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Review

Technological Innovations in Sustainable Civil Engineering: Advanced Materials, Resilient Design, and Digital Tools

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Abstract

Civil engineering today faces the challenge of responding to climate change, rapid urbanization, and the need to reduce environmental impacts. These factors drive the search for more sustainable approaches and the adoption of digital technologies. This article addresses three principal dimensions: advanced low-impact materials, resilient structural designs, and digital tools applied throughout the infrastructure life cycle. To this end, a systematic search was conducted considering studies published between 2020 and 2025, including both experimental and review works. The results show that materials such as geopolymers, biopolymers, natural fibers, and nanocomposites can significantly reduce the carbon footprint; however, they still face regulatory, cost, and adoption barriers. Likewise, modular, adaptable, and performance-based design proposals enhance infrastructure resilience against extreme climate events. Finally, digital tools such as Building Information Modeling, digital twins, artificial intelligence, the Internet of Things, and 3D printing provide improvements in planning, construction, and maintenance, though with limitations related to interoperability, investment, and training. In conclusion, the integration of materials, design, and digitalization presents a promising pathway toward safer, more resilient, and sustainable infrastructure, aligning with the Sustainable Development Goals and the concept of smart cities.

Keywords: geopolymers; sustainable infrastructure; building information modeling; digital twins; artificial intelligence; 3D printing; smart cities

1. Introduction

Civil engineering is undergoing a structural transformation in response to global challenges, including climate change, environmental degradation, and resource scarcity. In this context, sustainability has been consolidated as a strategic axis that demands reducing the carbon footprint, improving energy efficiency, promoting the circular economy, and employing lower-impact materials. Currently, digitalization is transforming the infrastructure life cycle through tools such as Building Information Modeling (BIM), Digital Twins (DT), the Internet of Things (IoT), Big Data (BD), and Artificial Intelligence (AI). These technologies enable process optimization, improved resource utilization, waste reduction, and increased resilience to climate and urban risks [1,2]. Their adoption is closely linked to advancements in green development, particularly when combined with technological innovation and operational efficiency. However, they also entail risks: inadequate management can increase energy consumption and generate electronic waste (e-waste), undermining the expected environmental benefits [3,4].

This technological and conceptual evolution does not occur in isolation but rather in response to a series of global challenges that are redefining civil engineering priorities. The growing impact of climate change is reflected in the increasing frequency and intensity of extreme events, such as floods, heatwaves, or landslides, which threaten the integrity and functionality of critical infrastructure. Added to this is rapid urbanization in many regions worldwide, which exerts sustained pressure on transportation, sanitation, energy, and housing systems, exacerbating social inequalities and structural vulnerabilities. In this scenario, the development of resilient and adaptive infrastructure becomes crucial to ensure basic services, mitigate risks, and maintain urban quality of life under increasingly uncertain and complex conditions [5–8].

In response to this challenging scenario, an integrated approach is proposed that encompasses three key dimensions throughout the infrastructure life cycle. First, the choice of alternative materials, such as geopolymer composites derived from waste with a low carbon footprint, represents an effective way to reduce emissions significantly in the construction sector [9,10]. Second, climate-adaptive design and environmentally responsive architecture, including solutions such as smart envelopes capable of responding to variable environmental conditions, allow the optimization of thermal, structural, and functional performance in civil works [11,12]. Finally, digital tools such as BIM, DT, IoT, and 3D printing facilitate proper material selection, enhance decision-making, and enable traceability and performance evaluation from the earliest stages of a project through its operation [13–15]. Advanced materials, resilient design, and digital tools form an interconnected system that drives the transformation of civil engineering. Innovative materials enable more adaptive designs, which in turn rely on digital tools for simulation and validation. Digitalization also facilitates the optimal selection of materials and their performance assessment, creating a feedback cycle that integrates technology and sustainability to address the challenges of climate change and rapid urbanization.

In addition, sustainable civil engineering is closely linked to the 2030 Agenda, particularly to Sustainable Development Goals (SDGs) 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action), which promote resilient infrastructure, sustainable cities, responsible consumption patterns, and climate action. This article presents an integrated analysis of the advances transforming civil engineering within the framework of sustainability. This approach enables the identification of synergies among these key dimensions, providing a solid foundation for guiding future research and decision-making in increasingly complex environmental, technological, and urban contexts. This article differs from previous reviews in that it poses the following central question: how do advanced materials, resilient design, and digital tools interact in the transformation of civil engineering? The proposal integrates these dimensions into a unified framework, highlighting their interdependence and providing a distinct perspective compared to previous studies. Figure 1 illustrates the conceptual framework of sustainable civil engineering, emphasizing the interplay among materials, design, and digital tools.

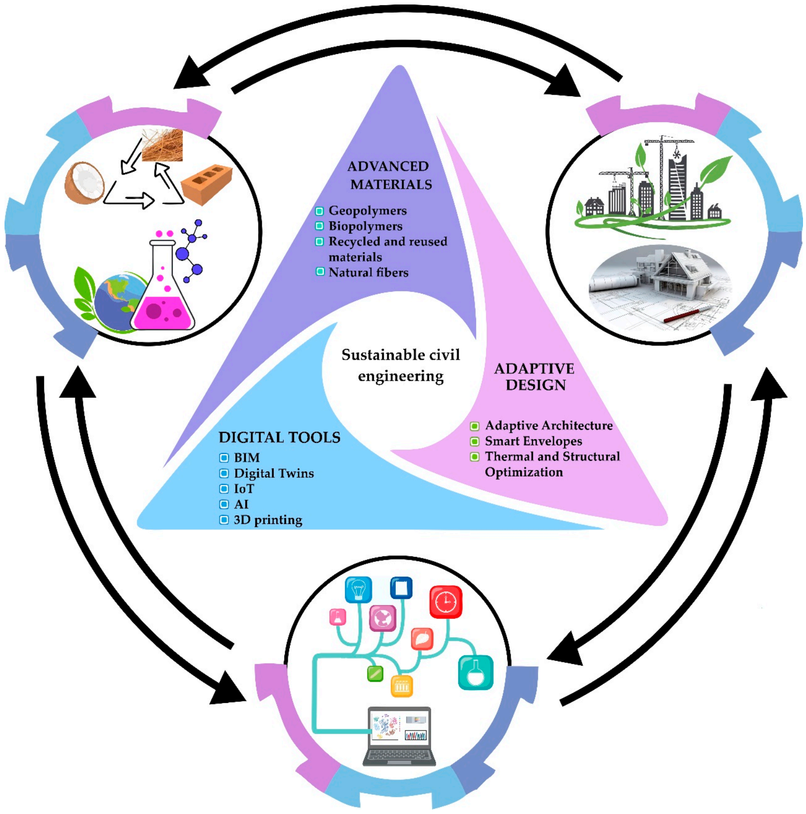

Figure 1. Conceptual framework of sustainable civil engineering: interaction among materials, design, and digital tools.

