deformation within the granular substructure (Dahlberg, 2001; Indraratna *et al.*, 2005; Suiker & de Borst, 2003). While ballast absorbs a significant proportion of impact energy, sub-ballast controls stress diffusion toward the formation soil and therefore plays a decisive role in limiting subgrade strain accumulation and long-term geometry deterioration.

Under repeated axle loading, granular materials exhibit an initial rapid accumulation of plastic strain followed by a slower stabilization phase, if particle breakage and drainage remain controlled (Sun *et al.*, 2016). Materials that fail to reach this stabilized response generate progressive settlement, increasing the frequency of tamping interventions and accelerating track degradation.

In this context, four interdependent mechanical domains govern sub-ballast performance:

(1) Resilient modulus and stiffness evolution;

(2) Permanent deformation resistance;

(3) Particle degradation and breakage;

(4) Interaction with drainage and moisture conditions.

5.1 Steel slags: stiffness-dominated behavior and durability advantages

Steel industry slags, including BOF, EAF and BF slags, exhibit mechanical characteristics particularly well suited to sub-ballast applications. Their angular morphology, rough surface texture and high intrinsic strength promote strong interparticle interlock, resulting in elevated friction angles and enhanced load distribution capacity (Motz & Geiseler, 2001; Tossavainen *et al.*, 2007).

Cyclic triaxial testing consistently reports resilient modulus values between 200 and 400 MPa for well-graded slag mixtures, exceeding or matching those of conventional crushed rock sub-ballast (Delgado *et al.*, 2021; Gashaw, Kishida, & Mylonakis, 2025). Importantly, this stiffness advantage is accompanied by reduced sensitivity to confining pressure variations, suggesting greater robustness under heterogeneous track support conditions.

Permanent deformation under cyclic loading typically remains below 2% when slag aggregates are adequately compacted and aged, reflecting their resistance to crushing and fabric collapse (Santos, Coelho, Monteiro, Marques, & Guimarães, 2024; Torabi-Kaveh, Mohammadi, & Mehrnahad, 2025). Field observations further confirm lower settlement rates relative to limestone or granite aggregates, attributed to sustained particle interlock and limited generation of fines (Cosme & Fernandes, 2025).

However, untreated BOF slags may exhibit volumetric expansion due to hydration of free lime and periclase. Aging, weathering or blending strategies are therefore essential to stabilize volume prior to field application (Proctor *et al.*, 2000; Tossavainen *et al.*, 2007). When such treatments are implemented, slags demonstrate exceptional durability under both mechanical and environmental exposure.

From a mechanistic perspective, steel slags behave as stiffness-dominated materials, providing efficient stress diffusion and reduced subgrade loading. This makes them particularly attractive for heavy haul corridors, where high axle loads amplify cyclic degradation processes.

5.2 Recycled concrete aggregates and CDW blends: heterogeneity and fabric evolution

RCA and CDW blends exhibit more heterogeneous behavior due to variability in source material, residual mortar content and internal porosity. Typical resilient modulus values range from 120 to 250 MPa, depending strongly on grading, moisture content and compaction energy (Naeini *et al.*, 2021; Sindi *et al.*, 2025).

Early loading stages are characterized by pronounced fabric rearrangement and mortar detachment, resulting in relatively rapid accumulation of permanent strain. With continued cycling, deformation rates often stabilize, provided that fines generation remains limited and drainage is preserved (Castro *et al.*, 2025; Ferreira *et al.*, 2024).

Stabilization strategies – including blending with natural aggregates, glass particles or recycled plastics – have been shown to significantly improve stiffness and deformation resistance (Arulrajah, Naeini, Mohammadinia, Horpibulsuk, & Leong, 2020; Naeini *et al.*, 2021). These composite systems mitigate the inherent weakness of adhered mortar by enhancing particle interlock and reducing void collapse.

Nevertheless, RCA-based materials remain more susceptible to compaction-induced particle breakage, which may alter gradation during construction and affect long-term drainage behavior (Sindi *et al.*, 2025). This highlights the need for controlled processing, optimized compaction protocols and pre-placement quality assurance.

Mechanically, RCA and CDW blends can achieve acceptable sub-ballast performance, but they demand tighter specification limits than slag or mining residues, particularly with respect to fines content and moisture sensitivity.

5.3 Mining residues and quarry wastes: emerging stiffness-stable alternatives

Mining and quarry residues, including slate waste and phosphate rock, represent an emerging class of low-carbon sub-ballast materials with promising mechanical stability. Their crystalline mineralogy and angular particle shapes promote high stiffness and limited plastic deformation when properly graded.

