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Systematic Review

Industry 4.0 Technologies for Sustainable Transportation Projects: Applications, Trends, and Future Research Directions in Construction

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Abstract: This study presents a mixed-method systematic literature review (SLR) investigating the applications of Industry 4.0 (I4.0) technologies for enhancing sustainability in transportation infrastructure projects from a construction perspective. A corpus of 199 scholarly articles published between 2009 and November 2023 was meticulously selected from the Scopus database. The thematic analysis categorised the publications into four main clusters: infrastructure type, technology types, project lifecycle stages, and geographic context. The scientometric analysis revealed a burgeoning interest in the integrating of I4.0 technologies to enhance sustainability—particularly environmental sustainability. Among these, Building Information Modelling (BIM)-related tools emerged as the most extensively studied domain (33.50%), followed by the Internet of Things (IoT) and sensors (14%), and Artificial Intelligence (AI) (13.22%). The findings demonstrate that roads, highways, and bridges are the most studied infrastructure types, with BIM being predominantly utilised for energy assessment, sustainable design, and asset management. The main contributions of this review are threefold: (1) providing a comprehensive framework that categorises I4.0 applications and their sustainability impacts across transportation infrastructure types and project lifecycle stages, (2) identifying key technical challenges in integrating I4.0 technologies with sustainability assessment tools, and (3) revealing underexplored areas and providing clear directions for future research. The findings provide actionable insights for researchers and industry practitioners aiming to adopt integrated, sustainability-driven digital approaches in transport infrastructure delivery.

Keywords: transportation projects; Industry 4.0; sustainable development; construction industry; mixed-method review

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1. Introduction

Considerable empirical evidence underscores the direct and indirect influence of engineering design and construction methods on sustainable development [1,2]. For instance, the built environment in Europe contributes significantly to environmental impacts, accounting for 40% of total energy consumption, 32% of CO_2 emissions, 50% of all extracted (fossil) materials, and 25% of the generated waste on an annual basis, and the transportation construction sector stands out as a significant contributor to carbon emissions [3,4]. These emission levels and material consumption are on the rise due to global economic

growth, creating an unsustainable situation. Despite this, the construction of transportation infrastructure, such as roads, bridges, and highways, is gaining momentum in several countries. Evidently, the 2020–2021 Australian budget demonstrated a strong commitment to transport mega projects with a substantial allocation of over 100 billion AUD, highlighting investment growth in new infrastructure initiatives. The New South Wales (NSW) government has pledged significant resources across the lifecycle of state infrastructure, with an additional $93 billion in capital expenditure planned from 2019 [5]. Similarly, in the UK, the general government spent £23.8 billion on building transportation infrastructure in 2021, with the majority of this amount, £20.7 billion, allocated to the construction of transportation infrastructures such as roads, airports, harbours, and railways. Moreover, the international community recognises the importance of sustainable construction in transport projects for countries in special situations through frameworks like the Sendai Framework for Disaster Risk Reduction and the United Nations (UN) Sustainable Development Goals.

Although investments in constructing transportation infrastructure are theoretically beneficial to the whole economy, they can have significant environmental consequences due to the high energy requirements associated with the construction and maintenance of infrastructure systems. The construction of transportation projects has a considerable environmental impact on a global scale, involving extensive consumption of natural resources and the staggering generation of two to three billion tonnes of construction waste annually [6]. For example, the construction of roads in China is a significant factor contributing to environmental degradation, resulting in substantial pollution [7]. Furthermore, the immediate effects of building rail transit systems have been found to negatively impact air quality. The 2018 China State Bulletin on Ecological Environment emphasised the country's challenges in maintaining acceptable air quality levels, with around 64.2% of cities at and above the prefectural level, including 217 cities out of 338, exceeding the national air quality standard. This highlights the formidable task of ensuring satisfactory air quality in most Chinese cities, necessitating further attention and measures to mitigate the environmental impacts associated with economic growth and infrastructure development [7].

In this context, the adoption of Industry 4.0 (I4.0) technologies presents a valuable opportunity to enhance the efficiency of construction projects while addressing the environmental impacts [8]. Countries such as Australia, China, and the UK are witnessing a surge in investment in constructing transportation infrastructure projects [9,10], creating a significant opening for both the public and private sectors to leverage I4.0 technologies, including digitalisation, automation, and data analytics, to bolster the sustainability of these projects. Nevertheless, the implementation and utilisation of I4.0 technologies in transportation construction projects have been sluggish, particularly when it comes to promoting sustainability. The integration and effective application of I4.0 technologies in infrastructure construction projects can be complex, as multiple stakeholders are involved. The successful delivery of public infrastructure projects necessitates seamless coordination among numerous parties operating across various sub-contracts. These parties must navigate intricate technical decisions while adhering to legal and contractual requirements, managing time, cost, site access, staging, resource allocation, and addressing community concerns. Furthermore, despite the utilisation of these technologies in certain transportation construction projects, most sustainability reports and assessments of key performance indicators for these projects still depend on conventional criteria like renewable energy and community impact. These reports frequently lack evidence or justification concerning how these deployed technologies contribute to sustainability performance and criteria [3,4].

Several studies have investigated how various digital technologies, including Building Information Modelling (BIM), Internet of Things (IoT), and artificial intelligence (AI), aid sustainable development in various scales of the built environment [11] and industrialised

buildings [12]. However, literature reviews of digital technologies have, thus far, focused on specific areas, such as underground infrastructure construction [13], infrastructure construction and maintenance [14], BIM application for design, construction, and maintenance of transportation infrastructure projects [15,16], and mainly narrowing their focus on one aspect of sustainability only. Nonetheless, for sustainable development in the built environment to be effective, it must integrate social, economic, and environmental aspects simultaneously [11,12]. Although existing studies provide comprehensive insights into I4.0 for their respective domains, particularly from an operational perspective [17], a holistic review of these technologies across the entire construction project lifecycle—including planning, design, construction, and maintenance of transportation infrastructure—remains elusive.

To address this knowledge gap, this paper aims to provide a systematic literature review (SLR) of the implementation and applications of I4.0 technologies for transportation construction projects to advance sustainability. The review encompasses current trends and topics, applications and uses, emerging technologies, benefits, limitations and challenges, research gaps, and future needs. This SLR aims to address the following research question: "How can the integration of I4.0 technologies enhance sustainability in different stages of transportation projects, from planning and design to construction and operation?" The findings of this review provide project stakeholders, policymakers, and researchers with crucial insights to make informed decisions, develop strategies for leveraging I4.0 technologies throughout the lifecycle of transportation infrastructure, and aid in creating comprehensive sustainability reports and establishing key performance indicators for digitally enabled transportation construction projects.

The main contributions of this SLR are threefold. First, it provides a comprehensive overview of the current state of knowledge regarding the application of I4.0 technologies for advancing sustainability in the planning, design, construction, and maintenance of transportation infrastructure. Second, it identifies the key research gaps and future opportunities in this domain, guiding the direction of future research efforts. Third, it offers practical insights and recommendations for project stakeholders and policymakers to effectively integrate I4.0 technologies into the transportation infrastructure lifecycle to promote sustainability.

The remainder of the paper is organised as follows: Section 2 presents the theoretical background, including the application of sustainability and I4.0 technologies for transportation construction projects, providing essential context for the study. This is followed by Section 3, which outlines the methodology used for the systematic literature review process. In Section 4, we present the results and findings, including both qualitative and quantitative insights based on the identified themes in the literature. Moving on to Section 5, we present the discussion, where we analyse the findings, identify research gaps, and propose future research opportunities. Finally, in Section 6, the conclusion summarises the key findings and contributions of this SLR will be presented.

2. Theoretical Background

2.1. Sustainability in Transportation Construction Projects

The concept of sustainability has gained significant attention in recent years, particularly in the context of transportation infrastructure development. Sustainability is often described through economic, social, and environmental considerations, also known as the three pillars of sustainability [18]. In the context of transportation construction projects, sustainability refers to the ability to design, construct, and maintain transportation systems in a way that meets the current needs of society without compromising the ability of future generations to meet their own needs. Economic sustainability in transportation infrastructure projects is concerned with the financial viability and long-term economic benefits of

the project. It involves the efficient allocation of resources, cost-effectiveness, and the ability to generate economic growth and development [19]. Social sustainability involves ensuring that the project benefits all members of society, including vulnerable and marginalised groups, and promotes social equity, inclusivity, and well-being [20]. It encompasses issues such as accessibility, safety, health, and community engagement. Environmental sustainability in transportation infrastructure projects aims to minimise the negative environmental impacts associated with the construction, operation, and maintenance of transportation systems. It involves reducing greenhouse gas emissions, conserving natural resources, protecting biodiversity, and promoting the use of renewable energy sources [21].

A range of tools, regulations, and indicators are employed to evaluate the sustainability of transportation construction projects and their economic, social, and environmental impacts. According to Jeon and Amekudzi [22], the establishment of sustainability objectives entails the contemplation of multiple factors. Stakeholders, such as community members, regulatory agencies, investors, and other interested parties, must be primarily identified. A sustainability assessment should be conducted using tools such as the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) (U.S. Federal Highway Administration), Envision (Institute for Sustainable Infrastructure), GreenLITES (New York State Department of Transportation), and CEEQUAL (UK Institution of Civil Engineers) to identify the project's environmental, social, and economic impacts. Sustainability goals should also be prioritised based on assessment results, such as reducing carbon emissions or improving social equity. For each sustainability goal, measurable targets need to be set to track and evaluate progress, aligned with relevant industry standards, such as ISO 14001 or ISO 26000.

Most sustainability reports and assessments of key performance indicators for transportation infrastructure projects rely on conventional criteria, such as renewable energy and community impact. However, less evidence or justification exists regarding how deployed technologies contribute to sustainability performance and criteria. There are numerous opportunities for integrating I4.0 technologies to achieve sustainability goals [23].

Furthermore, the sustainability of transportation construction projects is sometimes assessed in conjunction with their resilience, taking an integrated perspective [24]. The ability of these infrastructures to withstand and recover from disruptive events is vital for their long-term viability [25]. Industry standards like ASCE 7-16 and the International Building Codes provide guidelines for designing infrastructure that can resist natural hazards [26,27]. The impact of infrastructure projects must account for both everyday societal benefits (sustainability) and performance under extreme events (resilience), integrating probability-based assessments into a comprehensive evaluation [24]. Integrating I4.0 technologies, such as AI-driven predictive maintenance, IoT-based real-time monitoring, and Digital Twin simulations, further enhances this resilience by enabling proactive risk mitigation and adaptive recovery strategies [28]. This technological approach ensures that sustainability and resilience assessments are not static but continuously updated based on evolving risk factors and infrastructure performance data.

2.2. Industry 4.0 Technologies and Their Integration

The fourth industrialised revolution, commonly known as Industry 4.0 (I4.0), refers to the integration of advanced digital technologies into industrial processes, leading to digitisation and automation. I4.0 technologies, including Artificial Intelligence (AI), Internet of Things (IoT), Digital twin (DT), Big Data, Drones, Virtual and Augmented Reality (VR/AR), and Machine Learning (ML) [29], are rapidly transforming the construction industry, enabling companies to operate more efficiently and sustainably [30]. Table 1 presents a list of I4.0 technologies along with their corresponding definitions. I4.0 consists of the following

four main categories of disruptive technologies that have the potential to drastically change different parts of the value chain: (1) Connectivity, Data, and Computational Power—cloud technology, the Internet, blockchain, and sensors all work together to improve connectivity and enhance data processing capabilities. (2) Analytics and Intelligence—advanced analytics, machine learning, and artificial intelligence offer valuable insights and predictive abilities. (3) Human–Machine Interaction—virtual reality (VR) and augmented reality (AR), in addition to robotics and autonomous guided vehicles, are transforming the way humans interact with machines. (4) Advanced Engineering—additive manufacturing and renewable energy solutions are driving innovation in the industry [29]. Table 1 provides the I4.0 technology domains and definitions.

