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A multidisciplinary review on the role of recycled steel in circular construction and structural sustainability

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Abstract

This research paper provides a multidisciplinary review of recycled steel's role in advancing sustainable construction and circular economy practices. It critically examines lifecycle material circularity, the potential for decarbonization through scrap steel utilization, and the transformative impact of recycled steel in modern architectural design. The paper also explores cross-industry collaborations as enablers of low-carbon steel supply chains and evaluates the structural performance of recycled steel in extreme environments, including thermal, seismic, and corrosive conditions. Drawing on global case studies and empirical research, the paper highlights the growing synergy between digital innovation, architectural reuse, and lifecycle sustainability in steel applications. The findings underscore that recycled steel is not merely a substitute for virgin materials but a high-performance, eco-efficient solution central to the transition toward resilient, climate-conscious infrastructure.

Keywords: Recycled steel, circular construction, lifecycle assessment, scrap steel utilization, low-carbon architecture, structural sustainability, industry 4.0, thermal and seismic performance, cross-sector collaboration, corrosion resistance

Introduction

Material Circularity and Lifecycle Thinking in Steel Applications

Material circularity is a foundational concept in sustainable construction, particularly for steel—a highly recyclable and essential material across infrastructure and industrial sectors. Rather than following a linear “take-make-dispose” trajectory, circularity promotes a looped lifecycle where materials are reused, repurposed, and reintegrated into new applications. This paradigm shift relies on lifecycle thinking, which evaluates a product's environmental, economic, and performance impacts from raw material extraction to end-of-life reuse or recycling.

In China, a national-scale dynamic material flow analysis of steel revealed major gains in productivity and emissions reduction, yet emphasized the urgent need to improve recycling rates and material loop closure. The study proposed a framework to track steel flows through production, usage, and disposal stages, and highlighted the gap between current recycling efficiency and circular economy goals (Wang *et al.*, 2013) ^[1].

Within the European steel sector, circular economy strategies have been widely adopted to enhance resource conservation and energy efficiency. This includes redesigning steel products for durability, improving waste recovery systems, and using industrial symbiosis to transform by-products into inputs for other sectors. These innovations are reshaping the industry into a more climate-resilient and economically sustainable system (Matino & Colla, 2024) ^[2].

In the U.S., researchers modeled a circular steel economy and discovered that a significant portion of steel scrap currently being landfilled or exported could be redirected into domestic production. This would reduce the need for primary steel, lower environmental impacts, and strengthen national material independence (Cooper *et al.*, 2020) ^[3].

Despite progress, several challenges remain. A bibliometric review highlighted research gaps in environmental monitoring, standardized lifecycle indicators, and strategies for managing waste and residual pollutants. There is a growing call for more integrated methodologies that combine lifecycle assessment (LCA) with real-time environmental data, especially for soil and water impacts often overlooked in current assessments (Casazza & Barone, 2023) ^[4].

Lifecycle analysis of large steel mills has offered practical insight. A comprehensive study of a facility in Italy revealed major environmental burdens during blast furnace and coke oven operations, but also opportunities to reuse by-products such as slag and excess heat. These findings reinforce the importance of refining LCA tools to capture localized impacts and enhance the industry's sustainability roadmap (Renzulli *et al.*, 2016) ^[5]. At the design level, applying lifecycle principles early in product development can yield large benefits. A new framework for designing modular steel products supports multiple lifecycles, thereby reducing raw material consumption and extending the usefulness of components. Such approaches ensure steel remains valuable across generations of reuse and support a systemic transition to circularity (Asif *et al.*, 2021) ^[6].

Decarbonizing the Construction Sector through Scrap Steel Utilization

The construction industry is a major contributor to global carbon emissions, largely due to its reliance on energy-intensive materials like cement and virgin steel. In response to climate goals set forth in agreements such as the Paris Accord, decarbonization has become a core target for both the construction and steel sectors. Among the most effective strategies for carbon reduction is the increased use of scrap steel, which can drastically lower emissions compared to primary steel production. This shift not only aligns with circular economy principles but also reduces the dependency on fossil fuels, while maintaining the material quality necessary for construction standards.

Steelmaking through traditional blast furnace (BF) and basic oxygen furnace (BOF) routes is one of the most carbon-intensive industrial processes. By contrast, using electric arc furnaces (EAFs) powered by electricity, especially from renewable sources, enables steel to be produced from scrap with significantly lower emissions. A three-dimensional analysis of China's steel sector illustrated that transitioning to EAF-based production and increasing scrap use could reduce overall emissions substantially. The analysis emphasized improvements in resource utilization, energy cleanliness, and process efficiency as critical to effective decarbonization (Lu *et al.*, 2022) ^[7]. Another global systems-level study highlighted that scrap steel, alongside zero-emission electricity and limited geological carbon storage, forms one of the three pillars of feasible steel sector decarbonization. However, scrap availability and contamination issues limit its scalability. The research stressed the need to develop advanced upcycling technologies that can produce high-quality steel from contaminated scrap, especially for high-performance applications such as automotive manufacturing (Watari & McLellan, 2024) ^[8].