Recent investigations report resilient modulus values exceeding 220 MPa for phosphate waste rock blends, with deformation behavior comparable to crushed limestone (Inabi *et al.*, 2025). Similarly, slate waste exhibits high cyclic stiffness and low permanent strain accumulation, satisfying European sub-ballast performance requirements (Santos *et al.*, 2025).

Unlike RCA, these materials typically contain minimal residual binder phases, resulting in lower susceptibility to early-stage fabric collapse. Environmental screening generally confirms low leaching potential, enabling direct reuse following basic processing. Mining residues therefore combine mechanical robustness with substantial circular economy benefits, particularly in regions where such materials are locally abundant.

5.4 Rubber-modified granular systems: energy dissipation vs stiffness loss

Crumb rubber and tyre-derived aggregates introduce viscoelastic behavior into granular matrices, increasing damping capacity and reducing impact-induced degradation. However, rubber inclusion also decreases overall stiffness, with resilient modulus reductions ranging from 10% to 40% depending on rubber content and particle size (Koohmishi & Azarhoosh, 2021; Sol-Sánchez *et al.*, 2015).

While reduced stiffness limits their suitability for primary load-bearing sub-ballast layers under heavy haul traffic, rubber-modified blends offer advantages in vibration-sensitive zones and transition regions. Hybrid systems combining rubber with stiff industrial by-products (e.g. slag-rubber composites) have demonstrated balanced performance, preserving stiffness while enhancing energy dissipation and durability (Indraratna, Malisetty, Arachchige, Qi, & Rujikiatkamjorn, 2024; Qi & Indraratna, 2020).

Excessive rubber content (>10–15%) leads to unacceptable permanent deformation under cyclic loading, restricting application to specialized contexts rather than full-depth sub-ballast replacement.

5.5 Interface effects and system-level behavior

Sub-ballast performance cannot be considered independently of interface conditions within the track system. Sleeper-ballast contact geometry, ballast degradation and geosynthetic inclusions all influence stress transmission to the sub-ballast layer.

Experimental and field studies demonstrate that geosynthetics and under-sleeper pads redistribute contact stresses, delay degradation and reduce settlement accumulation (Chi, Xiao, Wang, Zhang, & Nadakatti, 2024; Indraratna & Nimbalkar, 2013; Le Pen, Watson, Hudson, & Powrie, 2018). Interface shear behavior significantly affects load transfer efficiency and residual settlement, particularly in zones with unsupported sleepers (Navaratnarajah, Mayuranga, & Venuja, 2022; Sysyn, Przybylowicz, Nabochenko, & Liu, 2021).

For waste-derived sub-ballast systems, these interactions are especially critical: materials with marginal stiffness or higher deformation susceptibility may perform adequately only when combined with stress-mitigating interfaces.

To consolidate the principal performance metrics reported in the reviewed studies, Table 2 summarizes the main mechanical, hydraulic and durability indicators used for performance-based qualification of railway sub-ballast, including their typical ranges, test methods and engineering relevance for waste-derived materials.

As synthesized in Table 2, resilient modulus, permanent strain, hydraulic conductivity and degradation resistance should be interpreted as coupled performance domains rather than isolated acceptance parameters. Delgado *et al.* (2021), Castro *et al.* (2025), Inabi *et al.* (2025) and Santos *et al.* (2025) collectively indicate that steel slags and selected mining residues consistently occupy the upper stiffness envelope and exhibit lower permanent strain accumulation, whereas RCA and CDW blends present broader variability associated with source composition, fines generation and moisture sensitivity. Rubber-modified blends form a distinct damping-oriented domain with lower stiffness and higher deformation susceptibility at elevated rubber contents. From an engineering standpoint, this means that sub-ballast qualification should be based on the stability of the coupled mechanical-hydraulic response under cyclic loading rather than on initial index properties alone.

6. Hydraulic behavior, durability and environmental compatibility

6.1 Drainage performance and moisture sensitivity

Hydraulic conductivity governs the ability of sub-ballast to dissipate infiltrating water and prevent pore pressure buildup within the formation. Reduced permeability accelerates softening of underlying soils, amplifying permanent deformation and compromising track geometry (Ferreira & Teixeira, 2012; Paiva *et al.*, 2015).

Steel slags and well-graded mining residues generally exhibit hydraulic conductivities comparable to natural aggregates (10^{-3} – 10^{-4} m/s), provided that fines content is controlled below approximately 5%. RCA and CDW blends display greater variability, with permeability strongly dependent on residual mortar content and compaction-induced fines generation.

Rubber-modified systems typically present increased void ratios but may experience clogging when fine rubber particles migrate, emphasizing the importance of particle size control and filter compatibility (Ho, Humphrey, Hyslip, & Moorhead, 2013; Qiang *et al.*, 2023). Long-term drainage performance therefore depends not only on initial permeability but also on resistance to gradation evolution under cyclic loading.