Within the broader I4.0 paradigm, Construction 4.0 has emerged as the construction sector's adaptation to digital transformation. Construction 4.0 reflects the industry's acknowledgment of digitalisation's importance and encompasses four fundamental elements: digital data, automation, connectivity, and digital access to information [31]. Rather than developing as an independent concept, Construction 4.0 has evolved through the application of I4.0's theoretical framework to address the unique challenges and characteristics of construction projects. This specialised adaptation enables more integrated approaches to infrastructure development, enhancing efficiency, sustainability, and resilience throughout the project lifecycle [32]. The technologies examined in this study serve as critical enablers of Construction 4.0 implementation, particularly within the broader framework of I4.0 in transportation infrastructure projects, supporting the sector's transition toward more sustainable and efficient practices.

I4.0 technologies play a pivotal role in advancing the three pillars of sustainability—economic, social, and environmental—in transportation construction projects. These technologies are increasingly integrated across the project lifecycle, such as construction quality management, bridge engineering, reinforced concrete bridge inspections [33], and generating as-built models of tunnelling projects [34]. From an economic perspective, technologies such as BIM, DT, and IoT can reduce construction costs, improve cost estimation, optimise schedules for faster and less expensive construction, and enhance operational efficiency, reducing costs and improving asset management [35,36]. Social sustainability benefits from technologies like BIM, DT, AR, and VR, which facilitate stakeholder engagement [12], improve community understanding of project impacts and enhance safety by reducing accidents and improving worker welfare [37]. These technologies help address the complex sociotechnical dimensions of transportation projects, which are shaped by institutional norms, practices, and logic [38]. Environmental sustainability is bolstered by technologies such as BIM-authoring tools and IoT sensors, which support the design of energy-efficient and environmentally friendly infrastructure. They enable material optimisation, waste reduction, recycling, and monitoring of energy consumption and emissions, contributing significantly to sustainable construction practices [39,40].

Table 1. Industry 4.0 technologies and their corresponding definitions.

Technology	Definition	References
Internet of Things (IoT)	IoT refers to a network of connected physical devices that collect and transmit real-time data to enable automation, remote monitoring, and smarter decision-making in civil infrastructure systems, enhancing operational efficiency, safety, and maintenance.	[41]
Big Data Analytics	Big Data analytics swiftly processes vast datasets, providing critical insights for continuous evaluation, enhancing decision-making, and planning in various business scenarios.	[42]

Table 1. *Cont.*

Technology	Definition	References
Artificial Intelligence (AI)	AI systems emulate human intelligence, learning and improving through data and algorithms. Widely used in routing, traffic management, and security, AI enhances technological aspects.	[43]
Blockchain	Blockchain's decentralised ledger technology securely records data changes, revolutionizing industries by providing transparency without central authority.	[44]
Autonomous Robots	Autonomous robots in construction and inspection are self-operating systems equipped with sensing and control technologies that can independently perform tasks such as navigation, mapping, building, and monitoring civil structures without human intervention, offering improved efficiency, precision, and sustainability.	[45]
Drones/Unmanned Aerial Vehicle (UAV)	UAVs, or drones, are pilotless flying devices controlled remotely, offering versatile applications in aerial surveillance and data collection due to their unmanned nature.	[46]
Additive Manufacturing (AM)/3D printing	AM, or 3D printing, creates precise items layer by layer, minimizing waste. It is eco-friendly and finds increasing use in production, aligning with sustainability and technological goals.	[47]
Augmented Reality (AR)	AR refers to a technology that overlays virtual information onto the real world in a blended 3D environment, enabling improved inspection, monitoring, coordination, and safety in civil infrastructure projects by enhancing visual perception and supporting automation.	[48]
Virtual Reality (VR)	VR is a technology that creates a simulated, immersive environment through computer-generated experiences. It enables project stakeholders to experience a digital representation of the building in a highly interactive and immersive way.	[49]
Building Information Modelling (BIM)	BIM refers to the digital representation of the physical and functional aspects of the built facility, acting as a shared knowledge resource to ensure consistent data for informed decision-making across the building facility's entire lifecycle, from inception onward.	[50]
Digital twin (DT)	DT refers to the virtual replica of the physical built environment or the system. DT represents the digitalisation of the systems that enable real-time and/or dynamic updating of information (e.g., new data derived by sensors, routine inspection activities, operational conditions, stakeholders' changes, etc.).	[51]

3. Methodology

A mixed methods systematic review (MMSR) [52] was employed to amalgamate and analyse both quantitative and qualitative methods to comprehensively and more nuanced scrutinise the existing literature [53]. MMSRs offer a more comprehensive understanding of a topic and the integration of diverse synthesis methods. By combining qualitative and quantitative approaches, discrepancies between primary-level study findings can be uncovered and explained. Following the recommendations of Heyvaert et al. [54], a protocol for the MMSR was developed to ensure the accuracy and rigour of the review process. This protocol documented all methodological and substantive choices that were made throughout the MMSR process a priori, providing a tool to delineate the strategies required to achieve the review objectives and provide insightful answers to the review

question, including the selection of the most suitable MMSR design, search strategies, inclusion and exclusion criteria, and synthesis approaches.

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [55]. The review was not registered in any systematic review registry. The PRISMA checklist guided our methodology, data extraction, and reporting processes to ensure transparency and reproducibility of the review.

3.1. Search Strategy

The search was conducted using the Scopus electronic database. We limited our search to articles published between 2009 and November 2023 to cover the peak period of I4.0's popularity and adoption. This timeframe ensures we access the latest and most relevant research, offering up-to-date insights on the topic. Initially, a keyword search was performed using terms such as "sustainability", "transportation projects", and "I4.0 technologies", as well as related terms. The search strategy was designed to comprehensively capture the intersection of transportation infrastructure, I4.0 technologies, and sustainability. The search string was constructed using Boolean operators to combine three primary domains. For the transportation infrastructure domain, we adopted the categorisation framework from Costin et al. (2018) [15], incorporating terms related to bridges, roads, highways, railways, tunnels, aviation, airports, ports, and harbours. The technology domain encompassed both broad I4.0 terminology and specific technologies, including Building Information Modelling (BIM), Digital Twin (DT), Internet of Things (IoT), Artificial Intelligence (AI), blockchain, Virtual and Augmented Reality (VR/AR), Unmanned Aerial Vehicles (UAVs), additive manufacturing/3D printing, autonomous robots, and Big Data analytics. To ensure comprehensive coverage of BIM applications, related terminologies such as Bridge Information Modelling (BrIM) and Transportation Information Modelling (CiM) were included. The sustainability domain was captured using wildcard operators (sustainable*, environment*, economy*, social*) to encompass environmental, social and economic aspects. These three domains were strategically combined using AND/OR operators to ensure retrieved articles addressed the integration of I4.0 technologies in sustainable transportation infrastructure projects. This search strategy retrieved 1985 papers in November 2023, which were then screened for relevance based on inclusion and exclusion criteria, as described in the following section. Following the three-stage screening process depicted in Figure 1, the papers were narrowed down to 199 records.

3.2. Inclusion and Exclusion Criteria

To be included in the systematic literature review, studies had to meet the following criteria: (1) be published in English-language peer-reviewed journals or conference proceedings, (2) focus on the use of I4.0 and digital technologies for improving sustainability in transportation infrastructure projects. Thus, the review sets a clear exclusion criterion for papers that do not utilise I4.0 technologies for transportation infrastructure. This ensures that the analysis focuses solely on the relevant technologies and their application within the context of transportation infrastructure projects. (3) the review includes research that directly applies to the design, construction, and maintenance of transportation infrastructure rather than papers discussing potential applications. Thus, only peer-reviewed articles that have been tested or validated for use in transportation infrastructure projects and provide sufficient details on the applications of I4.0 technologies for transportation projects are considered. (4) be published between 2009 and November 2023. White papers and industry reports were excluded. In cases where a study was published in both conference proceedings and a journal article, the journal version was preferred. For the technology inclusions,

we have utilised the framework established by Oesterreich and Teuteberg [29]. This framework is widely recognised and accepted in the field of I4.0 research, making it a reliable and comprehensive resource for identifying the relevant technologies. Furthermore, these technologies are interconnected and often complement each other in I4.0 ecosystems. Studying them collectively allows us to explore the synergistic effects and interdependencies among these technologies. This understanding is crucial for infrastructure projects seeking to leverage multiple I4.0 technologies simultaneously to achieve transformative outcomes.

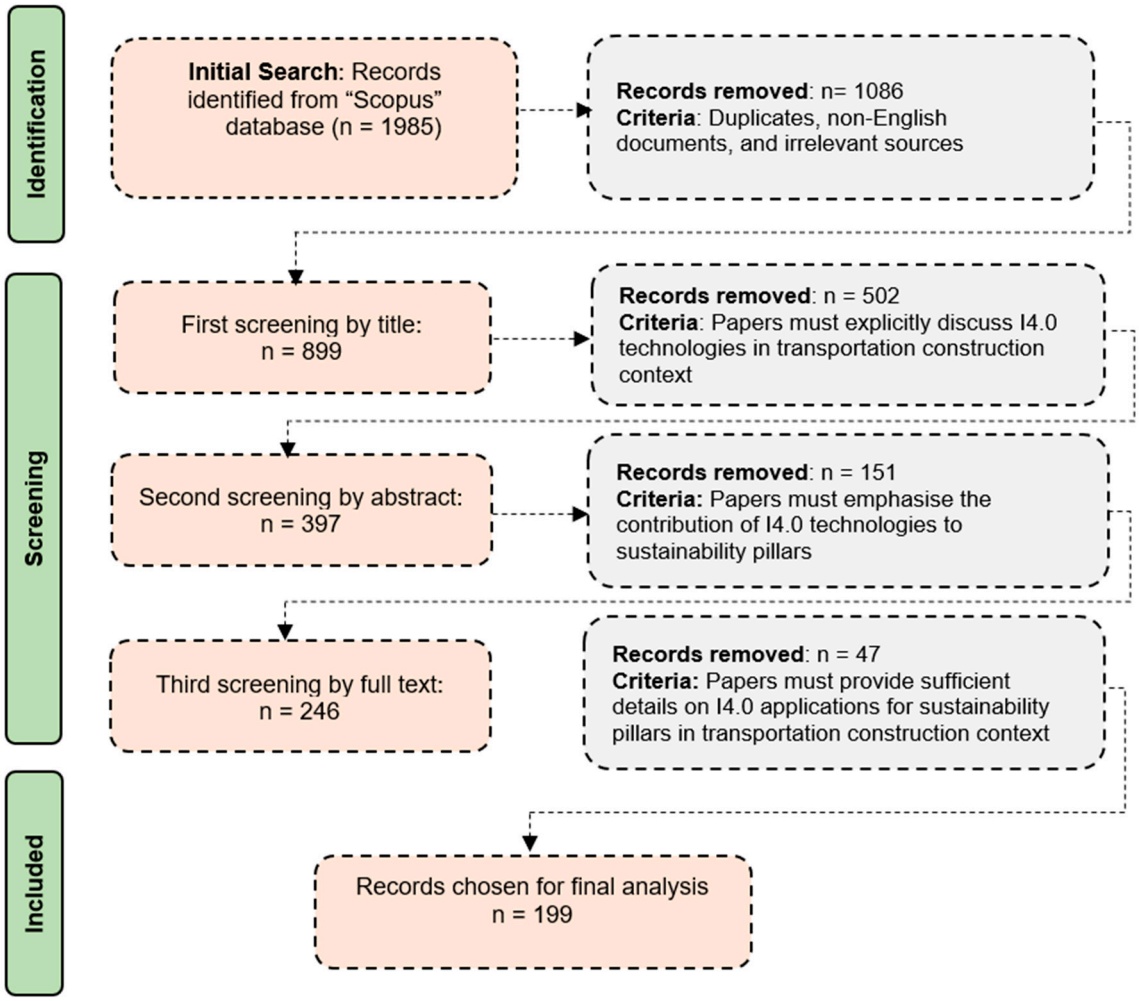


Figure 1. The refinement process in the SLR based on the PRISMA flow diagram.