2. Methodology

This review article was conducted using a structured literature search to ensure a transparent and comprehensive overview of recent advances. Searches were conducted in Scopus, ScienceDirect, SpringerLink, Taylor & Francis, MDPI, Wiley, and PubMed, considering studies published between 2020 and 2025 [16–18].

The search strategy included keywords related to sustainable civil engineering, low-impact materials, adaptive design, BIM, DT, IoT, and the circular economy in construction. After removing duplicates and reviewing titles and abstracts, inclusion criteria were applied, considering thematic relevance, methodological rigor, and pertinence to the field of civil engineering. Studies outside the construction domain or with insufficient experimental validity were excluded.

In total, 133 articles were selected for full analysis and critical synthesis. These encompass both experimental studies and recent reviews, enabling the integration of advances into three main dimensions: (i) innovation in sustainable materials, (ii) performance- and resilience-oriented design, and (iii) digital tools applied throughout the infrastructure life cycle. A formal publication bias analysis was not conducted; however, priority was given to studies published in peer-reviewed and indexed journals, thereby ensuring the quality and practical relevance of the collected evidence.

Analysis of the reference base shows that most of the citations correspond to open-access scientific journals, with a predominance of Sustainability (MDPI) and Buildings (MDPI), which together account for more than 25% of the citations, followed by Materials, Applied Sciences, and Energies (~15%). In addition, more than 70% of the articles correspond to recent publications (2023–2025), confirming the topicality of the material considered. The inclusion criteria focused on articles published between 2020 and 2025 in indexed and peer-reviewed journals, with a focus on sustainability in civil engineering, low-impact materials, resilient design, and digital tools. Documents outside the field of construction, studies with insufficient experimental validity, gray literature, and works without full-text access were excluded from the analysis.

3. Innovations in Materials for Sustainable Civil Engineering

This section reviews the most relevant advances in the use of materials that contribute to more sustainable civil engineering. Emphasis is placed on recycled and reused materials, which reduce natural resource consumption and waste generation, as well as on alternative cements and geopolymers, which can significantly decrease carbon dioxide (CO_2) emissions compared to Portland cement. Biopolymers and natural fibers are also included as reinforcements in concretes and composites, along with nanomaterials that enhance durability and provide new functionalities to infrastructure. The analysis aims to demonstrate how these innovations not only provide environmental benefits but also create technical opportunities to meet the demands of resilience and efficiency in modern construction, aligning with the Sustainable Development Goals.

3.1. Recycled and Reused Materials

In sustainable construction, recycled materials have evolved from marginal solutions to viable alternatives when performance and environmental traceability criteria are applied. Recycled aggregates derived from construction and demolition waste are classified into recycled coarse aggregate (RCA), obtained from crushed concrete and mortar fragments, and recycled fine aggregate (RFA), originating from sand-like particles. Their use reduces natural resource extraction and landfill disposal, although it may decrease strength and durability due to the presence of adhered mortar and higher porosity. These effects can be mitigated through pretreatments such as washing, accelerated carbonation, or the use of supplementary cementitious materials. Recent evidence shows that, under controlled conditions, concretes with RCA and RFA are suitable for structural applications and provide verified environmental benefits in life cycle assessments, especially when transport distances and recycling processes are optimized [19–21].

In addition, steel slags from basic oxygen furnaces (BOF) and electric arc furnaces (EAF) are also employed as aggregates, showing good mechanical and durability performance. Their added value lies in providing additional functionalities. However, expansion due to the presence of free calcium oxide (CaO) and magnesium oxide (MgO) must be controlled, which can be achieved through aging, stabilization, or carbonation processes prior to use [22].

The recycling of plastics in concrete is achieved through two main approaches. The partial replacement of fine or coarse aggregates with recycled plastic particles decreases density and improves thermal and acoustic insulation, although excessive amounts reduce workability and strength. The use of recycled high-density polyethylene (HDPE) fibers in small proportions helps control cracking, enhances toughness, and, in specific environments, acts as a barrier against chloride penetration into reinforcing steel [23,24].

Finally, the use of crumb rubber from waste tires reduces compressive strength as its content increases, but provides greater energy absorption, damping capacity, and improved performance under dynamic loads. The effects depend on particle size and dosage, with low additions proving more favorable [25].

3.2. Materials Geopolymers and Alternative Cements

Geopolymers have emerged as a promising alternative to Portland cement due to their lower environmental footprint. Produced through the alkaline activation of industrial by-products such as fly ash or granulated slag, these materials can achieve a reduction in CO_2 emissions of up to 80–90% compared to conventional cement [26,27]. In this way, they utilize industrial residues and contribute to mitigating the climate impact of the construction sector. Beyond the environmental aspect, they stand out for their functional properties: high mechanical strength, good durability against sulfates and chlorides, and lower thermal expansion. They are already being applied in precast elements, pavements, and structural concretes [28]. Nevertheless, their adoption faces challenges, including the chemical and mineralogical variability of precursors, the lack of specific standards, the costs and environmental footprint of alkaline activators, and, in some cases, the requirement for thermal curing [9,29–36]. These limitations explain the gap between laboratory advances and industrial applications, highlighting the need for applied research and coordinated regulatory development.

3.3. Biopolymers and Natural Fibers

The use of biopolymers and natural fibers in concrete and composites has emerged as a sustainable alternative to conventional reinforcements. Recent experimental work with hybrid mixes combining alkaline-treated bamboo fibers and wheat straw has reported gains of 4–9% in compressive strength, higher energy absorption, and greater post-cracking ductility. In rigid concrete pavement design, under the criteria of the American Association of State Highway and Transportation Officials (AASHTO) 1993 standard, applying the procedure with the higher flexural strength measured for this hybrid mix, while keeping traffic, reliability, and subgrade conditions the same, allows a reduction in slab thickness from 175 to 156 mm (≈11%) [37]. Similarly, the addition of raw bamboo fibers has been shown to increase fracture tensile strength by up to 19.8% and enhance flexural performance, although at the cost of reduced workability of the mix [38]. Nevertheless, recent reviews highlight that despite these advantages, challenges remain related to fiber variability, fiber–matrix adhesion, and long-term durability, which require improvements in production processes and surface treatments [39]. These aspects suggest that natural fibers can be a valuable resource provided that adequate manufacturing controls are implemented and their performance is evaluated under real construction conditions.