Table 2. Main mechanical and hydraulic performance indicators for railway sub-ballast

Domain	Indicator	Typical values	Test methods	Key references
Stiffness	Resilient modulus (Mr)	120–400 MPa	Cyclic triaxial	Indraratna *et al.* (2005), Delgado *et al.* (2021)
Deformation	Permanent strain (εp)	<2–4%	Repeated load triaxial	Castro *et al.* (2025), Santos *et al.* (2024)
Degradation	Breakage index	Material-dependent	LA abrasion, Micro-Deval	Guo *et al.* (2022)
Hydraulic	Conductivity (k)	10^{-3} – 10^{-4} m/s	Constant-head	Paiva *et al.* (2015)
Durability	Freeze-thaw resistance	Variable	Weathering tests	Torabi-Kaveh *et al.* (2025)

6.2 Durability under coupled mechanical-environmental exposure

Sub-ballast materials are subjected to combined mechanical cycling and environmental weathering, including freeze-thaw and salt crystallization in temperate climates. Steel slags generally exhibit excellent resistance when aged, whereas RCA may develop microcracking due to residual cement paste (Sindi *et al.*, 2025; Torabi-Kaveh *et al.*, 2025).

Mining residues such as slate demonstrate favorable durability owing to their crystalline structure and low porosity (Santos *et al.*, 2025). These characteristics translate into stable gradation and limited degradation over time. Durability performance directly influences life-cycle sustainability: materials that require frequent replacement negate initial carbon savings.

However, long-term qualification cannot rely on single-factor durability indicators alone. Torabi-Kaveh *et al.* (2025) showed that even steel slag systems with strong initial mechanical performance may undergo weathering-sensitive changes under combined freeze-thaw and salt crystallization exposure. For more heterogeneous granular materials, Sindi *et al.* (2025) highlighted that compaction-induced breakage in RCA may modify gradation and influence subsequent mechanical response. Taken together, these findings indicate that repeated loading, moisture variation, particle breakage and climatic weathering should be treated as coupled degradation pathways rather than independent phenomena.

This issue is especially relevant in sub-ballast layers because hydraulic deterioration and mechanical instability may evolve simultaneously. When cyclic loading accelerates fines generation and pore restriction, permeability loss may intensify moisture retention and, in turn, amplify permanent deformation. Future durability assessment should therefore integrate repeated-load testing, post-conditioning permeability measurement and weathering protocols within a single qualification framework. Such an approach is consistent with the long-term track-bed perspective advanced by Ferreira and Teixeira (2012) and Castro *et al.* (2024, 2025).

6.3 Environmental safety and leaching behavior

Environmental acceptance requires systematic evaluation of leaching potential for heavy metals and alkaline compounds. Most studies report that stabilized slags and mining residues comply with regulatory thresholds, particularly after aging treatments (Inabi *et al.*, 2025; Proctor *et al.*, 2000).

RCA and CDW materials require contamination screening to prevent sulphate, organic or hydrocarbon migration (Vieira & Pereira, 2015). When appropriate quality control is implemented, environmental risks remain manageable.

Table 3 provides a comparative synthesis of the overall performance of the main waste-derived material categories for railway sub-ballast, integrating mechanical response, hydraulic behavior, durability indicators and environmental compatibility.

Table 3. Comparative performance of low-carbon materials for railway sub-ballast

Material	Mr (MPa)	εp (%)	Hydraulic k	Durability	Environmental risk	Representative studies
Steel slag	200–400	<2	High	Excellent	Moderate (requires aging)	Delgado *et al.* (2021), Cosme and Fernandes (2025)
RCA	120–250	2–4	Moderate	Moderate	Low	Naeini *et al.* (2019), Sindi *et al.* (2025)
CDW blends	100–220	3–5	Variable	Variable	Low-moderate	Ferreira *et al.* (2024)
Mining waste	200–300	<3	High	High	Low	Inabi *et al.* (2025), Santos *et al.* (2025)
Rubber blends	80–200	3–6	High	High	Low	Sol-Sánchez *et al.* (2015), Ngo, Indraratna, Coop, and Qi (2023)

The comparative evidence presented in Table 3 highlights that aged steel slags and slate waste combine stiffness retention with stable permeability and favorable durability, whereas RCA-based systems and rubber-modified blends exhibit greater sensitivity to fines generation and moisture conditions. This reinforces the need for integrated mechanical-environmental screening prior to field implementation.