3.3. Screening Process

The screening process followed a two-stage approach. In the first stage, the first two authors independently screened the titles and abstracts of all identified studies against the predefined inclusion and exclusion criteria. Studies that clearly did not meet the inclusion criteria were excluded. In the second stage, full-text articles were obtained for all potentially eligible studies and again independently assessed by the same two reviewers. Throughout both stages, any disagreements between reviewers were resolved through discussion until consensus was reached, with a third reviewer available to resolve persistent disagreements, though this was not necessary. No automation tools were used in the screening process. The selection process followed the PRISMA flow diagram as illustrated in Figure 1, which details the number of records identified, included, and excluded at each stage, along with reasons for exclusions.

3.4. Data Extraction

A standardised data extraction form was developed to systematically collect relevant information from each included study. The form captured bibliographic details (authors, year, title, publication type), study characteristics (methodology, sample size if applicable), infrastructure type, technology types, project lifecycle stages, geographical context, sustainability dimensions addressed, key findings, and limitations reported by the authors. Data extraction was performed by the first author and independently verified by the second author to ensure accuracy and completeness. Any discrepancies were resolved through discussion. When the necessary information was unclear or missing, we contacted the corresponding authors of the primary studies for clarification, though this was required in only a few instances. The extracted data were then compiled in a spreadsheet for subsequent analysis and synthesis.

3.5. Data Synthesis

The main outcomes sought in this review were applications of I4.0 technologies, their contributions to sustainability in transportation infrastructure projects, and emerging trends and research gaps. For each study, we extracted data on infrastructure type, technology types, project lifecycle stages, geographical context, and sustainability dimensions addressed (environmental, social, economic). Data synthesis was conducted using a narrative approach complemented by scientometric analysis, as detailed in Section 3.7.

3.6. Risk of Bias Assessment

Given the heterogeneous nature of the studies included in this review, which encompassed various research designs and methodologies focused on I4.0 technologies for sustainable transportation infrastructure, a formal risk of bias assessment using standardised tools was not conducted. Instead, we focused on evaluating the quality and relevance of the research based on the clarity of methodology, alignment with the research question, and the comprehensiveness of reporting. Studies with unclear methodologies or insufficient detail were noted during the data extraction process.

3.7. Data Analysis Approach

3.7.1. Quantitative Analysis

The inaugural phase of the analysis entails the employment of scientometric analysis, as the manual appraisal of available studies is susceptible to biases and restrictions in terms of the number of studies that researchers can review in a domain brimming with the literature [56]. Scientometric analysis refers to the cartography and visual representation of a prodigious scholarly dataset within a particular knowledge domain [57]. This enables researchers to peruse the intellectual topography of a research area to fulfil the objectives of their research studies [58]. There is a broad spectrum of computer programs available for scientometric analysis, of which VOSviewer [57] has been utilised in this study using the Scopus database. Scopus encompasses a broader range of journals in the domain of Construction Project Management (PM) and Construction IT than the Web of Science and includes more recent publications relative to other databases [59]. The subject matter of the present study pertains to I4.0 and sustainable infrastructure as a relatively nascent area of the literature, with studies predominantly published in recent years.

3.7.2. Qualitative Thematic Analysis

Qualitative analysis adhered to the objective posited by Harden and Thomas [52] for the qualitative facet of mixed methods systematic review inquiries. This entailed juxtaposing the concepts, themes, and theories expounded upon in a judiciously chosen

cohort of studies in accordance with the tenets of the systematic review protocol and the theoretical framework of the study. The goal was to effectuate a qualitative synthesis, whereby the authors did not merely aim to discern the contents of disparate studies and to locate any lacunae therein.

4. Findings

4.1. Findings from the Quantitative Analysis

4.1.1. Distribution of Reviewed Studies by Year

The review found that the distribution of published papers on improving sustainability through I4.0 technologies in infrastructure projects has been increasing in recent years, as demonstrated in Figure 2. These findings underscore the increasing interest of researchers and practitioners in this field, particularly throughout 2021, 2022 and 2023. It is worth noting that the search was conducted up to November 2023. The significant upward trend in publications, particularly since 2016, can be attributed to several converging factors in the transportation infrastructure sector. The increased adoption of I4.0 technologies during this period coincided with a growing global emphasis on sustainable development goals (SDGs) and climate action, particularly following the Paris Agreement in 2015, which prompted a greater focus on sustainable infrastructure solutions. Additionally, the maturation of technologies like BIM, IoT, and AI, coupled with government initiatives promoting digital transformation in construction, has led to increased research interest in leveraging these technologies for sustainable infrastructure development.

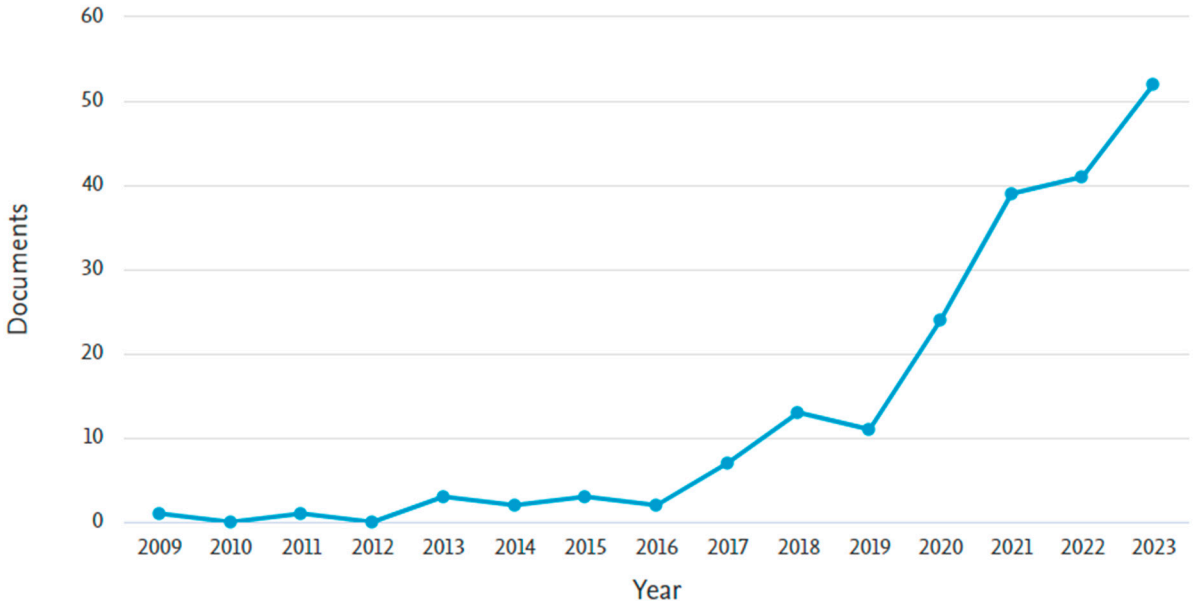


Figure 2. The distribution of reviewed studies according to the year of publication.

4.1.2. Distribution of Reviewed Studies Based on Technologies Used

The review analysis identified various technologies utilised to enhance sustainability in transportation infrastructure projects, as illustrated in Figure 3. BIM was employed in 33.50% of the papers, followed by IoT and sensors (14%) and AI (13.22%). Please note that these numbers have been rounded to the nearest whole number in Figure 3 for clarity in the data presentation.

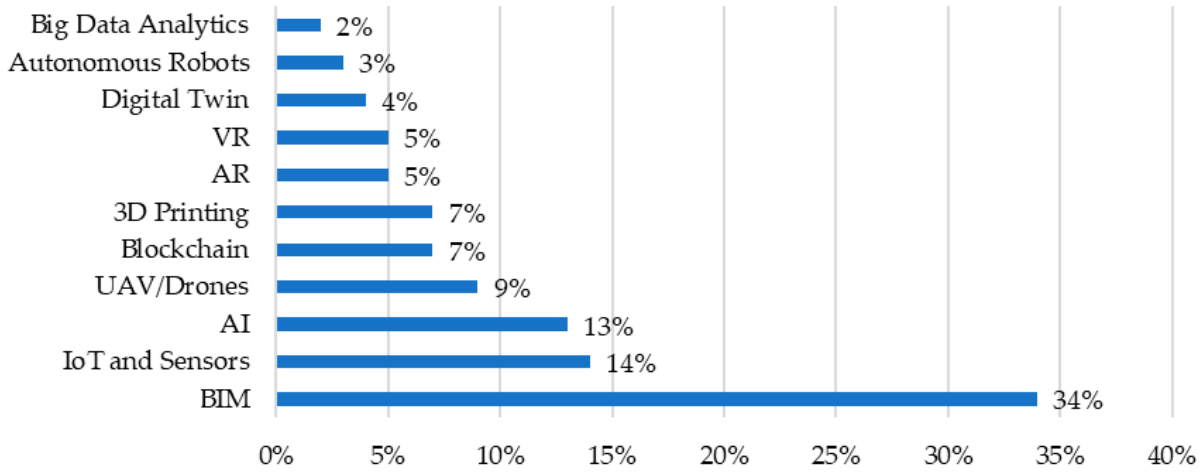


Figure 3. The distribution of reviewed papers according to the technology used.

4.1.3. Distribution of Reviewed Studies Based on the Publication Source

Figure 4 indicates that the majority of publications on improving sustainability through I4.0 technologies in transportation infrastructure projects were journal articles, followed by conference papers and review papers. The Journal of Sustainability had the highest number of publications, followed by the Automation in Construction journal.