Regarding biopolymers, their use as soil stabilization agents not only reinforces the environmental component but also contributes to improved mechanical and rheological properties. It has been documented, for instance, that biopolymers such as xanthan, guar, or inulin significantly increase unconfined compressive strength (UCS), with increases of up to 40 times at low concentrations (~2%). This effect is explained by the formation of hydrogel-type bonds that connect soil particles and reduce erosion under repeated wetting–drying cycles [40]. Similarly, in soils stabilized with biopolymers such as xanthan gum, cohesion and the plasticity index increase, the internal friction angle rises by about 1 to 3 percent, permeability decreases, and water retention improves. These changes delay cracking due to swelling or shrinkage and enhance erosion resistance [41]. Recently, it has been demonstrated that the chemical structure of biopolymers plays a decisive role in their efficiency for soil stabilization. In the case of galactomannans, the galactose–mannose (G:M) ratio is critical: a 1:5 ratio, characteristic of cassia gum, can triple UCS, whereas a 1:2 ratio, as in guar gum, can reduce UCS by up to 85%, underscoring the importance of appropriate biopolymer selection and molecular design according to soil type [42]. These results confirm that biopolymers are a viable alternative for soil stabilization, offering benefits in both strength and sustainability.

Despite these advances, critical limitations remain in the durability and compatibility of biopolymers and natural fibers applied in construction. Experimental tests have shown that in alkaline environments typical of concrete, fibers tend to undergo chemical and thermal degradation, leading to mass loss, surface deterioration, and reduced adhesion to the matrix [43]. Additionally, the natural variability of the material, its susceptibility to moisture, and its low compatibility with polymeric matrices necessitate treatments such as alkalization, silanization, or acetylation to ensure better performance [44]. In recent years, innovative proposals have been developed, such as biodegradable chitosan fibers that generate internal stresses during concrete curing, improving resistance to freeze–thaw cycles and chloride penetration [45]. These experiences reinforce the notion that the future of these materials lies in hybrid strategies, chemical modifications, and specialized treatments to ensure reliable and stable long-term performance. In summary, biopolymers and natural fibers offer a promising pathway toward sustainable construction, although they still need to overcome technical and regulatory barriers that limit their large-scale application.

3.4. Nanomaterials and Functional Systems

Nanotechnology has enabled the development of building materials with properties that cannot be achieved at the micro- or macro-scale, thus significantly enhancing their sustainability potential. Examples include glass with up to 75% improvements in energy efficiency, wood reinforced with nanocoatings that enhance its strength, durability, and performance against fire and ultraviolet radiation, and the use of nano-limestone in cement to accelerate strength development in cold climates. These advances demonstrate how nanotechnology improves both the functional and environmental performance of traditional materials, highlighting their role in paving the way for more innovative and resilient infrastructure [46].

The incorporation of nanomaterials, such as nano-silica (NS), graphene oxide (GO), and carbon nanotubes (CNTs), into cementitious matrices is emerging as a promising pathway to reinforce the microstructure, improve durability, and enable smart functionalities (e.g., self-sensing) in infrastructure. Due to its high pozzolanic reactivity and large specific surface area, NS reduces porosity and absorption, densifies the interfacial transition zone (ITZ), and enhances the strength and impermeability of concrete [47,48]. In the case of GO, recent reviews highlight improvements in chloride/sulfate resistance, pore refinement, and hydration acceleration, along with the challenge of achieving homogeneous dispersion and maintaining the workability of the mix [49]. CNTs, on the other hand, confer high electrical and thermal conductivity, making them useful for applications in smart buildings and structural monitoring; however, their cost and dispersion issues continue to limit their large-scale adoption [47]. Taken together, these findings show that nanomaterials hold great potential to transform the properties of concrete, provided that their technical benefits are balanced with economic feasibility.

In addition to their role as reinforcements, nanomaterials are also being applied in innovative developments. For instance, they have been used in cementitious coatings with hydrophobic nanoparticles that reduce water absorption and chloride penetration, thereby extending the service life of surfaces [50]. Antibacterial coatings have also been designed using photoactive nanocomposites, such as titanium dioxide combined with graphene oxide (TiO_2/GO), which can significantly reduce the bacterial load on cementitious surfaces under visible light [51]. In the realm of functional autonomy, self-healing systems based on encapsulated agents such as microcapsules, granules, or pellets have been shown to seal cracks spontaneously and efficiently, thereby enhancing the overall durability of the material [52]. These innovations represent a paradigm shift in construction, where materials not only serve a structural purpose but also incorporate active capabilities that extend their service life and reduce maintenance costs.

For an integrated perspective, Table 1 summarizes the main technical and environmental properties of innovative materials in comparison to traditional ones. This integrated vision allows a better understanding of their contributions to the transition toward more sustainable civil engineering.

In addition to technical and environmental properties, quality, cost, and availability must also be taken into account. Although geopolymers offer high performance and a lower carbon footprint, their large-scale adoption is hindered by the variability of precursors, the absence of specific standards, and cost sensitivity, particularly for activators and curing agents [29–36]. In biopolymers and natural fibers, resource variability, long-term durability in alkaline environments, and the need for surface treatments affect the perception of quality and manufacturing costs, thereby limiting their standardized availability [39,43,44]. In nanomaterials, despite the benefits in microstructure and durability, high costs and dispersion challenges continue to restrict their mass adoption [47,49]. These considerations complement the technical-environmental comparison and clarify the practical compromises compared to traditional materials with established supply chains and standards.

Table 1. Comparison of technical and environmental properties of innovative materials versus traditional materials used in construction.