6.4 Integrated mechanical-environmental perspective

The collective evidence indicates that mechanical performance, hydraulic behavior, durability and environmental compatibility are inseparable in determining the long-term viability of waste-derived sub-ballast systems. Materials exhibiting high initial stiffness, but poor durability or drainage stability ultimately increase maintenance demand, undermining sustainability benefits.

Conversely, materials combining moderate stiffness with enhanced durability and environmental safety may deliver superior life-cycle performance. This systems-level perspective underscores the necessity of performance-based qualification frameworks integrating cyclic mechanical testing, durability assessment and environmental screening.

7. International standards for railway sub-ballast and regulatory gaps

Despite growing experimental evidence supporting the structural and environmental viability of low-carbon materials in railway sub-ballast layers, current standards worldwide remain largely prescriptive and poorly aligned with cyclic performance requirements. Most regulatory frameworks still rely on index properties – such as particle size distribution, plasticity limits and bearing capacity – while offering limited guidance on stiffness evolution, permanent deformation resistance, hydraulic stability or durability under repeated axle loading. This disconnect represents a critical barrier to large-scale implementation of waste-derived sub-ballast systems.

Across Europe, sub-ballast specifications are typically embedded within national railway or geotechnical standards and emphasize gradation envelopes, fines limits and minimum bearing capacity. While resilient modulus is increasingly recognized as a relevant parameter, it is rarely enforced through explicit acceptance thresholds. Environmental requirements are generally restricted to basic leaching compliance, without integration into structural qualification procedures.

North American practice follows a similar philosophy. Sub-ballast acceptance remains governed primarily by particle size limits and CBR-type indicators, supplemented by abrasion resistance tests. Cyclic mechanical performance and drainage stability are not formally incorporated into material approval pathways, despite extensive research demonstrating their relevance for track settlement control.

Asia-Pacific standards, particularly in Australia and parts of East Asia, show more advanced consideration of cyclic behavior through laboratory triaxial testing and large-scale box experiments. However, even in these contexts, waste-derived materials are typically evaluated case-by-case rather than through standardized performance-based frameworks.

In Brazil, railway sub-ballast design is regulated primarily through DNIT ISF-212 (2015), which specifies gradation envelopes, plasticity thresholds, expansion limits and minimum soaked CBR values. Although resilient modulus is mentioned as a potential design parameter, no quantitative stiffness ranges, permanent deformation criteria or hydraulic conductivity thresholds are defined. Consequently, low-carbon materials such as steel slags, recycled aggregates and mining residues are implicitly treated as conventional soils or aggregates, rather than being assessed according to their distinct cyclic and durability characteristics.

Recent experimental studies, including slate waste and phosphate residue investigations, demonstrate that several low-carbon materials achieve resilient modulus values exceeding 220–250 MPa and exhibit deformation behavior comparable to crushed rock sub-ballast.

However, these performance attributes are not captured by existing acceptance criteria, reinforcing that compliance with index properties alone is insufficient to guarantee long-term track stability.

Overall, the reviewed standards share three fundamental limitations:

(1) Predominant reliance on index properties (gradation, CBR, plasticity) rather than cyclic response.

(2) Absence of permanent deformation limits for repeated loading representative of railway traffic.

(3) Lack of integrated mechanical/hydraulic/environmental qualification, particularly for waste-derived materials.

These gaps explain why technically viable low-carbon sub-ballast systems remain confined to pilot projects or laboratory studies.

Table 4 summarizes the main international approaches to sub-ballast specification and highlights the mismatch between regulatory requirements and the performance domains identified in this review.

From a systems perspective, these regulatory shortcomings prevent the translation of laboratory-scale success into network-level deployment. The evidence synthesized in Sections 5 and 6 clearly indicates that resilient modulus, permanent deformation resistance, drainage stability and durability govern long-term sub-ballast performance. Yet none of these parameters are consistently embedded in existing standards.

A transition toward performance-based sub-ballast specifications is therefore essential. Within existing regulatory frameworks, this transition can be operationalized through a staged qualification route. A first level should retain the conventional screening criteria already embedded in railway practice, including gradation, plasticity, bearing capacity, expansion and environmental compliance. A second level should incorporate repeated-load triaxial assessment, minimum resilient modulus ranges under representative confinement, allowable permanent strain limits and post-compaction hydraulic conductivity targets. A third level should address durability through post-conditioning testing, including freeze-thaw exposure, wet-dry cycling, particle breakage and retention of drainage capacity. Finally, pre-approval field validation should be required through instrumented pilot sections capable of tracking settlement, stiffness evolution and maintenance demand. This logic follows the performance-based philosophy already

Table 4. Comparison of international sub-ballast standards and key regulatory gaps for low-carbon materials