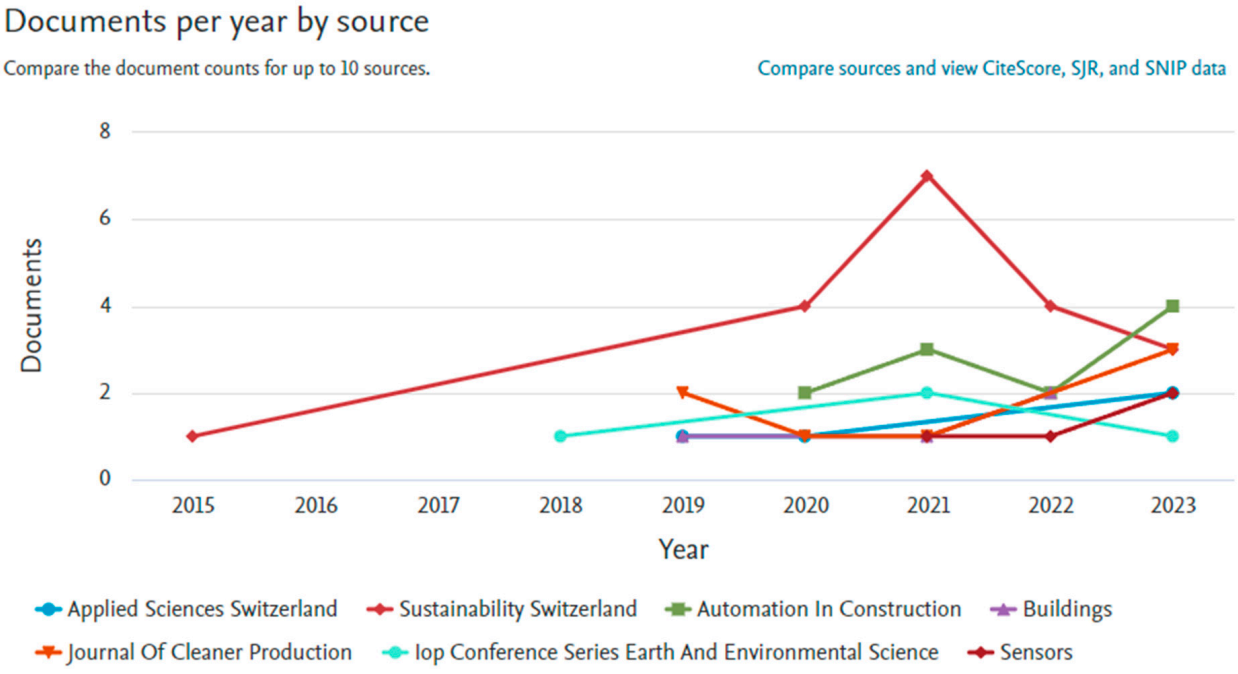
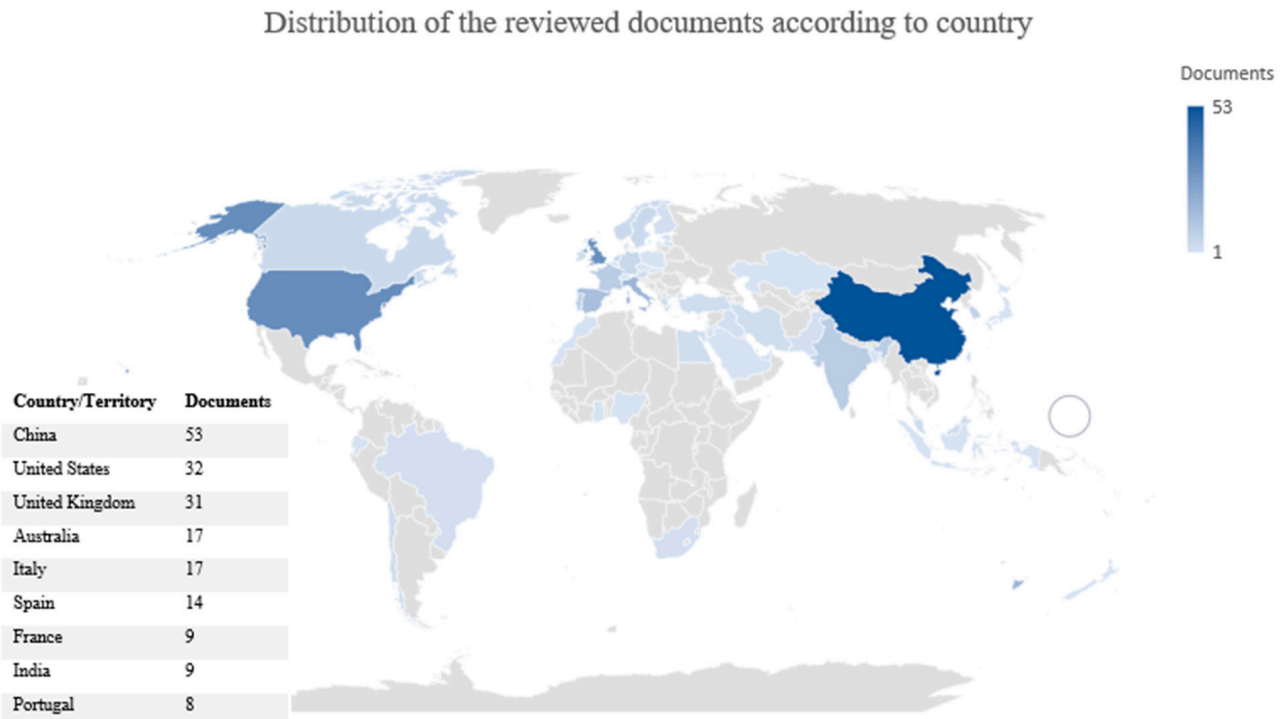


Figure 4. The distribution of reviewed papers according to the publication source.

4.1.4. Distribution of Reviewed Studies Based on Geographic Context

The analysis reveals a distinct pattern in geographical distribution, with China (53 papers), the US (32 papers), and the UK (31 papers) emerging as the primary contributors to the literature (Figure 5). This distribution strongly correlates with economic capacity and infrastructure investment patterns, as exemplified by China's remarkable GDP growth from US$293.6 billion in 1978 to US$10.8 trillion in 2018, with GDP per capita rising from US$307 to US$7752 [7]. The geographical concentration of research in these regions reflects not only their economic capabilities but also their diverse funding mechanisms

(including public funding, private investments, and public–private partnerships), government policies promoting digital transformation, and varying infrastructure challenges based on geographical vulnerabilities such as coastal storms, seismic activity, and flooding risks. However, this concentration also highlights a concerning gap in research from developing nations where sustainable infrastructure development is equally crucial but faces different geographical and economic challenges.



Country/Territory	Documents
China	53
United States	32
United Kingdom	31
Australia	17
Italy	17
Spain	14
France	9
India	9
Portugal	8
South Korea	7
Netherlands	6
Germany	5

Figure 5. The distribution of reviewed papers based on geographical locations.

4.1.5. Scientometric Analysis

In the visualised scientometric analysis results, most recurrent keywords that appear frequently together are clustered into colour groups, as shown in Figure 6. The categories having a high number of shared links are placed in the centre of the map to ensure greater equidistance to their shared links. If two categories have a strong link strength, indicating that they frequently appear together in the literature, they are located near each other on the map. According to the network results shown in Figure 6, road and bridge projects occupy a central position, with bridges primarily analysed in conjunction with inspection and UAVs, while roads are strongly linked to BIM and safety considerations. Moreover, the clustering of "BIM model", "BIM technology", and "BIM implementation" suggests that BIM serves as a central framework for incorporating various technologies in different transportation infrastructure projects. BIM provides a common platform for data exchange, collaboration, and visualisation, facilitating the seamless integration of technologies like Digital Twins, IoT, and 3D printing.

One prominent theme emerging from the analysis is the focus on lifecycle management. The close connection between terms like "lifecycle", "BIM", and "digital twin" suggests a growing emphasis on managing infrastructure assets throughout their entire lifespan, from planning and construction to operation and maintenance. Digital twins, which are virtual representations of physical assets, enable data-driven decision-making

and predictive maintenance, optimizing resource allocation and extending the life of infrastructure components. Another significant cluster of keywords revolves around safety and monitoring technologies. The grouping of "lidar", "robot", "inspection", and "unmanned aerial vehicle" indicates the adoption of advanced technologies for assessing the structural integrity and safety of infrastructure assets, particularly in the context of bridge projects.

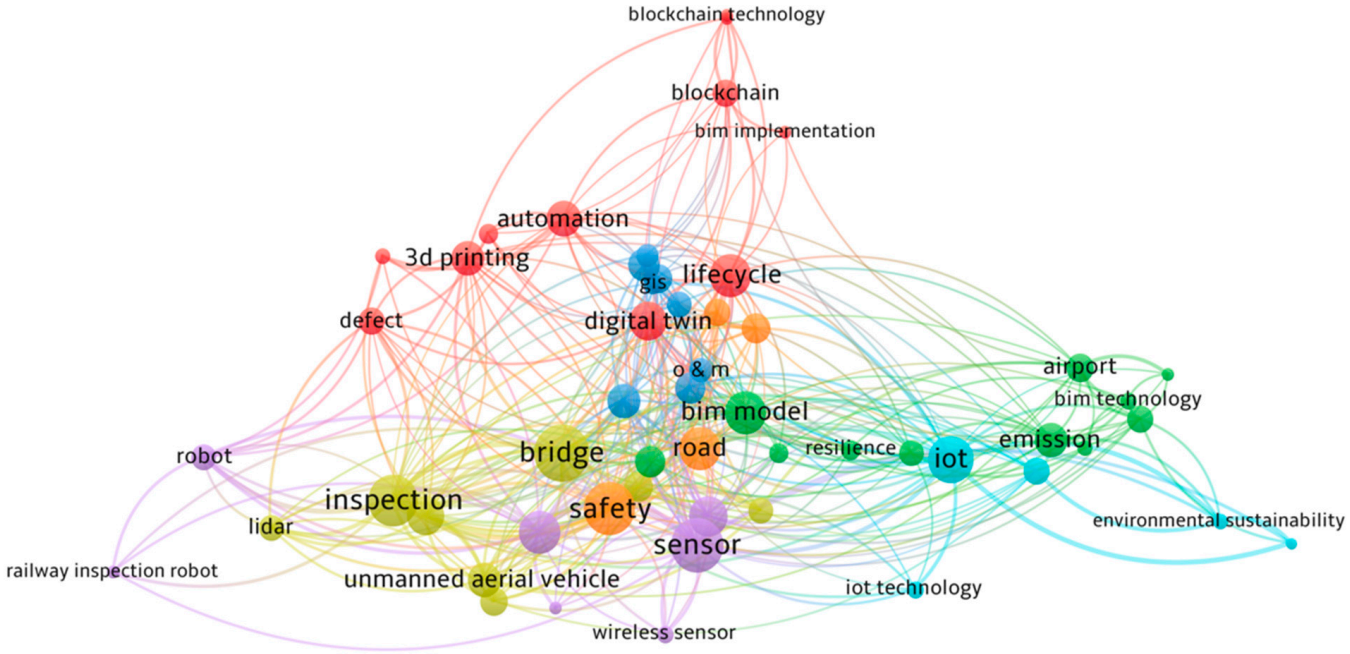


Figure 6. Co-occurrence map of the reviewed categories.

The proximity of "environmental sustainability" to various infrastructure types underscores the increasing importance of sustainability in infrastructure development and management. The integration of IoT sensors and BIM can support sustainable practices by enabling real-time monitoring of environmental parameters and optimizing resource consumption. The network diagram shows a strong link between sensors, robots, and railway projects. Railway inspection robots likely use sensors, such as lidar, to collect data on the condition of railway infrastructure. Lidar enables precise 3D mapping and measurement, helping assess structural integrity, detect defects, and plan maintenance. The diagram also indicates a relationship between CO_2 emission, resilience, BIM, and airport projects. The proximity of "emission" to "airport" suggests that reducing CO_2 emissions is a key concern in airport development. The close link between BIM-enabled technologies and "airport" and "resilience" implies that these technologies have been widely employed to address this challenge by providing a digital representation of airport infrastructure. This enables stakeholders to analyse energy consumption, optimise designs, and simulate scenarios to minimise CO_2 emissions.

4.2. Findings from the Qualitative Thematic Analysis

In this section, the selected publications are categorised into four main clusters through thematic analysis: (1) Infrastructure type, (2) Technology types, (3) Project lifecycle stages, and (4) Geographic context. The sub-categories for each cluster are presented in Figure 7. The following section explores the research trends and key findings associated with each cluster, drawing on the existing literature.

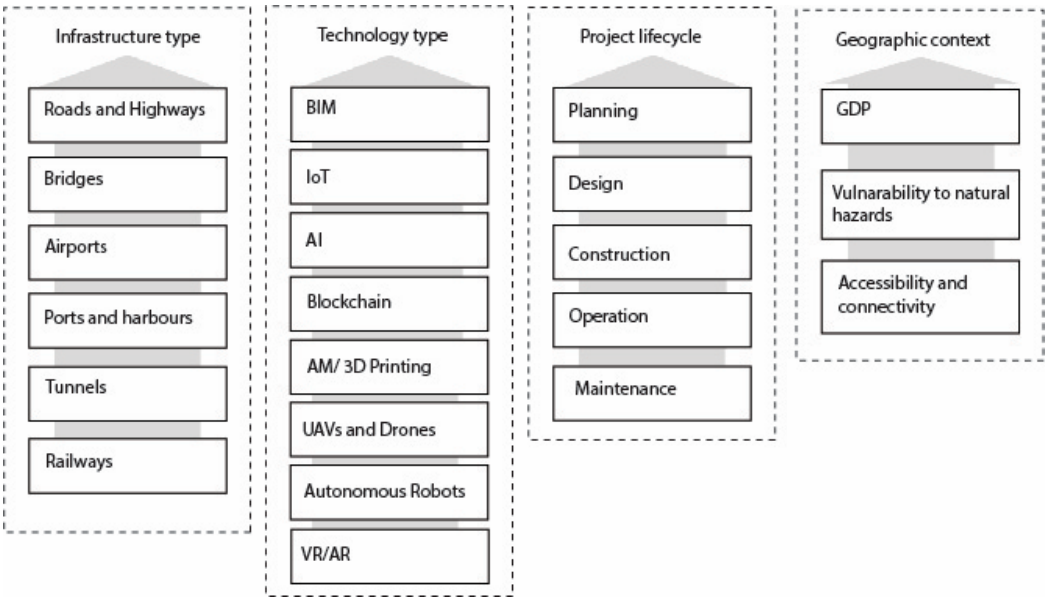


Figure 7. Research topics in each theme/cluster.