Innovative Material	Technical Properties	Environmental Properties	References	Traditional Material	Technical Properties	Environmental Properties	References
Bioplastics	Generally lower mechanical strength, though improvable through reinforcement with natural or inorganic fibers. Compatible with conventional molding and printing processes.	Produced from renewable resources. Biodegradable or compostable under controlled conditions. Lower carbon footprint than fossil plastics, although with higher costs and energy demands.	[53–55]	Petroleum-derived plastics	High strength, durability, and versatility. Good barrier properties against gases and liquids.	Non-biodegradable, persisting for centuries in the environment. High carbon footprint and dependence on fossil fuels. Contribute to waste accumulation and microplastics.	[56,57]
Biocomposites	Lightweight, with good specific strength; favorable thermal and acoustic properties; processable using conventional techniques (injection, extrusion, compression).	Manufactured from natural fibers (flax, kenaf, jute, bamboo, sisal) and biodegradable or recyclable matrices; low carbon footprint and composting potential; reduced dependence on fossil-based polymers.	[58–60]	Synthetic composites	High mechanical strength and durability; standardized and widely used in structural and automotive applications.	Difficult to recycle, high energy consumption in production, dependence on fossil resources; limited biodegradability.	[61–63]

Table 1. *Cont.*

Innovative Material	Technical Properties	Environmental Properties	References	Traditional Material	Technical Properties	Environmental Properties	References
Biocements/ Geopolymers	High mechanical strength (>80 MPa); excellent thermal stability (retains >90% of compressive strength after exposure to 800 °C).	Reduction of CO_2 emissions by 40–80%; use of industrial residues such as fly ash and granulated slag.	[27,64,65]	Portland cement	Excellent strength and global standardization as a base construction material.	Very high CO_2 emissions (global 2 Gt in 2018); ~7% of global CO_2 emissions.	[66,67]
Mycelium	Low mechanical strength (far below conventional structural materials); good thermal insulation for envelope applications; acoustic insulation performance	Cultivated on agricultural/ lignocellulosic residues; biodegradable/ compostable.	[68–70]	Synthetic insulators such as polyurethane (PU), expanded polystyrene (EPS), and extruded polystyrene (XPS)	Good thermal insulation (low thermal conductivity, widely used in buildings).	Non-renewable; recycling challenges (especially PU); additives with toxicological concerns (e.g., Hexabromocyclododecane (HBCD) in EPS/XPS); higher environmental impact (XPS is ranked among the least favorable materials in life cycle assessment (LCA)).	[71–74]
Cellulose and derivatives	Good thermal and acoustic insulation; applicable as panels or cavity fillers; acceptable fire resistance when fire-retardant additives are used.	Renewable and biodegradable; enable valorization of lignocellulosic residues; reduce carbon footprint compared with synthetic insulators; contribute to improved energy efficiency in buildings.	[75–77]	Conventional insulators (mineral wool, fiberglass)	Good thermal efficiency, proven durability, and regulatory standardization.	Significant environmental impact during production (high energy consumption in melting furnaces); occupational risks during installation; non-biodegradable with problematic end-of-life disposal.	[78,79]

In summary, recycled materials, geopolymers, biopolymers, and nanomaterials represent converging pathways toward more sustainable construction. Although each presents particular challenges, together they demonstrate that innovation in materials constitutes a key pillar for reducing environmental impacts, enhancing structural performance, and paving the way for more resilient designs and digital technologies applied throughout the infrastructure life cycle. These innovations are directly related to SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), reinforcing their relevance within the framework of sustainable construction.

Beyond these environmental and structural benefits, the specific mechanical and durability properties of geopolymers, natural fibers, and biopolymers significantly influence infrastructure's capacity to withstand and recover from extreme events. These advances, therefore, underpin the resilient design strategies discussed in the following section.

4. Smart and Resilient Structural Design

Smart and resilient structural design is framed as a key strategy to integrate sustainability, structural performance, and digitalization in civil engineering. This approach not only seeks to ensure safety against extreme loads but also to optimize resources, facilitate adaptability through modular solutions, and guarantee the functional continuity of infrastructure in dynamic urban contexts.

4.1. Principles of Resilience in Structural Design

Currently, structural resilience is understood as the capacity of buildings to limit losses, maintain minimum service levels, and recover functionality within defined timeframes after an extreme event. This concept has evolved beyond simple collapse prevention to incorporate metrics such as functional recovery time and repair trajectory, enabling a more accurate assessment of a disaster's impact on infrastructure operability. Within this framework, probabilistic performance quantification has become a key tool for linking event intensity with expected damage levels, considering both structural and non-structural components as well as logistical constraints. These advances are encompassed within Performance-Based Design (PBD) and Performance-Based Earthquake Engineering (PBEE), applied through consolidated methodologies such as FEMA P-58 (*Seismic Performance Assessment of Buildings*), developed by the United States Federal Emergency Management Agency (FEMA), and REDi (*Resilience-Based Earthquake Design Initiative*), proposed by the international engineering and design firm Arup, based in London. Both tools enable the estimation of economic losses, downtime, and recovery trajectories, offering a more realistic vision for decision-making in complex urban contexts [80–83].

In practical terms, structural resilience aims to ensure that buildings and infrastructure not only withstand extreme events but also continue to fulfill their essential functions for the community. A hospital that remains operational after an earthquake or a school that quickly reopens following a flood are clear examples of this approach. By prioritizing service continuity, resilience connects structural design with direct social benefits, protecting lives, reducing interruptions in critical activities, and maintaining public confidence in the safety of the built environment.

In the case of floods, resilient design incorporates raising the Design Flood Elevation (DFE) to account for sea-level rise. This is complemented by dry and wet protection solutions, repairable materials, and foundation criteria tailored to the expected hydrodynamic forces and velocities. The recent literature highlights the shift from measures focused solely on hydraulic control toward adaptive approaches that integrate the building, public space, and users. Structural damage forecasting models based on flow impact have also been proposed to guide construction detailing and post-event inspection protocols [84–86]. At the urban scale, risk analyses by building typology and community resilience frameworks enable the prioritization of interventions, informed land-use planning, and reduction of aggregate losses [87,88].

Regarding extreme wind events, structural resilience incorporates passive aerodynamic controls, such as surface roughness, balconies, or canopies, to reduce peak pressures and vibrations. In addition, the envelope and its anchorage systems are detailed as the "first fuse" to prevent progressive damage and openings that compromise overall integrity. Recent evidence suggests that geometric modifications of façades can reduce drag or redistribute pressure fields at greater heights. In environments with windborne particles, such as sand or dust, the fluctuating component of the load is intensified, demanding higher design factors and attention to fatigue and local detachments [89–91].

Transversally, the principles of redundancy, modularity, and replaceable components, together with passive and active monitoring and control schemes, promote faster and more predictable recovery trajectories. Understanding the building as an interconnected system enables the establishment of explicit functional objectives and the coordination of decisions on design, operation, and repair, thereby linking resilience and sustainability throughout the building life cycle [80,92]. In summary, the principles of structural resilience ensure that infrastructure not only withstands extreme events but also guarantees functional continuity and rapid recovery. In this way, the connection between safety, sustainability, and social well-being is reinforced.

4.2. Structural Modeling and Life Cycle

Current structural modeling transcends the simple verification of resistance against extreme loads. Its objective is to project the behavior of buildings throughout their entire life cycle, integrating sustainability and efficiency criteria.