Scrap steel utilization is also featured as a decarbonization lever in integrated climate-energy models. These simulations show that up to 63% of global steel production could be electrified by 2050 with sufficient scrap supply and robust recycling infrastructure. Electrification and increased scrap use were shown to be more effective when combined with material efficiency measures, carbon capture, and hydrogen-based steel production (Keramidas *et al.*, 2024) ^[9].

Material heterogeneity is a notable barrier to the widespread use of scrap in high-grade steel products. Innovations such as AI-powered hyperspectral imaging are helping overcome

this by enabling accurate sorting and quality assessment of scrap. A recent study developed an artificial intelligence model capable of distinguishing materials like ferritic and stainless steels, copper, zinc, and rubber within mixed scrap, significantly improving feedstock control and reducing quality rejection rates (de la Peña *et al.*, 2023) ^[10].

Beyond technical innovation, lifecycle carbon accounting reveals the significant advantages of recycled steel. The carbon footprint of EAF-produced steel from scrap is approximately half that of BF-BOF steel. For example, in automotive supply chains, scrap-based steel reduces emissions by up to 47%, providing a compelling case for car manufacturers to collaborate with steel producers on green procurement strategies (Shen *et al.*, 2025) ^[11].

Thermodynamic studies further support the shift toward scrap-based production, especially for flat steel products used in infrastructure and vehicles. Although scrap-related impurities such as copper pose challenges, advances in microstructural engineering and impurity control are enabling the production of high-performance steels that meet rigorous mechanical and durability standards (Raabe *et al.*, 2024) ^[12].

In regions like East Africa, where infrastructure demand is growing and virgin material imports are costly, scrap steel utilization is emerging as both a sustainability strategy and an economic opportunity. Studies suggest that optimizing scrap steel flows within regional markets could support both decarbonization and local development, reinforcing the idea that environmental goals and economic growth need not be mutually exclusive (Commonwealth Secretariat, 2023) ^[13].

Integration of Recycled Steel in Modern Architectural Design

Recycled steel is not only a sustainable building material but has also become a pivotal element in the creative evolution of modern architecture. With the increasing pressure on the construction sector to reduce its environmental footprint, architects are reimagining steel's potential—not just as a structural necessity but as a design feature that supports both aesthetic innovation and ecological responsibility. The integration of recycled steel into architectural design is driven by its flexibility, strength, and environmental merits, allowing for bold structural expression while aligning with the goals of sustainability.

Historically, steel was often concealed behind finishes in buildings, but contemporary architecture celebrates steel's raw, industrial appearance. This shift is not purely stylistic—it underscores a growing commitment to material transparency and resource reuse. The Modern Movement, for example, significantly influenced the use of steel as a visible structural element, merging aesthetics and performance. Buildings designed with visible steel skeletons now symbolize innovation, functionality, and environmental awareness, especially when recycled steel is utilized (Campos & Bernardo, 2020) ^[15].

Modern architectural projects increasingly use recycled steel for both structural framing and as cladding or decorative components. Its modularity and compatibility with prefabricated elements make it ideal for sustainable construction, supporting shorter construction times and reduced waste. Moreover, its ability to be reused multiple times without degradation enables design approaches that embrace lifecycle thinking. This evolution has transformed recycled steel into a medium through which architecture can

reflect circular economy principles and environmental ethics.

Recycled steel also plays a prominent role in architectural narratives that emphasize reuse and regeneration. Several prominent projects have embraced recycled steel components not only to reduce carbon emissions but also to convey ideas of renewal, heritage, and cultural continuity. The concept of “architectural recycling,” where elements from old structures are reinterpreted in new designs, fosters both creativity and conservation. This design philosophy sees old materials not as waste but as valuable artifacts that carry history and character into new spaces (Kiaček, 2021) ^[16].

The symbolic use of recycled steel in architecture extends to large-scale urban projects as well. High-rise buildings increasingly feature exposed steel framing, not only for structural efficiency but also for its expressive visual impact. These designs often require advanced fireproofing solutions and compliance with safety standards, but the visual reward is significant: steel contributes to a sense of strength, transparency, and modernity, all while reducing environmental harm (Nassetta, 1969) ^[17].