4.2.1. Infrastructure Type Focus

Infrastructure type focus in the literature refers to the specific type of infrastructure project in which I4.0 technologies are applied to improve sustainability. Among the 199 review papers analysed, the distribution of focus on various infrastructure types is as follows: 14% on bridges (n = 28 papers), 9% on railways (n = 18 papers), 12% on highways and roads (n = 24 papers), 7.5% on tunnels (n = 15 papers), 9.5% on airports (n = 19 papers), and 7% on ports and harbours (n = 14 papers). Notably, 41% of the reviewed papers (n = 81 papers) did not specify any particular type of project in their research focus (see Figure 8).

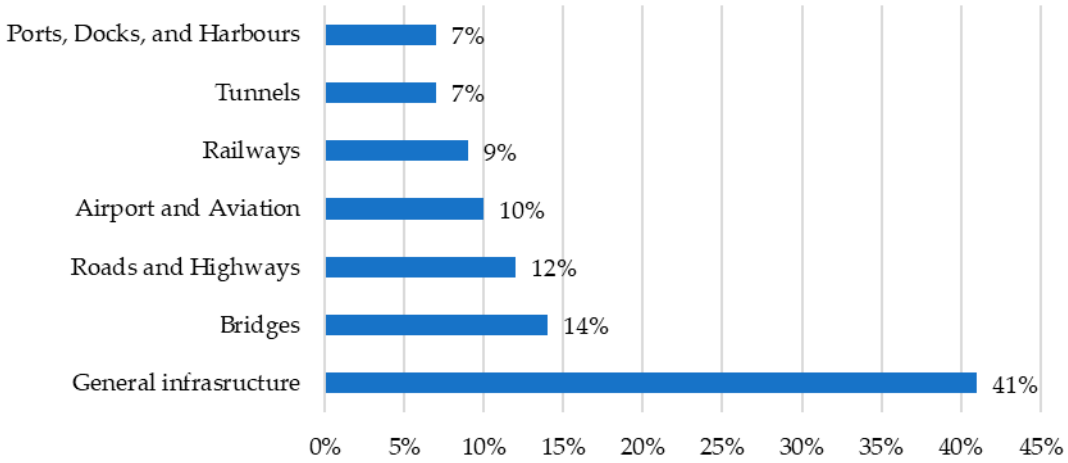


Figure 8. Distribution of the reviewed papers per project type.

Roads, highways, and bridges are the most studied infrastructure types in the context of I4.0 technologies for sustainability. BIM plays a significant role in road infrastructure projects [2], while IoT and sensor technologies are widely used in the railway sector for efficiency, safety, and maintenance purposes [51]. Bridges and tunnels benefit from I4.0 technologies for structural health monitoring, hazard detection, and early defect detection. Airports and ports utilise I4.0 technologies for surveillance systems, passenger flow management, and automation of processes [60,61].

4.2.2. Technology Focus

In the context of this study, BIM-related tools and systems emerged as formidable subjects within the corpus of the reviewed literature, with 76 papers dedicated to comprehending its multifaceted applications. This prominence highlights its pivotal role in the digital transformation of the infrastructure transport industry. The exploration of AR and VR in 10 and 9 papers, respectively, calls for further investigations to uncover its possibilities in design, training, and interactive experiences. The innovative domain of autonomous robots, examined in 7 papers, demonstrates a growing curiosity about its applications in recent years and calls for further study in areas such as scalability and environmental sustainability. The review revealed a noteworthy emphasis on IoT and sensor technologies, with 32 papers devoted to unravelling their significance in the context of this study. With blockchain technology covered in only 14 of the reviewed studies, this underscores the limited attention it has received and highlights the need for further research. Figure 3 presents the quantities of each technology as per the reviewed papers. It is worth noting that while Figure 3 illustrates the distribution of 11 distinct technologies identified in the reviewed literature, the following section focuses on the eight most prominent technologies that demonstrate significant applications in sustainable transportation infrastructure. The three technologies not extensively discussed—Digital Twin, GIS, and sensors—were often integrated as supporting technologies within larger technological ecosystems rather than serving as standalone solutions. Digital Twin, for instance, frequently appears as an extension of BIM implementation, while sensors are typically discussed as components of IoT systems.

The following section reviews the research trends towards the application of each technology in the context of sustainable transportation infrastructure.

Building Information Modelling (BIM)

BIM refers to the process of producing and maintaining asset-related information throughout the various phases of its lifecycle. BIM requirements, functions, and the use of BIM for sustainability indicators are the three key themes from our literature findings. BIM requirements for transportation infrastructure encompass elements for successful BIM implementation, interdisciplinary collaboration, client requirements, data governance, available tools and technologies, and adherence to standards and guidelines (such as ISO 19650). Our investigation shows that several software tools, including the BRE Green Guide, eToolLCD, and One Click LCA, can be effectively utilised as Revit plugins for Life Cycle Assessment (LCA). Nevertheless, these tools predominantly focus on evaluating the environmental aspects of sustainability. BIM functions encompass a range of capabilities and tasks facilitated by BIM-related technologies like 3D modelling, data management, visualisation, simulation, and task automation within the context of transportation infrastructure. The BIM requirements and BIM functions are interconnected; for instance, clear client data requirements are necessary for quality analysis and 3D modelling. The outcomes of BIM requirements and functions enhance the utilisation of BIM for the three aspects of sustainability (see Figure 9).

BIM for sustainability indicators refers to the utilisation of BIM technologies, processes, and policies to assess, measure, and improve the sustainability performance of transportation infrastructure projects, involving the incorporation of BIM tools and methodologies to evaluate various environmental, social, and economic factors.

Environmental sustainability is the most extensively studied theme in the existing literature. This category explores how BIM can be utilised to improve environmental sustainability in infrastructure projects, such as reducing carbon emissions, energy consumption, and waste generation. BIM models can be used to generate detailed bills of

materials and energy and water consumption data, which can be used to estimate the environmental impacts of a building or infrastructure project across its entire lifecycle. Notably, van Eldik et al. [3] developed a BIM-based automated environmental impact assessment for infrastructure projects. Patel and Ruparathna [2] created a Life Cycle Sustainability Assessment (LCSA) framework, a BIM-based tool that helps infrastructure managers choose the most sustainable road construction method in line with the United Nations Sustainable Development Goals (SDGs). Laali et al. [62] integrated BIM and rating systems to offer automated, sustainable solutions, providing a reliable source for comprehensive sustainability measurement.

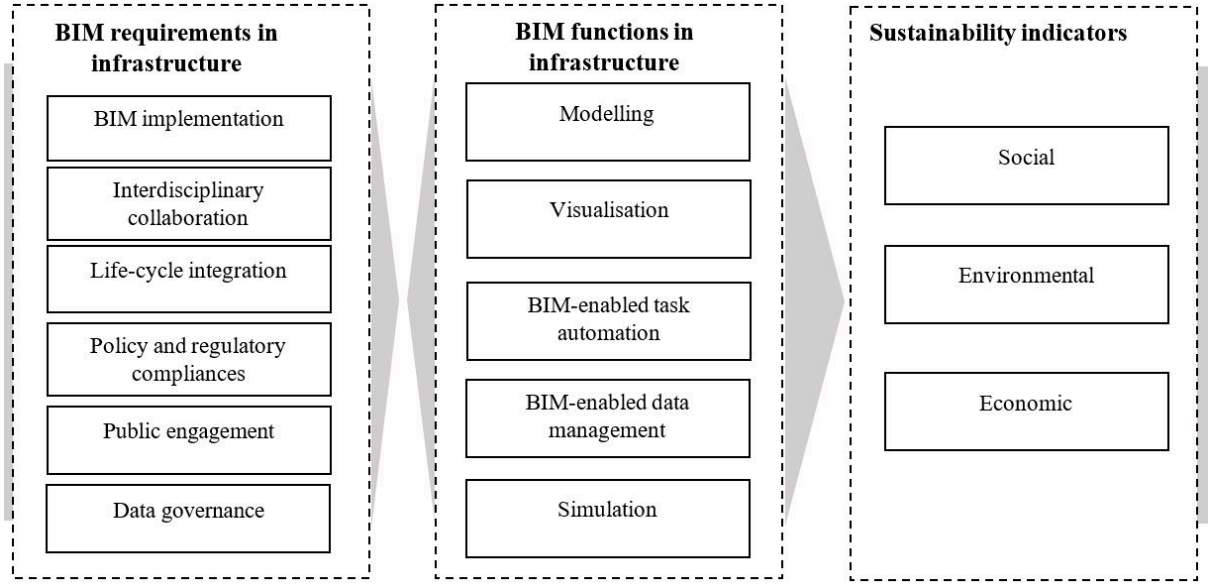


Figure 9. The interrelation of BIM requirements, functions, and sustainability indicators in transportation infrastructure projects.

BIM also plays a significant role in enhancing economic sustainability within infrastructure projects by contributing to cost reduction, improving efficiency, and increasing overall profitability. Massimo-Kaiser et al. [63] conducted a study on the impact of BIM on the economic aspects of tunnelling projects, with a particular focus on the optimised use of resources. Their research aimed to assess how BIM implementation can enhance project efficiency and cost-effectiveness. By leveraging BIM methods and tools, such as advanced visualisation, clash detection, and resource management, tunnelling projects achieved better resource utilisation and improved overall economic sustainability. According to Chong et al. [64], the quantification of economic sustainability presents a more intricate challenge due to the paucity of data that accurately pinpoints the emergence and growth of the green economy. The literature often combines the economic aspect of sustainability with the environmental aspect in the context of BIM studies. For instance, a decision support system (DSS) has been developed by Oreto et al. [65] for road infrastructure projects, aimed at facilitating both reactive and predictive maintenance by considering multiple factors, including economic, financial, environmental, and technical-operational indicators, that are associated with the degradation of specific status indicators. This DSS adheres to the ISO 19650 information management protocols and streamlines the creation of a multiyear maintenance plan for a road pavement section.

Social sustainability focuses on the role of BIM in enhancing social sustainability, such as promoting public health and safety, ensuring equitable access, and increasing community engagement. Compared to the other two aspects of sustainability, the social dimension of BIM has received less attention. However, there have been some notable studies exploring

this topic. Chong et al. [64] discovered the need for an innovative procurement system to integrate social sustainability into BIM projects. Rahim et al. [66]) explored BIM's potential for promoting social sustainability in Malaysia, revealing a lack of understanding and awareness regarding its capabilities. Our SLR identified a significant research gap in studying how BIM enhances social sustainability in infrastructure projects, particularly in areas like community engagement and accessibility. Nonetheless, BIM can support infrastructure design that meets community needs, fosters safer transportation, and enhances public spaces [64]. It also improves stakeholder communication and collaboration, enabling better-informed decisions for social equity and inclusivity. Massimo-Kaiser et al. [63] assessed BIM's impact on social and economic aspects in tunnelling projects, finding that its effective implementation optimises project delivery, leading to increased social sustainability through improved communication and teamwork. Table 2 presents a summary of studies on BIM contributions to sustainability in transportation infrastructure projects.

Table 2. BIM contributions to sustainability in transportation infrastructure projects.