Region	Primary acceptance criteria	Cyclic mechanical requirements	Hydraulic/ drainage criteria	Environmental provisions	Main regulatory gaps
Europe	Gradation envelopes, fines limits, CBR	Rarely specified	Indirect (via fines control)	Basic leaching	No resilient modulus or permanent strain thresholds
North America	Gradation, abrasion, CBR	Not standardized	Not explicit	Limited	No cyclic deformation criteria; waste materials assessed ad hoc
Asia-Pacific	Gradation, density, selected cyclic tests	Partially considered	Case-dependent	Project-specific	Lack of unified performance framework
Brazil	Gradation, PI/LL, expansion, CBR (DNIT ISF-212)	Not enforced	Not defined	Generic	Index-based approval; no stiffness or durability limits

consolidated in pavement and geotechnical practice and is consistent with the evidence reported by Delgado *et al.* (2021), Castro *et al.* (2024, 2025) and Santos *et al.* (2025).

In this context, performance-based regulation should not be understood as a replacement of current standards, but rather as an additional qualification layer capable of distinguishing between materials that merely satisfy index properties and those that can preserve structural and hydraulic functionality over the service life of the track. For low-carbon sub-ballast materials, this distinction is decisive because long-term field behavior depends on cyclic response stability, drainage retention and resistance to progressive degradation.

8. Integrated life-cycle assessment and structural performance of low-carbon sub-ballast systems

8.1 Infrastructure-related carbon footprint in railway systems

Although railway transport is widely regarded as a low-carbon mobility mode, infrastructure-related emissions remain substantial when assessed over the full life cycle. LCAs consistently demonstrate that material production and construction activities contribute between 30% and 60% of total greenhouse gas emissions associated with rail corridors, depending on traffic intensity and maintenance regimes (Chester & Horvath, 2009; Kiani *et al.*, 2008; Stripple & Uppenberg, 2010).

Track-bed materials, including ballast and sub-ballast, represent a dominant share of embodied emissions due to the large volumes involved and the energy-intensive nature of aggregate extraction and processing (Celauro *et al.*, 2023; Pons *et al.*, 2020; Rozycki *et al.*, 2003). In heavy haul and high-speed lines, repeated maintenance operations further amplify environmental impacts through additional material consumption and machinery use.

Within this context, sub-ballast layers emerge as a strategic leverage point for decarbonization. Compared to ballast, sub-ballast occupies larger volumes while being subjected to lower impact stresses, making it particularly amenable to substitution with engineered low-carbon materials without compromising operational safety.

8.2 Life-cycle performance of waste-derived sub-ballast materials

Several studies have quantified the environmental benefits of incorporating industrial by-products and recycled materials into railway substructures. Kiani *et al.* (2008) demonstrated that replacing virgin aggregates with steel slag in track-bed layers can reduce embodied carbon by up to 40%, primarily through avoided quarrying and reduced transportation distances.

Bressi, Santos, Giunta, Pistonesi, and Presti (2018) reported life-cycle emission reductions between 25% and 50% for sub-ballast mixtures incorporating alternative materials, depending on processing requirements and hauling distances. Celauro *et al.* (2023) further showed that construction choices involving recycled aggregates significantly improve sustainability metrics at the corridor scale, even when modest stiffness penalties are observed.

Mining residues and quarry wastes offer particularly favorable carbon balances, as they often require minimal processing prior to reuse (Inabi *et al.*, 2025; Santos *et al.*, 2025). When sourced locally, these materials can achieve reductions exceeding 50% in embodied emissions relative to conventional sub-ballast.

Rubber-modified systems provide additional environmental benefits by diverting end-of-life tires from landfills; however, their carbon performance is sensitive to processing energy and rubber content (Qiang *et al.*, 2023). Hybrid blends combining rubber with steel slag or recycled aggregates have demonstrated optimized life-cycle outcomes by balancing mechanical stiffness with enhanced durability and vibration mitigation (Indraratna *et al.*, 2024; Qi & Indraratna, 2020).

8.2.1 Methodological variability in life-cycle assessment results. A closer comparison of the reviewed life-cycle studies indicates that the environmental advantage of waste-derived sub-ballast materials is not controlled by material substitution alone, but also by the methodological architecture of the assessment itself. Pons *et al.* (2020) evaluated railway track substructures under a whole-system framework, whereas Vignali (2024) used a declared unit of 1 km of railway infrastructure and showed that comparative conclusions may shift when service life and maintenance frequency are explicitly incorporated. Bressi *et al.* (2018) reported that emission reductions in alternative railway sub-ballast mixtures are highly sensitive to processing intensity and transport distance. Navarro, Villalba, Yepes-Bellver, and Alcalá (2024), in turn, demonstrated that the interpretation of sustainability changes when the assessment boundary is expanded to include social life-cycle indicators. Ataee and Stephan (2025) further highlighted that transport-infrastructure LCAs still suffer from inconsistent system boundaries, uneven treatment of maintenance stages and limited harmonization of data sources. These differences show that reported carbon savings should not be interpreted simply as fixed material properties. Rather, they reflect methodological choices regarding functional unit, system boundary, reference service life, maintenance modelling, transport assumptions and end-of-life allocation.