Life Cycle Assessment has been established as a crucial tool for quantifying the environmental impacts associated with the design, construction, operation, maintenance, and end-of-life stages of structures. In particular, approaches that combine LCA with BIM enable the automation and acceleration of impact calculations, such as greenhouse gas emissions, from the early stages of the project [93]. At the same time, other reviews highlight the growing use of structural modeling methodologies that incorporate deterioration, extreme events, and informed decision-making in order to achieve more resilient and sustainable environments [94].

Energy analysis also plays a central role by linking structural performance with operational efficiency. Recent studies have shown that the shape, orientation, and envelopes of buildings can optimize energy consumption by up to 17.9% [95,96]. Moreover, the early integration of energy models into the design process, through BIM tools or simulation software, has proven to reduce the gap between theoretical predictions and actual performance.

Ultimately, material efficiency is a crucial factor in achieving sustainability and resilience. Recent research has developed frameworks to evaluate the embodied impacts of materials throughout their life cycle, with particular emphasis on reuse and end-of-life phases. This approach promotes a holistic vision that should also be integrated into education and professional practice [97]. Structural and life cycle modeling provides a means to articulate sustainability, efficiency, and resilience from the design stage. The integration of LCA, BIM, energy analysis, and material efficiency fosters the creation of infrastructures with a lower environmental footprint and a greater adaptive capacity over time.

4.3. Modular and Adaptable Design

The use of modularization and prefabrication shifts much of the construction process to controlled environments, allowing shorter execution times, minimized waste, and higher quality assurance. At the same time, it facilitates the application of approaches such as Design for Manufacture and Assembly (DfMA) and the use of modular kit catalogs that standardize joints and tolerances. The most recent studies indicate that this strategy is complemented by digital tools such as BIM and DT, which integrally link design, production, and assembly. These technologies support more accurate decisions regarding costs and embodied carbon throughout the entire LCA. Altogether, modularity and digital support enable the conception of buildings that can be more easily upgraded and reconfigured, thereby reducing the impact of future modifications [98–102].

Complementarily, lightweight construction offers benefits in both assembly and the efficient use of materials. Cross-laminated timber (CLT) systems stand out for their high strength-to-weight ratio and their ability to achieve significant reductions in building-level energy consumption and embodied carbon. At the same time, advances in lightweight concrete (LWC) broaden the possibilities of application in structural elements with lower self-weight, which facilitates logistics, improves seismic performance, and optimizes the construction process, provided that appropriate design and detailing are carried out. Taken together, these alternatives strengthen the use of volumetric and panelized prefabrication, accelerating execution and commissioning times [103,104].

Spatial flexibility and adaptability throughout the life cycle are achieved through modular grids, demountable partitions, plug-and-play service systems, and principles of Design for Adaptability, Disassembly, and Reuse (DfADR), as well as Design for Disassembly (DfD). In practice, the latest conceptual frameworks suggest distinguishing between support and infill elements (open building) and incorporating structural grids, technical strips for installations, and reversible connections from the outset. This approach facilitates the reconfiguration of uses and components without requiring modifications to the primary structure, while also integrating end-of-life planning to promote material recovery and reuse [105–107].

Together, the principles of resilience, life cycle modeling, and modular and adaptable design constitute a solid foundation for advancing toward safer, more sustainable, and flexible infrastructure. These strategies enable the reduction of vulnerabilities, optimization of resource use, and maintenance of building functionality under adverse scenarios.

In summary, resilience, life cycle modeling, and modular and adaptable design complement each other to form a comprehensive framework of structural innovation. Figure 2 presents a schematic representation of these components and their interrelationships, synthesizing the overall vision of intelligent and resilient structural design. Collectively, these approaches align with SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), consolidating their relevance within sustainable construction strategies.

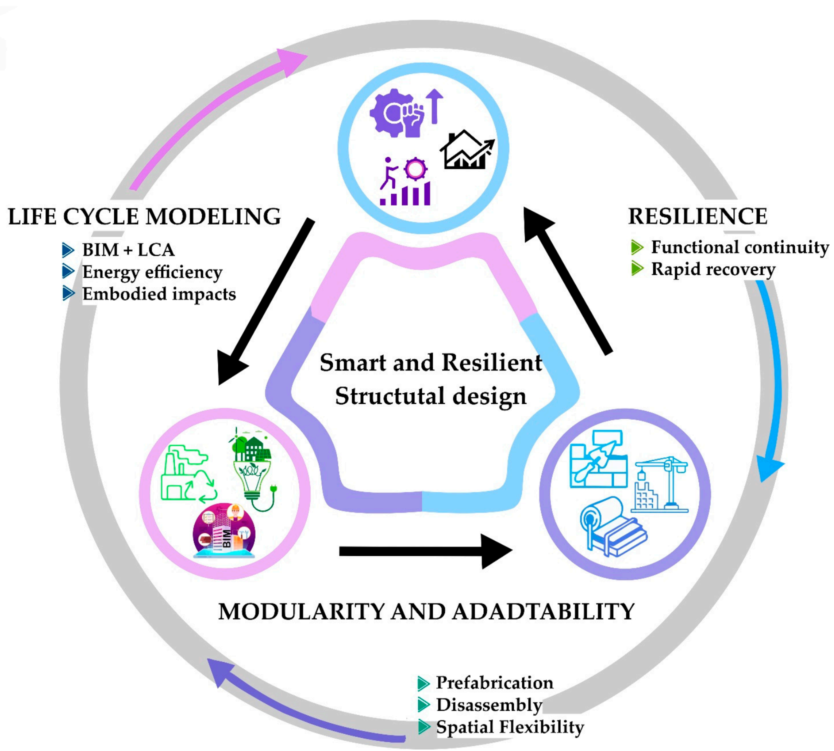

Figure 2. Schematic of intelligent and resilient structural design: resilience, life cycle modeling, and modularity.

In summary, this section addresses resilience as a design practice: material selection, structural solutions, and digital flows are evaluated against explicit objectives of functionality, recovery time, repairability, and carbon and cost throughout the life cycle. The approach transcends single-threat checks by translating multi-threat exposure into criteria for adaptability, modularity, and disassembly, and by employing life cycle analysis alongside BIM and digital twins to inform decisions at all stages. The result is a coherent framework that links safety, sustainability, and adaptability, offering a more applied reading than studies that address these issues separately.

5. Digital Tools and Emerging Technologies

Digitalization is profoundly transforming the infrastructure life cycle, from planning to operation, through the incorporation of technologies such as BIM, DT, AI, IoT, and 3D printing. These tools not only optimize coordination and resource use but also enhance the ability to anticipate risks, improve structural performance, and reduce environmental impacts, consolidating their role as catalysts for a civil engineering practice oriented toward efficiency, resilience, and sustainability.