Infrastructure Type	BIM Application	Contribution to Sustainability	Reference
Road	Ontological approach to integrate operation and maintenance information in BIM for road infrastructure	Improves maintenance practices and extends infrastructure lifespan through better information integration, reducing resource consumption and maintenance costs.	[67]
Highway	Overcoming BIM adoption challenges in highway project	Specific sustainability contributions are not clearly identified in the study.	[68]
Bridge	Framework enhancing maintenance management system using BIM and BMS	Enhances maintenance effectiveness through integrated systems, potentially reducing resource use and extending asset lifespan.	[69]
Mountain road	Methodology for road design optimisation to minimise shady areas and increase safety	Improves road safety through BIM-enabled design optimisation that reduces shady areas and accident risks while minimising environmental impact.	[70]
Highways	Integrated lifecycle data management leveraging Big Data with BIM	Supports lifecycle management through improved data integration, potentially reducing environmental impacts, optimizing economic performance, and enhancing user experience.	[71]
Bridge	BIM-based Bridge Management System for safety diagnosis and repair	Enhances public safety through improved diagnosis and repair planning for bridges, reducing accident risks and service disruptions.	[72]
Road infrastructure	Integration of GIS, BIM, IoT, and VR/AR for intelligent management	Enables more intelligent infrastructure management, potentially reducing maintenance costs and resource consumption through preventive interventions.	[73]
Bridge	Blockchain-based BIM data provenance model for improved information exchange	Specific sustainability contributions are not clearly identified in the study.	[74]
Transportation projects	State-of-the-Art review of BIM applications with new ICTs	Enables resource optimisation through data-driven decision-making in facility management.	[75]
Road	Comparative analysis of BIM adoption in road projects between Australia and China	Specific sustainability contributions are not clearly identified in the study.	[76]

Table 2. *Cont.*

Infrastructure Type	BIM Application	Contribution to Sustainability	Reference
Airport	BIM for energy analysis, solar analysis, and wind analysis to achieve energy-efficient airport design	Reduces energy consumption and associated carbon emissions through energy-efficient design informed by detailed analyses.	[77]
Bridge	Comparative analysis of impacts and benefits of BIM on accelerated bridge construction	Achieves cost savings through reduced change orders and rework in bridge construction projects, improving resource efficiency.	[78]
Road	Improving road designs by applying FEA tools in BIM data exchange	Enhances road building quality and supports efficient and timely maintenance through improved design, potentially reducing lifecycle costs and resource use.	[79]
Tunnel	Parametric lifecycle carbon assessment model for automating data integration	Facilitates low-carbon design decisions through automated carbon emissions calculation and visualisation, supporting climate change mitigation.	[80]
Bridge	6D BIM approach for lifecycle asset management	Supports comprehensive lifecycle management, potentially optimizing economic, environmental, and social dimensions of sustainability through improved decision-making.	[81]
Bridge	Digital twins for sustainability and vulnerability assessments	Directly addresses sustainability through improved assessment methods, potentially enhancing ecological, economic, and social dimensions of bridge infrastructure.	[82]
Railway	Digital twin and BIM for railway bridge maintenance and resilience optimisation	Enhances sustainability through resilience optimisation of railway bridge maintenance, improving infrastructure longevity and performance under varying conditions.	[51]
Airport	BIM for designing airports with controlled energy consumption	Reduces energy consumption by enabling precise design and simulation of energy performance in airport buildings.	[83]
Airport	BIM to improve building sustainability through solar panels and alternatives	Reduces energy use and emissions while lowering operational costs through renewable energy integration and sustainable design alternatives.	[83]
Airport	Comprehensive and adaptive Airport BIM (ABIM) management framework	Specific sustainability contributions are not clearly identified in the study.	[84]

Internet of Things (IoT)

Our SLR identifies that the applications of IoT for transportation infrastructure can be categorised into three main areas: condition monitoring and inspection, data collection and transmission, and environmental monitoring. These applications include structural health monitoring, energy usage monitoring, tracking air quality and noise levels, and data collection, such as collecting data on recycling and waste collection routes. A significant area of focus is to utilise IoT primarily to monitor and manage the maintenance of the transportation infrastructure. For instance, Dong et al. [85] developed a Pavement Management System (PMS) that integrates IoT, Big Data, and AI. The PMS comprises three subsections: pavement detection and 3D modelling, data analysis, and decision support. Using IoT technology, pavement condition data are collected for accurate 3D modelling. Big Data techniques are applied to analyse the data and extract insights for informed decision-making.

Researchers have explored integrating IoT with other technologies, like BIM, to develop tools and frameworks for environmental initiatives. Bapat et al. [86] proposed a framework that combines BIM and IoT to automate decision-making for energy savings in metro rail stations. By using sensors to monitor and control various aspects of the infrastructure, such as lighting, escalators, and fire safety devices, this integrated approach optimises energy demand. Data from temperature, motion, and light sensors are incorporated into the BIM model, creating a real-time monitoring and control system that ensures an energy-efficient metro rail station. Table 3 presents the contributions of IoT to sustainability in transportation infrastructure projects.

Table 3. IoT contributions to sustainability in transportation infrastructure projects.

Infrastructure Type	Sustainability Measure	Contribution to Sustainability	Reference
Roads, railways and highways	Improved maintenance efficiency	Reduced maintenance costs via predictive management systems; Prolonged infrastructure lifecycle, reducing resource consumption; Improved safety and service reliability through early fault detection.	[87]
Roads, railways, airports	Energy efficiency	Reduced operational costs through renewable energy harvesting systems and energy-efficient designs (e.g., lighting); Reduced carbon footprint and energy consumption; Enhanced access to reliable and efficient infrastructure, particularly in remote areas.	[7,87,88]
Bridges, railways, piers, general transport	Structural health monitoring (SHM)	Cost-effective SHM via IoT-driven solutions such as AI/ML-enabled predictive models; Minimised waste by extending asset life and preventing catastrophic failures; Improved safety by detecting critical failures early; enhanced public confidence.	[36,89–91]
Railways	Railway-specific monitoring systems	Improved efficiency of railway maintenance via IOT-based condition monitoring; Reduced energy wastage in railway operations, e.g., switch heating management; Safer rail operations with real-time monitoring and autonomous system designs.	[92]
Airports	Airport-specific solutions	Optimised project delivery performance and operational cost reduction through integrated IoT and BIM systems; Reduced embodied energy and operational cooling loads through advanced energy management; Enhanced operational quality and passenger safety.	[93]
Coastal piers and wharfs	Coastal infrastructure monitoring	Cost reduction via fiber-grating-based monitoring systems; Reduced damage through early detection of structural vulnerabilities; Enhanced safety and resilience for coastal communities.	[94]
Highways	Smart highways and lighting	Cost-effective designs for smart lighting and energy-efficient highway management systems; Decreased energy use through IoT-integrated smart lighting and traffic systems; Safer and more efficient highways with automated emergency management.	[95]
Airports	Construction process optimisation	Enhanced efficiency through digital monitoring systems, reducing rework and waste; Reduced resource and material usage in construction; Higher-quality infrastructure delivery during airport foundation treatment.	[96]

Artificial Intelligence (AI)

AI in transportation infrastructure projects focuses on five main themes to enhance sustainability. These include (1) resource optimisation, which aims to improve the effectiveness of energy, water, and material usage; (2) risk management, which entails identifying potential hazards like accidents, delays, and cost overruns; (3) performance monitoring, which involves tracks efficiency, including energy, water, and waste reduction; (4) decision-making, which aids in selecting sustainable materials, energy-efficient buildings, and optimised transportation routes; finally, (5) collaboration and communication which facilitate cooperative efforts among stakeholders to ensure shared sustainability goals are met.

The literature on AI's role in infrastructure projects can be categorised into two areas: using AI for decision support and AI's autonomous utilisation. Our SLR highlights that AI provides decision support in project and site selection, design optimisation, risk management, cost estimation management, predicting maintenance needs, improving energy efficiency, schedule performance, and quality assurance. Pan and Zhang [97] discuss that AI can benefit infrastructure projects through its ability to automate tasks, mitigate risks, improve efficiency, and enhance computer vision. AI is applied in three key areas: modelling and pattern detection, prediction, and optimisation. Pattern detection is particularly valuable for feature extraction from images or videos, helping assess infrastructure conditions and ensure construction safety by recognizing damage, cracks, and unsafe conditions. Research has focused on crack detection, damage detection, fastener damage detection, insulator damage detection, spalling detection, and stiffness degradation detection in different applications such as bridges, tunnels, highways, railways, concrete buildings, and steel buildings [98,99].

According to Hintze and Dunn [23], while AI can contribute to more sustainable infrastructure megaprojects and inform human decisions, its potential to enhance social sustainability is often overlooked. The use of AI for decision support raises concerns about algorithmic transparency and encoded biases. Additionally, when AI acts autonomously, new concerns emerge, particularly regarding its influence on the everyday use and operations of infrastructures. Research into AI ethics highlights three sources of potential negative impacts of AI: the system's design, the training data, and the complex interactions leading to unforeseen outcomes when AI interacts with the environment.

The integration of AI in advancing environmental, social, and economic sustainability within transportation infrastructure is summarised in Table 4 and reveals significant gaps that hinder its full potential. In environmental sustainability, inefficiencies persist in AI-driven circular economy practices, particularly in the reuse and recycling of materials like road pavement, where AI applications remain underexplored. While energy efficiency research predominantly targets operational phases, such as road lighting systems, the potential for AI to optimise energy consumption during construction and decommissioning phases is largely untapped. Social sustainability faces challenges in inclusivity, as AI-enabled user-centric designs, such as VR/AR for railway asset management, often overlook accessibility for individuals with disabilities or underserved communities. Furthermore, AI-driven emergency management systems, though applied in scenarios like fire escape simulations, lack robust real-time effectiveness in dynamic disaster situations. Economically, the adoption of AI-based cost optimisation tools, such as blockchain-integrated systems, remains fragmented and limited to specific infrastructure types, with broader sector-wide implementation lacking. Moreover, the economic feasibility of AI technologies in low-income regions is a persistent barrier, leading to inequitable access to cost-saving benefits. Lastly, insufficient integration of AI with existing policy frameworks, such as port integration systems, highlights a misalignment with regional regulatory standards, limiting their effectiveness.

Table 4. AI contributions to sustainability in transportation infrastructure projects.

Infrastructure Type	Sustainability Measure	Contributions to Sustainability	References
Railways	Energy efficiency and lifecycle carbon reduction	AI predicts track behaviour, identifying key parameters to optimise rail operations, reduce costs, and improve competitiveness.	[100]
	Enhanced safety and operational efficiency	Human-centric AI models integrate VR and MR to improve asset management and maintenance processes, promoting inclusivity and efficient operation.	[101]
	Cost reduction in operations and maintenance	AI identifies track behaviour parameters that lower maintenance and operational costs while improving the reliability of rail networks.	[100]
Roads, Highways, and Rural	Reduced energy consumption, sustainable lighting systems	IoT and AI-enabled rural road lighting designs improve energy efficiency and optimise lighting management. AI-enabled digitalised highways support smart systems for traffic and emergency management.	[7,95]
	Improved safety and user experience	Real-time multimodal notifications through AI and AR enhance highway worker safety. AI aids in monitoring traffic flow and accident prevention to ensure safer road networks.	[102]
	Transparent cost estimation and efficient operations	Decentralised AI systems using blockchain enable accurate, auditable road construction cost estimation. AI-IOT integrated lighting systems reduce operational costs.	[7,103]
Bridges	Lifecycle sustainability and reduced emissions	AI frameworks for Structural Health Monitoring (SHM) support energy-efficient and reliable inspection processes, reducing the environmental footprint. Machine learning and deep learning for bridge damage detection are integrated with BIM for efficient damage restoration and lifecycle sustainability.	[90,94,104]
	Improved safety and reliability	AI-powered SHM systems provide real-time insights, ensuring user safety and structural reliability during operations. Analysing bridge damage using UAV-assisted inspection and deep-learning-based damage identification.	[91,104,105]
	Reduced maintenance costs and increased efficiency	AI automates bridge inspections, reducing dependency on human labour and increasing cost efficiency in maintaining bridge infrastructure.	[91]
Tunnels	Reduced CO_2 emissions and resource optimisation	AI-based stochastic models minimise total costs and emissions in tunnel maintenance. AI-powered robots enable efficient and automated tunnel inspections, reducing the environmental footprint.	[106,107]
	Improved safety through real-time monitoring	AI-enabled tunnel inspection systems provide 3D damage assessment, improving worker and user safety.	[106,107]
	Cost optimisation in maintenance	Machine learning models forecast tunnel surface settlement, improving efficiency and reducing over-excavation costs.	[108,109]
Airports	Green performance evaluation and energy efficiency	AI-powered green performance evaluation models provide actionable insights for reducing the environmental impact of airport facilities, including energy-efficient designs and operational sustainability.	[110]
	Enhanced safety in emergencies	AI and VR simulation frameworks improve fire escape strategies and training for airport safety.	[111]
	Efficient resource allocation	AI optimises airport resource management, reducing costs and improving operational efficiency.	[110]