For railway sub-ballast applications, this methodological variability has direct engineering implications. A cradle-to-gate comparison may favor a material with lower initial processing demand, whereas a whole-life comparison may favor a more durable alternative that reduces tamping frequency, ballast renewal and traffic disruption over time. Environmental superiority may therefore change once stiffness retention, drainage stability and maintenance demand are incorporated into the assessment. Future studies should adopt harmonized functional units, explicitly report transport and end-of-life assumptions, and couple environmental inventories with mechanical deterioration and maintenance scenarios.

8.3 Coupling mechanical durability and environmental sustainability

A critical insight emerging from the literature is that environmental performance cannot be decoupled from mechanical durability. Materials that exhibit reduced stiffness or accelerated degradation under cyclic loading require more frequent maintenance, offsetting initial carbon savings through additional tamping operations, material replacement and traffic disruptions (Dahlberg, 2001; Sysyn *et al.*, 2021).

Conversely, waste-derived materials such as aged steel slags and slate residues demonstrate high resistance to particle breakage and long-term deformation, contributing to extended service life and reduced intervention frequency (Cosme & Fernandes, 2025; Santos *et al.*, 2025). These durability advantages amplify life-cycle benefits by minimizing maintenance-related emissions.

Integrated assessments therefore indicate that the most sustainable sub-ballast solutions are those that simultaneously satisfy cyclic mechanical performance requirements and deliver substantial reductions in embodied carbon. This also means that mechanical durability should be treated not only as a structural requirement, but as a core environmental variable. When a material preserves stiffness, limits permanent deformation and maintains drainage capacity, the resulting extension of maintenance intervals directly amplifies the environmental gains captured by LCA.

8.4 System-level implications for railway asset management

From an asset management perspective, the adoption of low-carbon sub-ballast materials influences not only construction-phase emissions but also long-term operational performance. Improved stiffness distribution reduces subgrade strain accumulation, delaying track geometry degradation and extending maintenance intervals (Indraratna *et al.*, 2018; Suiker & de Borst, 2003).

Reduced settlement rates translate into fewer tamping cycles, lower ballast renewal demand and enhanced ride quality. These benefits align directly with performance-based maintenance strategies increasingly adopted by railway operators (Abadi *et al.*, 2015; Castro *et al.*, 2024). Furthermore, incorporating circular materials into sub-ballast supports broader sustainability objectives, including resource conservation, waste diversion and regional economic development.

9. Strategic roadmap for large-scale adoption of low-carbon railway sub-ballast

The experimental and field evidence synthesized in this review demonstrates that several low-carbon waste-derived materials, particularly aged steel slags, selected mining residues and optimized recycled aggregate blends, can deliver mechanical, hydraulic and durability performance comparable to conventional sub-ballast aggregates. Despite this technical maturity, large-scale adoption remains limited by fragmented qualification procedures and regulatory frameworks that are still largely index-based.

A structured transition toward network-level implementation therefore requires coordinated advances across testing standards, regulatory instruments and infrastructure management practices. In the short term (0–3 years), priority should be given to harmonizing cyclic triaxial testing protocols specifically tailored to railway sub-ballast stress paths, alongside standardized durability and leaching assessments. Establishing unified laboratory acceptance criteria for resilient modulus, permanent deformation and particle degradation would enable objective benchmarking of low-carbon materials against conventional aggregates. Parallel deployment of pilot sub-ballast sections incorporating steel slags and recycled aggregates, coupled with instrumented monitoring of settlement and stiffness evolution, is essential to validate laboratory-derived parameters under operational traffic.

In practical terms, the short-term phase should include four specific milestones. First, infrastructure agencies should publish provisional annexes or technical notes allowing waste-derived materials to be assessed beyond conventional index-based approval. Second, pilot projects should require a minimum monitoring package including track settlement, resilient response proxies, moisture condition and drainage evolution. Third, reporting of source variability, processing history and gradation control should be standardized across laboratory studies and field trials. Fourth, procurement procedures should begin to include environmental declarations or simplified life-cycle indicators for candidate sub-ballast materials. As discussed by Koohmishi, Kaewunruen, He, and Guo (2025) and Tan, Koohmishi, Jing, Kaewunruen, and Guo (2025), institutional adoption of circular materials in railway infrastructure depends as much on standardized evidence pathways as on material performance itself.