Beyond structural applications, architects also experiment with the form and narrative potential of recycled steel. Non-standard and sculptural uses of steel in artistic or thematic installations show how this material can transcend utilitarian functions. In particular, alternative design philosophies are challenging conventional aesthetics by using salvaged steel in unconventional ways—such as asymmetrical facades, industrial-inspired interiors, or experimental art spaces. These approaches redefine the boundaries of material reuse and demonstrate that sustainability can drive rather than limit creative freedom (Lianto *et al.*, 2024) ^[18].

Even in the realm of environmental performance, recycled steel offers key advantages. It facilitates the development of energy-efficient buildings due to its compatibility with high-performance insulation and lightweight systems. Techniques such as light steel framing enable integral design strategies where structure, envelope, and thermal performance are developed in tandem. This holistic approach optimizes both energy use and material efficiency, meeting the growing demand for net-zero and low-carbon buildings (Amundarain *et al.*, 2006) ^[19].

The integration of recycled steel is also part of a broader dialogue between past and present. The reuse of steel elements from decommissioned structures not only conserves resources but also embeds architectural memory into new developments.

Cross-Industry Collaboration for Sustainable Steel Supply Chains

The transition to sustainable steel supply chains hinges not only on technological innovation but also on strategic, cross-industry collaboration. Steel production and usage span across multiple sectors—including construction, automotive, energy, and manufacturing—which means that a coordinated, multi-sectoral approach is essential to create meaningful progress toward sustainability goals. These collaborations are emerging as key drivers in achieving low-carbon production, resource efficiency, and resilient supply chain practices.

Collaborations between suppliers, manufacturers, and recyclers are especially vital in integrating sustainable practices throughout the steel lifecycle. In the context of

Industry 4.0, supply chain networks are being restructured to facilitate smarter, more responsive collaboration. A systematic review of Industry 4.0 in logistics reveals that digital transformation has significantly altered how companies initiate partnerships, manage data flows, and share responsibility for sustainable outcomes. These technological shifts support real-time tracking, data-based decision-making, and predictive maintenance, enabling steel companies to co-innovate with downstream users (Veile *et al.*, 2022) ^[20].

One notable model of such collaboration is industrial symbiosis, where waste and by-products from one industry become valuable inputs for another. This approach has been shown to enhance sustainability and economic performance simultaneously. Industrial symbiosis networks within the steel industry facilitate the reuse of slags, flue dust, and other residuals, lowering both material costs and environmental impacts. Analysis of existing networks shows that organizational coordination and transparent resource exchange are critical to sustaining these collaborations (Herczeg *et al.*, 2018) ^[21]. Furthermore, strategic partnerships also emerge in developing certification systems and voluntary sustainability standards. The Australian steel industry’s “Responsible Steel” initiative is a prime example, where mining firms, steel producers, and recycling companies collectively formed the Steel Stewardship Forum. This cross-sector partnership aims to create a robust certification model that ensures environmental, social, and governance compliance across the supply chain, demonstrating how collaboration can enhance both market legitimacy and sustainability performance (Benn *et al.*, 2014) ^[22].

At the operational level, cross-sector collaboration offers efficiency gains through horizontal partnerships. For example, shared logistics and synchronized delivery systems among multiple firms have demonstrated significant reductions in transportation emissions and costs. A case study in Belgium revealed that companies adopting flexible attitudes toward delivery schedules and shared warehousing arrangements reduced distribution costs by up to 25%, with benefits distributed equitably among participants (Vanovermeire *et al.*, 2012) ^[23].

Small and medium-sized enterprises (SMEs) also stand to benefit from inter-sectoral collaborations, particularly through technology transfer and joint sustainability investments. Research shows that SMEs with collaborative agreements—either with suppliers or customers—are more likely to implement energy-saving technologies and sustainable practices. The success of these partnerships is often influenced by the identity of the partner (supplier vs. customer) and the nature of the sustainability investment (operational vs. strategic) (López-Cózar-Navarro *et al.*, 2024) ^[24].

The relational aspect of collaboration is equally important. Long-term partnerships based on trust and shared value creation have been found to outperform transactional or loosely coordinated models. Studies applying the McNamara partnership framework emphasize that true collaboration—characterized by mutual investment, shared goals, and transparent communication—enables proactive sustainable sourcing, unlike more limited cooperation models that fail to address systemic supply chain issues (Zarei *et al.*, 2023) ^[25].