Table 4. *Cont.*

Infrastructure Type	Sustainability Measure	Contributions to Sustainability	References
Maritime Ports	Environmentally sustainable port operations	AI integrates machine-learning models to evaluate the environmental impacts of port operations, optimizing energy use and emissions.	[112]
	Enhanced collaboration and operational efficiency	AI promotes port integration and collaboration among multi-port regions, fostering equitable development and sustainable practices.	[50]
	Sustainable market capacity and policy development	AI optimises market share trading and capacity adjustments for sustainable port operations, ensuring equitable compensation and effective government subsidy allocation.	[50]
General Transportation Infrastructure	Hazard analysis and carbon reduction	AI and CFD integration enables advanced hazard analysis and better functionality of AEC projects.	[113]
	Improved safety in operations and management	AI and AR integration improve worker safety and risk management across transport systems. AI supports autonomous decision-making for intelligent infrastructure management in smart cities.	[102]
	Enhanced productivity and quality in construction	AI-powered regression-based DNNs optimise heavy equipment tracking, improving productivity and lowering operational costs. AI-integrated 3D printing and selective laser sintering processes promote efficient manufacturing.	[114,115]

Blockchain

Blockchain, a digital ledger technology facilitating secure and transparent transactions without intermediaries, has multiple advantages in transportation projects. These include heightened transparency, traceability, and accountability in managing contracts, supply chains, and project delivery. Leveraging blockchain enables the establishment of smart contracts that automatically enforce terms and conditions, mitigating the risk of disputes and ensuring compliance with sustainability standards. Based on the existing literature, blockchain technology demonstrates significant potential across the three pillars of sustainability within transportation infrastructure. In terms of environmental sustainability, blockchain supports circular economy practices by enhancing waste management and promoting resource recycling within construction supply chains. This application ensures that materials are effectively reused and reduces environmental degradation associated with waste disposal. Regarding social sustainability, blockchain facilitates peer-to-peer collaboration and fosters trust among stakeholders through transparent and immutable data exchange. Additionally, it supports competence recognition, enabling equitable participation and reducing conflicts in collaborative environments. In maritime and port supply chains, blockchain's ability to adapt to cultural and legal complexities further strengthens its social impact by ensuring smoother integration of diverse stakeholders. From an economic sustainability perspective, blockchain contributes to cost efficiency by minimizing transaction costs and mitigating supply chain complexities. Its role in improving data transparency enhances process efficiency in critical operations, such as customs and logistics, thereby streamlining workflows and optimizing resource allocation. Figueiredo et al. [44] explored blockchain's usability for sustainable building practices, while Celik et al. [74] integrated blockchain with BIM for a bridge highway project using an IFC model in compliance with ISO standard 10303-21, securely preserving historical data and supporting data provenance with smart contracts to address interoperability requirements. A summary of blockchain contributions to sustainability pillars in the context of transportation infrastructure are summarised in Table 5.

Table 5. Blockchain contributions to sustainability in transportation infrastructure projects.

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
General Transport Infrastructure	Improved waste management and recycling	Quantifies stakeholder value in waste reuse and recycling; Reduces costs by enhancing waste recovery processes.	[116]
General Transport Infrastructure	Enhanced trust and collaboration	Improves peer-to-peer collaboration in project management; Reduces transactional inefficiencies and errors in data management.	[117]
Construction Supply Chain	Circular economy integration	Supports circular economy by identifying high-priority attributes; Enables cost savings through efficient resource use.	[118]
Road Construction	Decentralised AI for decision-making	Enhances transparency and trust in cost estimation processes.	[103]
Maritime and Port Supply Chains	Smart contracts for collaboration	Facilitates collaborative logistics and SME integration into supply chains; Reduces misalignment and transaction costs in supply chains.	[119]
Cross-Border Customs Procedures	Blockchain for customs processes	Reduces transaction and misalignment costs in cross-border logistics.	[120]
Port Supply Chain	Blockchain for legal and cultural adaptability	Enhances understanding of cultural, legal, and technological adoption factors; Improves efficiency in smart contract enforcement for supply chains.	[121]
Offshore Wind Energy Supply Chain	Complexity management in renewable energy	Reduces complexity-related inefficiencies in supply chain management.	[122]
Bridge Construction	Blockchain for BIM data provenance	Improves information exchange and competence recognition among stakeholders.	[74]

Despite the promising potential of blockchain in advancing sustainability within transportation infrastructure, notable knowledge gaps persist. One such gap is the limited focus on integrating blockchain with circular economy goals, particularly in operationalizing fully closed-loop systems that enhance resource efficiency and minimise waste. Additionally, challenges related to scalability and interoperability remain inadequately addressed, as few studies propose frameworks capable of implementing blockchain across diverse stakeholders and interconnected systems. Regulatory challenges also present significant barriers; the development of robust legal frameworks for blockchain and smart contracts, especially within global supply chains, has yet to be thoroughly examined. Furthermore, the integration of decentralised AI with blockchain for predictive and real-time decision-making remains underexplored, restricting its potential for optimizing and automating infrastructure management.

Additive Manufacturing/3D Printing

3D printing, also known as additive manufacturing (AM), is a method used to create various structures and intricate geometries using three-dimensional (3D) model data. 3D-printing technology has the potential to improve sustainability in infrastructure projects by reducing material waste and transportation emissions. It allows for the creation of complex geometries and customised concrete forms, minimising material usage and formwork waste [123]. In transportation infrastructure construction, 3D printing can be used to produce precast concrete elements, molds, and formworks, enabling customised shapes that fit perfectly into specific locations, increasing efficiency and reducing waste. The world's first metal 3D printed bridge, the MX3D Bridge, constructed using wire arc additive manufacturing, demonstrates how 3D printing can create flowing forms while maintaining

structural integrity. Similarly, the Netherlands constructed the world's first 3D-printed bicycle bridge, printing in sections and then assembling it on-site, reducing time and material requirements [124]. Moreover, to develop a novel railway fastener design, the China Academy of Railway Sciences (CARS) utilised 3D printing to create sand-casting moulds for steel fastener plates and optimise clip and screw geometry in railway fasteners.

In addition, laser-based additive manufacturing shows promise for infrastructure repair, particularly for aging transportation infrastructure such as corroded steel bridges. A case study demonstrated that laser-based AM could effectively repair damaged structural components, addressing all three sustainability pillars: environmental (reducing replacement waste), economic (lowering costs), and social (minimising disruption) [125].

The adoption of 3D-printed construction diminishes reliance on fossil fuels, as diesel-powered heavy equipment is minimised or eliminated, leading to an eco-friendly approach to infrastructure development. This is particularly significant as the construction industry accounts for approximately 40% of global greenhouse gas emissions [126]. To address environmental concerns related to concrete-based materials used in 3D printing, alternative renewable resources like peat, geopolymers, soil, and earth construction can be employed [127]. Various AM techniques have evolved for civil infrastructure applications, including contour crafting, which uses trowels to smoothen extruded cement paste, and D-shape, which employs powder-based materials with binders for complex structures [128]. Utilising locally sourced subsoil, water, and fibres offers comparable structural and thermal properties, making it suitable for remote areas with less stringent material quality requirements. Although 3D-printed earth construction may not achieve the same strength and durability as conventional concrete-based construction, it provides comparable structural and thermal properties, making it suitable for remote areas with less stringent material quality requirements [127]. While AM adoption in construction still lags behind other industries due to conservative practices [126], research interest has grown substantially since 2012, highlighting its potential to improve safety, speed up construction processes, and enhance design freedom. However, challenges such as extrusion speed, consistency, and continuity hinder the widespread application of 3D-printed earth construction. Incorporating recycled construction waste products, glass, mining tailings, organic materials, and other resources into concrete mixes can further enhance sustainability in construction. Table 6 presents the contributions of AM and 3D printing to sustainability in transportation infrastructure projects.

Table 6. Additive manufacturing/3D printing contributions to sustainability pillars in transportation infrastructure projects.

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
Roads and Highways	Material Optimisation and Recycling	Use of waste rubber powder in 3D printed asphalt to reduce material waste and improve high-temperature performance; Cost savings through reduced raw material use and waste management.	[128]
Marine Construction		CEM III (a type of blast furnace cement) binder for eco-materials in artificial reefs enhances mechanical properties and biomass colonisation, supporting sustainable marine ecosystems; Reduced material costs for artificial reef structures.	[129]
Asphalt Pavement Maintenance		Movable 3D-printing robots and UAVs using recycled materials for crack and pothole repairs; Reduced costs for pavement repair through mobile and scalable repair solutions.	[130]

Table 6. *Cont.*

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
General Transport Infrastructure	Energy Efficiency and Emissions Reduction	Rapid robotic 3D printing using local materials minimises transportation emissions; Reduces costs associated with material transportation and logistics.	[115]
Concrete Structures	Durability and Resilience of Structures	Testing of 3D printed concrete for sulfuric acid resistance supports long-lasting, low-maintenance construction in harsh environments; Reduces lifecycle costs due to improved durability and reduced repair frequency.	[131]
Metal Bridges		Vibration analysis of 3D printed metal bridges improves design and maintenance planning; Cost optimisation through early identification of potential design flaws.	[132]
Tunnels		Physical simulation using 3D printed sandstone analogues aids understanding of failure processes for improved safety; Enhances worker and user safety through better prediction of structural failures; Reduces costs by optimizing design before full-scale implementation.	[133]
Highway-Adjacent Housing	Rapid Construction for Displacement Solutions	Robotic 3D printing of housing units using local materials supports fast, affordable, and sustainable housing for displaced residents; Provides affordable housing and improves quality of life for displaced communities; Low-cost, scalable housing options for highway projects.	[134]
Asphalt Pavement Maintenance	Repair and Maintenance Innovations	Mobile 3D asphalt printing robots and UAVs enable precise, on-site repair of cracks and potholes; Reduces road closure times, improving public mobility and convenience; Reduces operational costs due to automated repair processes.	[135]
Concrete Structures		New 3D spall repair methods improve the speed and precision of repairs; Enhances safety for users through quick restorations of damaged areas; Cost efficiency in repair materials and methods.	[136]
Concrete Shells	Design Flexibility and Structural Optimisation	Innovative shape generation using FEM and 3D printed models enables ultra-thin concrete shells with minimal material use; Reduced costs due to material optimisation.	[137]
Tunnels, Bridges, and Pavements	Advanced Monitoring and Inspection	Embedded sensors in 3D printed tunnel models provide 3D monitoring networks for damage identification and residual strength estimation; Enhances safety through accurate monitoring of damage during loading; Reduces costs for post-construction inspection and maintenance.	[138]
Railway Infrastructure		Additive manufacturing improves smarter component design, track performance, and maintenance strategies; Economic efficiency through better performance and reduced downtime.	[139]
Asphalt Pavement Maintenance	Automation and Mobility in Maintenance	UAVs equipped with 3D-printing air-feeding devices provide solutions for crack repair in inaccessible areas; Improved mobility and accessibility for maintenance in remote areas; Cost-effective maintenance solutions for dense or slight cracks.	[135]

Unmanned Aerial Vehicle (UAV)/Drones

Drones have proven valuable for surveying, monitoring, and inspecting infrastructure projects, leading to increased efficiency and safety as well as reduced environmental impact. Guan et al. [140] conducted a review of the sustainability of infrastructure using unmanned aerial vehicles (UAVs) and highlighted the integration of navigation, sensing, and monitoring systems. Photogrammetry and LIDAR (also known as Light Detection

and Ranging) systems were emphasised, enabling tasks like construction site monitoring, infrastructure assessment, and surface and volume measurements. These systems can perform several tasks, including construction site monitoring, infrastructure assessment, and surface and volume measurements.