As illustrated in Figure 2, mid-term actions (3–7 years) should focus on expanding instrumented corridors across diverse climatic and loading environments, enabling development of coupled mechanical-environmental performance models. During this phase, LCA indicators

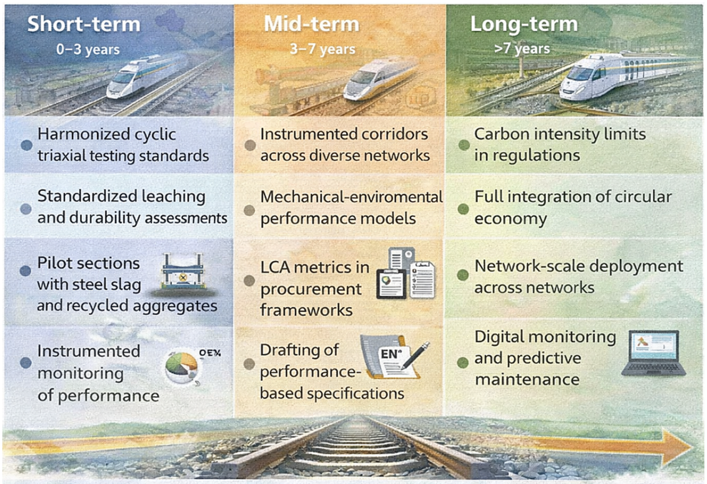

Figure 2. Strategic roadmap for large-scale implementation of low-carbon railway sub-ballast systems

must be formally incorporated into procurement frameworks, shifting material selection from lowest initial cost toward whole-life environmental and operational efficiency. Drafting of performance-based sub-ballast specifications, explicitly incorporating resilient modulus thresholds, allowable permanent strain limits and drainage stability criteria, represents a critical regulatory milestone.

During the mid-term phase, a key regulatory milestone is the conversion of provisional annexes into formal performance-based specifications linked to existing national documents. In the Brazilian context, this means complementing DNIT ISF-212 (2015) with explicit cyclic stiffness, permanent deformation, hydraulic stability and durability criteria, rather than replacing the current index-based structure. In parallel, multi-site pilot corridors should be used to calibrate numerical models and to define statistically robust acceptance envelopes for different material families, particularly for recycled aggregates, mining residues and hybrid blends.

In the long term (>7 years), the roadmap envisions full integration of circular economy principles within railway asset management systems. This includes implementation of carbon intensity limits in sub-ballast regulations, network-scale deployment of qualified low-carbon materials and adoption of digital monitoring platforms supporting predictive maintenance. Such integration enables continuous feedback between material performance, maintenance strategies and sustainability metrics, transforming sub-ballast from a passive structural layer into an active component of carbon-responsive infrastructure systems.

Crucially, this roadmap emphasizes that successful adoption is less constrained by material capability than by institutional adaptation. The convergence of performance-based standards, field evidence and asset management confidence constitute the primary pathway for mainstreaming low-carbon sub-ballast systems.

10. Research gaps and future directions

Although substantial progress has been achieved in characterizing low-carbon materials for railway sub-ballast, several scientific and methodological gaps continue to limit predictive design and regulatory standardization.

Most existing studies rely on short to medium duration cyclic laboratory tests, which do not fully capture long-term degradation mechanisms such as fines migration, moisture cycling and progressive particle breakage. Extended-duration testing protocols incorporating coupled mechanical/hydraulic/environmental loading are therefore required to better simulate in-service conditions, particularly under heavy haul traffic.

Scale effects represent a second major gap. While element-level triaxial and box tests provide valuable insight into intrinsic material behavior, translation to full-track response remains uncertain due to interface interactions with ballast, formation soils and geosynthetics. Multiscale experimental programs integrating laboratory testing with instrumented field sections and numerical modeling are needed to establish robust correlations between material properties and system-level performance.

Another critical frontier concerns the integration of multiscale numerical modeling with experimental characterization and field monitoring. Castro *et al.* (2025) demonstrated the value of combining laboratory investigation and modeling to assess alternative materials for sub-ballast and formation rehabilitation under heavy-haul conditions. However, this type of coupled framework remains uncommon in the broader waste-derived sub-ballast literature. Future research should move toward laboratory-field-model integration capable of predicting how stiffness, gradation, drainage and settlement evolve simultaneously over time.

From an environmental standpoint, future studies should also expand beyond static embodied-carbon reporting and incorporate uncertainty analysis, maintenance scenarios, service-life sensitivity and end-of-life reuse pathways. Such an approach would provide a more robust basis for corridor-scale decision-making and for integration of low-carbon materials into railway asset management systems.