5.1. BIM

BIM is a fundamental tool for integrating the planning, design, construction, and maintenance of infrastructures. Its application enables the centralization of geometric, material, and operational data into a single digital model, improving coordination among stakeholders and reducing conflicts during project execution. In the field of sustainability, the integration of BIM with LCA facilitates the estimation of environmental and economic impacts from the early stages of the project, enabling the comparison of design alternatives and the optimization of material and process decisions [1,93]. Complementarily, linking BIM with maintenance management systems enables predictive operation strategies, increasing asset durability and reducing costs throughout their life cycle [2,94]. Recent research highlights that the use of BIM as a collaborative platform not only accelerates project delivery but also strengthens information traceability and infrastructure resilience by incorporating real performance data into continuous feedback processes [1,13].

5.2. Digital Twins in Infrastructure

Digital Twins have become a strategic tool for predictive monitoring and operational control of infrastructures. A DT integrates virtual models with real-time data obtained from sensors and IoT systems, enabling simulation of structural performance and anticipation of failures or maintenance needs [15,108]. Moreover, in the context of sustainable construction, DT facilitates resource optimization and operational cost reduction throughout the life cycle by connecting operational data with evaluative models [15]. Their implementation enhances the resilience of critical infrastructures by enabling scenario simulation under extreme conditions and defining adaptive response strategies [109]. Recent studies also highlight the integration of DT with BIM, creating digital ecosystems that enhance information traceability and support real-time decision-making across all project phases [110,111].

5.3. AI, Sensors, and IoT

The combination of AI with advanced sensors and IoT technology has transformed structural monitoring. In particular, Structural Health Monitoring (SHM) systems use sensor networks that capture vibrations, displacements, or deformations, while AI applications detect anomalies, predict damage, and anticipate interventions [112]. A recent example utilizes distributed piezoelectric (PZT) sensors and machine learning techniques to estimate the strength of concrete in real time during curing with an accuracy of nearly 95% [113]. Likewise, systematic reviews underline the evolution of sensor technologies, including

Micro-Electro-Mechanical Systems (MEMS) and wireless networks, as well as their integration with AI and DT to strengthen diagnostic capacity in critical infrastructures [114]. Furthermore, the proliferation of self-powered sensors and distributed AI algorithms in Artificial Intelligence of Things (AIoT) architectures is driving the development of intelligent systems that operate autonomously, efficiently, and resiliently, especially in hard-to-access or energy-constrained environments [115]. Finally, specific studies on concrete bridges have confirmed that the combination of multimodal AI and deep learning techniques improves the accuracy and reliability of structural diagnosis, offering clear advantages over traditional manual methods [116].

5.4. 3D Printing and On-Site Automation

3D printing, also known as additive manufacturing, combined with automated systems, is transforming the construction industry through its precision, speed, and efficiency in material use. This technology enables the creation of complex elements with reduced waste and greater customization, while also reducing construction times and labor costs [117]. In smart cities, 3D printing has demonstrated its potential to deploy more sustainable infrastructures, such as affordable housing or modular urban furniture integrated with IoT sensors, fostering adaptability and technological governance [118]. Moreover, the incorporation of digital models and DT in 3D printing improves quality control across all life cycle stages, anticipating construction defects and optimizing the manufacturing of structures such as concrete bridges reported in China [119,120]. Developments have also been documented in the automated production of concrete mixes for printing, ensuring precise, repeatable, and effective on-site dosing, substantially improving productivity and quality [117,118]. Finally, recent studies indicate that the use of 3D printing in construction can reduce CO_2 emissions by up to 70%, depending on the material type and the level of automation applied [121].

5.5. Practical Applications of Advanced Digital Tools

As discussed in this review, recent studies have demonstrated how the integration of BIM–LCA can inform more sustainable decisions in real-world projects. A case study applied to a 60-story skyscraper in Chicago showed that concrete, which constitutes 91% of the structural mass, contributes 74% of the global warming potential, while steel, with 9% of the mass, accounts for 26% of that impact. These results, obtained using a BIM-LCA workflow with Revit and Tally, demonstrate that the product stage accounts for the majority of environmental impacts, underscoring the need to incorporate digital methodologies from the initial design phases to minimize the environmental footprint in civil construction [79].

Recent studies have demonstrated the usefulness of DT in bridge management through the integration of BIM and GIS. A case study applied to the River Neath Swing Bridge in Wales developed a web platform that combines real-time monitoring, drone inspections, and geospatial analysis, enabling defects to be identified with centimeter precision and linked directly to the bridge's 3D elements. This approach improved information traceability, optimized maintenance planning, and reduced operational downtime, consolidating DTs as strategic tools for predictive management and the resilience of critical infrastructure [122].

Structural monitoring systems powered by artificial intelligence have achieved very high levels of accuracy in real-world conditions. One example is the use of convolutional neural networks for the automatic detection of cracks in concrete structures, which achieves an accuracy of nearly 99.9%. These results confirm that the integration of AI–IoT schemes can provide highly reliable, real-time diagnostics in critical infrastructure, such as bridges, tunnels, and dams, thereby strengthening decision-making for predictive maintenance [123].

3D printing in construction has already demonstrated applications in both structural components and housing projects. A case study on 3D-printed permanent formwork with cementitious materials showed that, by using optimized mixes and incorporating low-clinker cements, it is possible to reduce CO_2 emissions by up to 50% compared to traditional formwork, in addition to decreasing material consumption, shortening execution times, and reducing waste generated on site [124]. Table 2 presents a comparative overview of digital technologies in the field of civil construction, covering their practical applications, key benefits, typical integrations, and limitations identified in the literature.

Table 2. Digital Technologies Applied in Civil Works: Applications, Benefits, Integrations, and Limitations.