Digitalization plays a key role in enhancing the effectiveness of collaborative efforts. Emerging tools like blockchain, IoT, and shared sustainability dashboards allow partners to co-monitor emissions, energy use, and waste streams across the value chain. These technologies increase accountability, reduce information asymmetry, and support data-driven sustainability strategies. However, researchers warn that without explicit environmental priorities, the digital transformation of supply chains may not automatically result in sustainability improvements (Kunkel *et al.*, 2022) ^[26].

Cross-sector collaboration also supports the integration of sustainability goals into supply chain design, enabling circular practices such as material recirculation, extended producer responsibility, and remanufacturing. In this context, supply chain design must account for resilience and social equity as well as environmental performance, necessitating joint planning across industries (Saffari *et al.*, 2023) ^[27].

Performance Optimization of Recycled Steel in Extreme Environments

As sustainability becomes a cornerstone of modern construction, the use of recycled steel is gaining prominence. However, optimizing its performance in extreme environmental conditions—such as high temperatures, freeze-thaw cycles, seismic zones, and corrosive atmospheres—presents unique challenges and opportunities. Addressing these environmental stressors is essential to ensure recycled steel can reliably replace or complement virgin steel in demanding structural applications.

One critical area of study involves the interaction between recycled steel bars and recycled concrete under corrosion conditions. Recent simulations demonstrate that the bond strength between corroded steel bars and recycled concrete diminishes with increasing corrosion rates. While higher concrete strength can partially compensate for this degradation, the bond-slip relationship still deteriorates as corrosion progresses, especially beyond a 5% corrosion threshold (Li *et al.*, 2023) ^[28].

In cold environments, freeze-thaw cycles also present significant durability issues. Research examining the use of nano-materials such as nano-SiO₂ and nano-Al₂O₃ in recycled concrete has shown promising results. These nano-additives improved adhesion strength by over 10% while offsetting the slip loss associated with repeated freezing. However, after 55 freeze-thaw cycles, adhesion strength still declined by nearly 41%, emphasizing the need for continued enhancement of recycled systems in cold climates (Zhang & Mei, 2024) ^[29].

Thermal environments present another major challenge. When recycled steel is embedded in recycled concrete exposed to high temperatures (up to 300 °C), compressive strength and bond strength deteriorate significantly more than in standard concrete. Tests reveal that recycled concrete can lose over 40% of its compressive strength at extreme temperatures, and bond strength between steel and concrete is correspondingly reduced. These findings stress the importance of thermal resistance treatment or protective design layers in high-heat applications (Wang *et al.*, 2023) ^[30]. From a structural engineering perspective, seismic performance is vital. Recycled concrete-filled square steel tube (RCFST) columns have been tested for ductility and

energy dissipation under cyclic lateral loads. Results show that these recycled systems exhibit ductility coefficients near 3.0 and maintain stable hysteresis loops, indicating that they can perform comparably to conventional systems under earthquake-like loading, provided that design parameters are carefully managed (Chen *et al.*, 2017) ^[31].

In response to such demands, high-strength reinforcement bars like CRB600H have been introduced in recycled concrete applications. These bars substantially improve beam shear strength and reduce the environmental impacts of structural members. A lifecycle analysis revealed that the use of CRB600H in 100% recycled aggregate concrete resulted in lower global warming potential, acidification potential, and cumulative energy demand compared to conventional reinforcement—offering a viable, performance-optimized solution for structural sustainability (Liu *et al.*, 2023) ^[28].

Optimization methods have also been explored through intelligent modeling. One study utilized particle swarm optimization (PSO) to maximize tensile strength and hardness while minimizing energy consumption in the steel recycling process. This advanced approach proved superior to traditional techniques, enabling the fine-tuning of process variables like furnace temperature and scrap composition to enhance performance characteristics under operational constraints (Baswaraj & Rao, 2019) ^[33].

Durability in corrosive environments, such as those rich in chloride ions, is also a key consideration. Recycled steel fibers used in concrete show excellent post-cracking behavior and retain mechanical properties even after accelerated corrosion testing through wet-dry cycles. However, visual inspections revealed aesthetic degradation, and long-term surface durability remains an area requiring further improvement to match that of virgin fiber systems (Graeff *et al.*, 2009) ^[34].

Conclusion

Recycled steel is redefining the boundaries of sustainable construction, emerging as both a material of strength and a symbol of circular transformation. Through innovations in lifecycle design, architectural integration, and digitalized supply chains, recycled steel is enabling a new era of climate-resilient infrastructure. Its successful application in high-performance and extreme environments, coupled with collaborative strategies across industries, illustrates its readiness to replace virgin steel in a wide array of construction contexts. As environmental demands intensify, embracing recycled steel is not just a choice—it is a necessity for building the sustainable cities of tomorrow.

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