The coupled evolution of stiffness and permeability also remains underexplored. For recycled aggregates and composite blends, gradation changes induced by cyclic loading may progressively reduce drainage capacity, accelerating subgrade softening and settlement accumulation. Future research should therefore prioritize simultaneous monitoring of mechanical response and hydraulic behavior over extended loading histories.

From a sustainability perspective, future investigations must move beyond static LCAs toward dynamic evaluations incorporating maintenance frequency, service disruption and end-of-life reuse scenarios. Such holistic frameworks are essential to quantify the true environmental benefit of low-carbon sub-ballast adoption across entire railway corridors.

Finally, regulatory science itself represents an emerging research frontier. Development of statistically robust performance envelopes for resilient modulus, permanent deformation and durability, supported by large, multi-source datasets, will be fundamental to replacing prescriptive index-based specifications with performance-driven standards. Collaborative initiatives between researchers, infrastructure managers and standards organizations are therefore critical to translating experimental evidence into operational design guidance.

Addressing these gaps will accelerate the transition from promising pilot applications toward standardized integration of low-carbon sub-ballast systems, enabling railway networks to achieve meaningful reductions in material-related emissions while preserving structural reliability and service quality.

11. Conclusion

This systematic review consolidates global evidence on the application of low-carbon solid waste materials in railway sub-ballast layers, integrating cyclic mechanical behavior, hydraulic performance, durability, environmental safety, life-cycle sustainability and regulatory frameworks.

The analysis demonstrates that several waste-derived materials, particularly aged steel slags, selected mining residues and engineered recycled aggregate blends, can achieve resilient modulus values between 200 and 400 MPa, permanent deformation below 2–3% under representative cyclic loading, and hydraulic conductivities comparable to conventional crushed rock sub-ballast. These performance levels satisfy the functional requirements of modern ballasted track systems while delivering substantial reductions in embodied carbon and natural aggregate consumption.

A central finding of this review is that sustainability gains are maximized only when mechanical durability and environmental performance are jointly considered. Materials exhibiting high initial stiffness but poor resistance to degradation or moisture sensitivity ultimately increase maintenance demand, offsetting initial carbon savings through additional tamping operations, ballast renewal and traffic disruption. Conversely, waste-derived materials characterized by stable particle morphology, limited breakage and preserved drainage capacity provide compounded life-cycle benefits by extending service intervals and reducing intervention frequency.

At the same time, the environmental conclusions of this review must be interpreted with methodological caution. As shown by Pons *et al.* (2020), Vignali (2024), Navarro *et al.* (2024) and Ataee and Stephan (2025), reported carbon savings vary not only because of differences among material categories but also because the underlying studies adopt different functional units, system boundaries, maintenance assumptions and reference service lives. For this reason, the most robust sustainability assessments are those that integrate mechanical durability, maintenance demand and life-cycle inventory choices within a single analytical framework.

Despite this technical maturity, large-scale implementation remains constrained by regulatory inertia. Current international standards for railway sub-ballast continue to rely predominantly on index-based acceptance criteria, such as grading envelopes and abrasion resistance, while cyclic stiffness, permanent deformation resistance and life-cycle carbon intensity are rarely incorporated into formal qualification pathways. This misalignment between scientific evidence and regulatory practice represents the primary structural barrier to circular economy integration in railway substructures.

To overcome this gap, the findings of this review support a transition toward performance-based sub-ballast specifications incorporating cyclic resilient modulus thresholds, permanent strain limits under representative axle loading, durability requirements under coupled mechanical-environmental exposure, standardized leaching protocols and explicit embodied carbon benchmarks. As illustrated in the proposed strategic roadmap, staged implementation combining laboratory qualification, instrumented field trials and progressive regulatory adaptation provides a realistic pathway for mainstream adoption.

Accordingly, the most consistent pathway for mainstream adoption is based on the convergence of three elements: harmonized evidence generation, staged performance-based qualification and whole-life sustainability assessment. When these three dimensions are jointly incorporated, low-carbon sub-ballast materials can be evaluated on functional merit rather than on the conservatism of legacy index-based specifications.

From a policy perspective, railway authorities and infrastructure managers are encouraged to integrate LCA into procurement criteria and asset management systems, enabling decarbonization of track-bed construction at corridor scale while preserving operational reliability.

Ultimately, low-carbon sub-ballast systems emerge from this review not as experimental alternatives, but as viable structural components capable of delivering measurable environmental benefits while maintaining mechanical integrity. Their deployment represents a critical opportunity to align railway engineering practice with circular economy principles and long-term sustainability objectives.

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