Technology	Applications	Key Benefits	Typical Integrations	Challenges and Limitations	References
Building Information Modeling (BIM)	Integrated planning, clash detection, material quantification, simulation of design alternatives; in operation and maintenance (O&M): asset inventory, maintenance management, as-built updating.	Reduction of conflicts and rework; single database; support for life cycle analysis; improvement of costs and schedules.	BIM–LCA (IFC, Industry Foundation Classes); BIM–FM (Facility Management)/CMMS (Computerized Maintenance Management System); BIM–IoT.	Interoperability and data quality, model updating, organizational maturity, adoption costs.	[93,125,126]
Digital Twins (DT)	Real-time monitoring, performance simulation, support for predictive maintenance, what-if visualization and analysis.	Virtual twin connected to IoT data; performance-based decisions; traceability; greater asset resilience.	DT–BIM, DT–IoT, DT for bridges with online updating.	Integration of heterogeneous sources, data governance, scalability, cybersecurity, standardization.	[15,108,127]
Artificial Intelligence (AI), Sensors, and Internet of Things (IoT)	Structural Health Monitoring (SHM) (vibrations, deformations, ultrasound); anomaly detection, damage diagnosis, service life prediction.	Automated diagnostics; reduced inspections; predictive maintenance; operation in remote environments with AIoT.	AI/ML (machine learning) with SHM signals; PZT for concrete properties; AIoT for distributed processing; integration with DT.	Thermal drift and sensor noise, data curation, energy availability at the edge, field validation.	[112,113,115,128, 129]
3D Printing and On-Site Automation	Additive manufacturing of elements; automated mixing; in-process quality control; 3D-printed housing and bridges.	Reduced waste and timelines; complex geometries; CO_2 reduction; digital traceability of the process.	3DCP (3D Concrete Printing) –DT, automated mixing, connection with BIM.	Industrial scalability, material formulations, regulations, dimensional and mechanical control.	[113,119,121]

Overall, the adoption of BIM, DT, AI, sensors, IoT, and 3D printing is transforming the infrastructure life cycle toward smarter, more efficient, and more sustainable models. These technologies optimize coordination, enhance monitoring and maintenance, and reduce environmental impacts, although they still face challenges related to interoperability, governance, and scalability. Looking ahead, their implementation aligns with SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), consolidating digitalization as a key driver of the transition toward safer, more resilient, and low-carbon infrastructures.

By analyzing the three dimensions of advanced materials, resilient design, and digital tools, it becomes evident that the transformation of sustainable civil engineering does not rely solely on isolated innovations but on the systemic interaction among them. This process can be understood at three levels:

- External pressures: phenomena such as climate change and rapid urbanization generate new demands on infrastructure, requiring more adaptive and resilient solutions.
- Technological responses: low-carbon materials, resilience-oriented design, and digital tools emerge as alternatives that converge toward sustainability.
- Dynamic interactions: innovative materials require digital simulations to validate their performance under real conditions; resilient designs become feasible through the use of these materials and reach maximum efficiency when optimized with BIM, digital twins, IoT, or artificial intelligence.

This dynamic constitutes the driving logic that guides the transition toward sustainable and resilient infrastructures aligned with global challenges.

6. Challenges, Barriers, and Opportunities

The adoption of digital technologies and innovative materials in civil engineering still faces multiple regulatory, economic, and institutional barriers, as well as gaps in technical training and research. Overcoming these barriers is a crucial condition for consolidating more sustainable, resilient, and adaptable infrastructures.

First, one of the main obstacles is related to outdated regulatory and normative frameworks that do not include specific standards for methodologies such as BIM, DT, intelligent monitoring through artificial intelligence, or 3D printing [130]. The lack of harmonized technical guidelines at the international level hinders the certification, interoperability, and acceptance of these solutions in large-scale projects, slowing down their widespread adoption.

Second, the economic dimension represents a significant barrier. The implementation of BIM, DT, AIoT, or 3D printing requires high initial investments in software, hardware, sensors, and specialized equipment. Added to this is the challenge of scalability: successful pilot projects often face difficulties when replicated in complex urban contexts due to the heterogeneity of stakeholders, industry fragmentation, and institutional resistance to transforming established practices [1,131,132]. Organizational inertia and the perception of financial risk limit the capacity to incorporate technological innovation in public and private procurement processes.

Finally, gaps in technical training and applied research persist. The effective adoption of these technologies requires professional profiles with competencies in digital modeling, data analysis, programming, and asset management—skills that are still not widely integrated into civil engineering curricula [133]. Moreover, in the scientific field, longitudinal and comparative studies are necessary to evaluate the actual impact of BIM, DT, AI, and 3D printing on the sustainability and resilience of infrastructures, particularly in developing countries.

Nevertheless, these challenges also represent strategic opportunities. Regulatory updates can catalyze innovation, investment in digital infrastructure can optimize resources in the long term, and the integration of interdisciplinary training can generate a new generation of engineers better prepared to respond to dynamic urban scenarios. Thus, turning these barriers into opportunities is fundamental to advancing toward an infrastructure model aligned with the Sustainable Development Goals and the transition to smart and resilient cities [2].

From our perspective, the real challenge lies not only in technological upgrading but also in the ability to articulate regulatory, economic, and training changes simultaneously and in a coordinated manner. Experience shows that technology alone does not guarantee sustainability or resilience unless it is accompanied by flexible regulatory frameworks, clear financial incentives, and human capital prepared to lead the transition. We believe the coming years will be decisive: civil engineering must advance toward a more open, interdisciplinary, and adaptive model, in which the integration of BIM, DT, AI, 3D printing, and other emerging technologies not only responds to a logic of technical efficiency but also to a social and environmental commitment that transforms current barriers into true catalysts of innovation.

Beyond the regulatory, economic, and training aspects previously discussed, it is also possible to identify specific technical bottlenecks in each of the analyzed areas. In advanced materials, the main limitation remains the absence of standards and certifications to support their widespread adoption. In resilient design, the difficulty lies in translating theoretical metrics into applicable building codes and guidelines. In the case of digital tools, the challenges focus on interoperability, initial costs, and the availability of trained professionals. Recognizing these limitations allows us to connect theory with practice and guide clearer implementation paths, complementing previous analyses. Figure 3 provides a graphical synthesis of the main challenges, barriers, and opportunities discussed in this review article, facilitating their understanding and visualization.

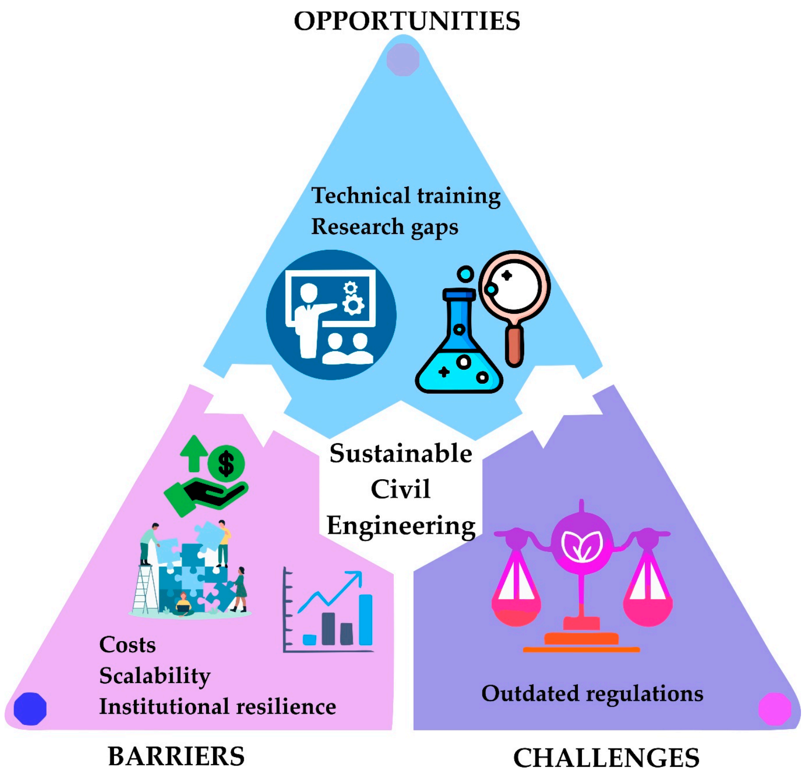

Figure 3. Challenges, barriers, and opportunities.

7. Future Perspectives and Research Directions

Research in civil engineering should focus on evaluating emerging technologies, considering their level of technological readiness (TRL). This criterion will enable the distinction between digital solutions—such as information modeling, digital twins, artificial intelligence applied to sensors, or 3D printing—that are ready for implementation and those that still require experimental validation. This will enable resources to be prioritized and efforts to be directed toward developments with greater potential impact.

At the same time, it is necessary to strengthen interdisciplinary integration between civil engineering, environmental sciences, and the digital domain. Infrastructure planning can no longer be approached from a single technical perspective; instead, it requires collaboration among specialists capable of combining ecological sustainability, data analysis, and project management. This approach will enable more effective responses to the complexity of current and future urban environments.

The development of smart infrastructure constitutes another priority axis. The incorporation of digital technologies into city planning and operations offers the potential to optimize resources, anticipate risks, and improve the quality of life through interconnected systems. The vision of a sustainable city requires that physical infrastructure be complemented by digital management and governance platforms capable of dynamically responding to social and environmental challenges.

From our perspective, the future of civil engineering must be consolidated under a systemic vision that combines technological readiness evaluation, interdisciplinary cooperation, and the development of smart infrastructures. The real challenge will not only be technical but also social and environmental: transforming innovations into solutions that promote sustainability, resilience, and urban equity. Figure 4 shows the identified future perspectives and research directions.

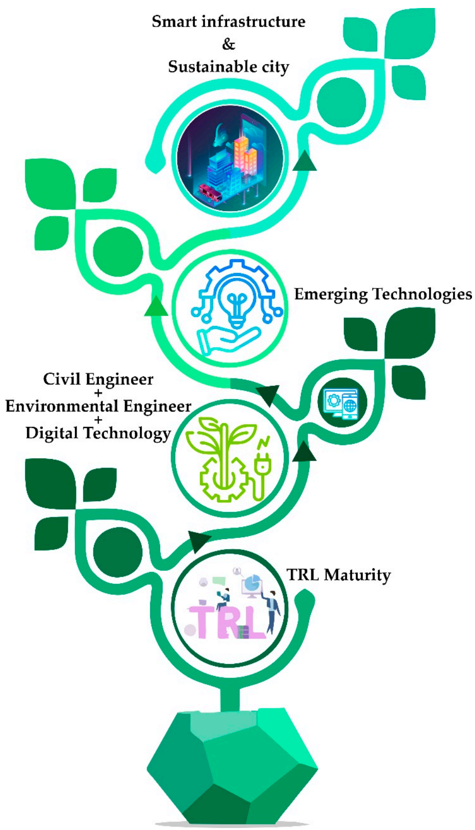

Figure 4. Future perspectives and research directions.

8. Conclusions

Sustainability in civil engineering depends on the integration of innovative materials, resilient structural designs, and digital technologies applied throughout the infrastructure life cycle. Alternative materials offer options with lower environmental impact, although their use still requires stronger regulatory and economic frameworks. Modular and adaptable design strengthens urban resilience, while tools such as BIM, digital twins, artificial intelligence, and 3D printing show high potential, even though they face cost and interoperability limitations. To move forward, engineers must strengthen digital and environmental competencies, academics must conduct applied research, and decision-makers must update regulations and support mechanisms.

The added value lies in the synergy among materials, design, and digitalization, which will enable the construction of safer, more efficient, and more sustainable infrastructures. Altogether, these advances constitute a strategic pathway that directly contributes to the Sustainable Development Goals (SDGs 9, 11, 12, and 13) and consolidates civil engineering as a key driver in facing the climatic and urban challenges of the 21st century.

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Abbreviations

The following abbreviations are used in this manuscript:

AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
AIoT	Artificial Intelligence of Things
Arup	International engineering and design firm based in London
BD	Big Data
BIM	Building Information Modeling
BOF	Basic Oxygen Furnace
CaO	Calcium Oxide
CLT	Cross-Laminated Timber
CMMS	Computerized Maintenance Management System
CNTs	Carbon Nanotubes
CO_2	Carbon Dioxide
DfADR	Design for Adaptability, Deconstruction, and Reuse
DfD	Design for Disassembly
DFE	Design Flood Elevation

DfMA	Design for Manufacture and Assembly
DT	Digital Twins
EAF	Electric Arc Furnace
EPS	Expanded Polystyrene
e-waste	Electronic Waste
FM	Facility Management
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
GO	Graphene Oxide
Gt	Gigatonnes
HBCD	Hexabromocyclododecane
HDPE	High-Density Polyethylene
IFC	Industry Foundation Classes
IoT	Internet of Things
ITZ	Interfacial Transition Zone
LCA	Life Cycle Assessment
LWC	Lightweight Concrete
MDPI	Multidisciplinary Digital Publishing Institute
MEMS	Micro-Electro-Mechanical Systems
ML	Machine Learning
MPa	Megapascal
NS	Nano-Silica
O&M	Operations and Maintenance
PBD	Performance-Based Design
PBEE	Performance-Based Earthquake Engineering
PU	Polyurethane
PZT	Piezoelectric Sensors
RCA	Recycled Coarse Aggregate
REDi	Resilience-Based Earthquake Design Initiative
RFA	Recycled Fine Aggregate
SDG	Sustainable Development Goals
SHM	Structural Health Monitoring
TiO_2	Titanium Dioxide
TRL	Technology Readiness Level
UCS	Unconfined Compressive Strength
XPS	Extruded Polystyrene
3D	Three-Dimensional
3DCP	3D Concrete Printing
°C	Degrees Celsius

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