Among the transportation infrastructure types, bridges have been extensively studied using UAV technology. For instance, Tang et al. [141] demonstrated that UAV 3D modelling combining oblique photography with inclined photography exhibits clearer textures, more complete lines, and higher accuracy than conventional methods, meeting accuracy requirements for topographic map control points and effectively aiding inspection of ailments such as steel structure coating corrosion and high-strength bolt loss in railway arch bridges. Similarly, Li et al. [142] showed that UAV-based concrete bridge crack inspection with image registration could achieve sub-millimetre measurement accuracy while providing a safe and cost-efficient monitoring solution. Beyond bridges, UAVs have been widely deployed to monitor other critical infrastructure types. Railway networks benefit from UAV-based inspections of tracks, overhead lines, and surrounding vegetation, providing comprehensive data without service disruptions [143]. Similarly, UAVs equipped with specialised sensors have transformed pipeline monitoring by efficiently identifying leaks, encroachments, and environmental impacts across vast distances, significantly improving detection rates while reducing inspection costs [144].

Building on these technological applications, existing studies highlight the role of UAVs in enhancing sustainability across environmental, social, and economic dimensions in transportation infrastructure projects. UAVs contribute to environmental sustainability by minimizing CO_2 emissions during inspections and optimizing material use in surveys and repairs, reducing unnecessary resource consumption. In terms of social sustainability, UAVs enhance worker safety by eliminating the need for high-risk physical inspections, particularly in hazardous environments such as bridges and underground infrastructure, thereby reducing accidents and improving operational safety. Economically, UAVs improve cost efficiency by lowering manual labour requirements, enabling faster damage detection, and streamlining resource allocation. Additionally, the integration of UAVs with digital tools such as BIM enhances construction monitoring, facilitates precise scheduling, and improves collaborative planning, further strengthening project efficiency and sustainability outcomes. Also, UAVs, in conjunction with Digital Twins, facilitate inspections in inaccessible or hazardous areas [145]. A summary of UAV and drones' contributions to sustainability pillars in the context of transportation infrastructure is summarised in Table 7.

Table 7. UAV and drone contributions to sustainability pillars in transportation infrastructure projects.

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
General Transport Infrastructure	Improved environmental monitoring and analysis	Facilitates hazard identification, enabling sustainable bridge management.	[146]
Port Infrastructure	Efficient surveying and inspections while reducing waste	Reduces resource waste through UAV surveying for asset management; Reduces costs of manual surveys and data inaccuracies.	[147]
Road Networks	Optimised road network sustainability	UAVs measure swept paths and model oversized vehicles, reducing environmental impacts.	[148]
Bridge and Viaducts	Reduction of CO_2 emissions during inspection	UAVs replace traditional inspection methods requiring heavy equipment; Improves worker safety by reducing physical inspection risks; Reduces inspection costs; Hastens inspection processes.	[149]
Urban Railway Networks	Precise 3D modeling for decision-making	Enhanced collaborative decision-making for rail upgrades; Saves costs with reliable 3D tools for railway transformations.	[143]

Table 7. *Cont.*

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
Bridges	Accurate damage detection for structural health	Minimises resource wastage through UAV-assisted NDT monitoring; Cost-effective damage identification leveraging UAV and deep learning; Identifies subsurface deterioration not visible through conventional methods; Enables early intervention before more resource-intensive repairs are needed.	[105,150,151]
Toll Roads	Efficient schedule adjustments	Improves progress tracking and adjustment of construction schedules; Reduces delays and resource allocation errors in toll road projects.	[152]
Underground Infrastructure	Enhanced underground inspections	Reduces worker risks in GNSS-denied conditions via UAV navigation; Reduces costs by automating underground monitoring and obstacle avoidance.	[144]
Asphalt Pavements	Sustainable maintenance and repair	Reduces material usage by combining UAVs with 3D printing for crack repairs; Reduces long-term maintenance costs by targeting dense cracks with UAVs.	[135]

Despite existing findings, several research gaps warrant further investigation to maximise the potential of UAVs in transportation infrastructure. A major challenge is the absence of standardised methodologies for integrating UAV data with BIM and other digital tools, which limits consistency and interoperability across projects. Regulatory challenges also persist, as technical and safety regulations for UAVs remain inconsistent, particularly in urban environments and large-scale applications where airspace management and privacy concerns are critical. Additionally, there is limited research on real-time UAV applications for dynamic traffic monitoring and immediate hazard responses, which could enhance proactive decision-making in infrastructure management. Another gap lies in feature recognition and AI integration, where advanced UAV navigation and obstacle avoidance for underground and complex environments remain underexplored. Addressing these gaps would significantly enhance the efficiency, safety, and scalability of UAV-based solutions in infrastructure projects.

Autonomous Robots

Robotic technologies offer numerous benefits across different phases of transportation infrastructure projects. The four main categories of robotics applications proposed for transportation infrastructure projects are off-site automated systems, on-site automated and robotics systems, drones and autonomous vehicles, and exoskeletons [153]. These technologies improve safety, efficiency, cost-effectiveness, and data accuracy in tasks involving challenging terrains, confined spaces, and expedited processes. Examples include flying robots [154], climbing and wheeled robots for inspecting bridges [155], vision-based robotic sensing for structural health monitoring (SHM) [156], and remote robotic sensing for SHM. While numerous studies have concentrated on the use of robotics technologies for the inspection and maintenance stages of construction, our SLR finds that there is a need for greater emphasis on the construction stage in future research.

To highlight the positive impact of robotics on sustainability, Pan et al. [157] identified indicators for evaluating the sustainability of construction robotics, including environmental, economic, and social indicators. Environmental indicators focused on material resource utilisation, energy consumption, land conservation, air and water resource management, and compliance with environmental regulations, while economic indicators reflected cost savings. Social indicators considered worker safety, job satisfaction, client satisfaction, and disturbance to site neighbours. While the study provides valuable insights into key indi-

cators for assessing the sustainability of construction robotics, there is a need for tailored performance indicators for infrastructure projects to effectively evaluate sustainability in this context, as highlighted by the potential gap in research. Table 8 presents the contributions of autonomous robots to sustainability in transportation infrastructure projects.

Table 8. Autonomous robots' contributions to sustainability pillars in transportation infrastructure projects.

Infrastructure Type	Autonomous Robots Application	Contribution to Sustainability	Reference
Various transportation projects	Off-site automated systems for 3D printing, prefabrication assembly	Improves safety protocols, reduces costs through automation, and enhances data accuracy, supporting economic, environmental, and social sustainability	[153,154]
Various transportation projects	On-site automation and robotics for steel welding, concrete laying	Increases safety in challenging environments, enhances precision in construction, and reduces labour costs and project timelines.	[153,155,156]
Bridges and tunnels	Drones and autonomous vehicles for inspection and data collection	Enhances efficiency in infrastructure inspections, reduces reliance on manual labour, and improves structural health monitoring accuracy.	[153,157]
Various transportation projects	Exoskeletons for worker safety and reduced physical strain	Improves workplace safety and ergonomics, enhances job satisfaction, minimises workplace injuries, and boosts efficiency in physically demanding tasks, contributing to social sustainability	[158,159]
Airport grounds, highway medians	Robotic lawnmowers	Reduces maintenance costs and operational time while lowering carbon emissions through electric alternatives, supporting economic and environmental sustainability.	[160]

Virtual and Augmented Reality

AR and VR fall under the larger umbrella of mixed reality (MR). In AR, the real-world environment remains unchanged, but it is enhanced with additional augmentations. On the other hand, VR creates a completely virtual environment, representing the physical surroundings. Even though there are emerging papers in the context of buildings, the applications of VR, AR, and MR have received far less attention in the context of this study. A primary application of VR, AR, and MR in the existing literature is improving visuals in construction, maintenance, and infrastructure repair. Technicians can overlay digital information on real-world components, detecting buried utilities and evaluating structural damage quickly. Malekloo et al. [161] developed an AR tool for field inspection using a Canny algorithm on a Microsoft HoloLens headset, combining visual inspection with automatic image-based crack detection. Ruotolo et al. [162] introduced a novel method for environmental noise assessment by combining VR technology and audio rendering techniques. Behzadan et al. [163] discussed AR's application in transportation infrastructure projects, presenting various validation test beds for collision avoidance, post-disaster inspection, and collaborative engineering simulations, all of which have sustainability implications. By optimising operation and timely maintenance, VR and AR can ensure sustainable infrastructure performance, enhancing infrastructure longevity, and reducing the need for exorbitant replacements. A summary of VR and AR contributions to sustainability pillars in the context of transportation infrastructure are summarised in Table 9.

Table 9. The contributions of AR/VR to the three pillars of sustainability based on the reviewed studies.

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
General Transport Infrastructure	Enhanced visualisation for SHM data management and decision-making	Improves stakeholder collaboration and data accessibility for better decision-making.	[164]
Underground Utilities	Improved workflows for infrastructure operation and maintenance	Enhances maintenance efficiency by enabling real-time AR-based inspections; Reduces time and costs associated with utility inspections.	[165]
Railway Infrastructure	Human-centric asset management	Improves operational safety and usability for railway workers; Enhances efficiency in asset lifecycle management.	[101]
Airport Fire Escape	Simulation training for emergency response	Provides realistic VR training environments to improve emergency preparedness; Reduces costs for physical training setups.	[111]
Pedestrian Bridge	Public education about infrastructure	Encourages environmental awareness among visitors; Enhances visitor engagement and understanding of sustainable infrastructure.	[166]
Highway Construction	Crane movement simulation for construction planning	Minimises environmental impact through optimised crane logistics; Reduces project costs through improved construction efficiency.	[49]
Port Construction	Underwater robot visualisation for port construction	Reduces environmental disruption by enabling precise construction; Reduces construction costs by improving accuracy and reducing rework.	[167]
Underground Utilities	AR-BIM-lean integration for utility relocation	Enhances lean principles, leading to improved workflows and reduced delays; Reduces overall project costs through better resource allocation.	[168]
Maritime Engineering	Maritime construction and navigation	Enables efficient planning for reduced resource use; Improves worker safety and collaboration; Enhances operational efficiency in maritime projects.	[169]
Highway Infrastructure	Connecting BIM models with human perception	Improves stakeholder understanding of construction progress and impacts.	[101]
Various Infrastructure Types	Simulation for training and planning	Enhances understanding and training for infrastructure project workflows; Reduces design and planning errors, lowering project costs.	[165]

Despite the identified benefits, AR/VR applications in transportation infrastructure still face several challenges and knowledge gaps. For instance, developing AR tools for transportation infrastructure faces challenges such as mobility, ruggedness (i.e., the ability to function in chaotic and harsh environments), power limitations, and adverse weather conditions, requiring further research and development to address these issues. The integration of AR/VR technologies into complex infrastructure projects remains challenging, with limited research on how they can seamlessly align with tools like BIM and IoT throughout the project lifecycle. Additionally, handling and securing the vast real-time data generated by AR/VR while ensuring data security and interoperability requires further exploration. The financial feasibility of AR/VR systems also lacks comprehensive cost-benefit analyses to evaluate long-term returns against initial investments. Practical adoption remains limited due to insufficient training programs and user-friendly designs for non-technical stakeholders. Moreover, the environmental impacts of AR/VR, such as energy consumption and hardware lifecycle, are underexplored, necessitating research into how these technologies can align with sustainability goals.

Big Data Analytics

Big Data analytics have emerged as a transformative tool in the transportation infrastructure sector, enabling data-driven decision-making for enhanced sustainability. By leveraging large datasets from historical records, sensors, and real-time monitoring systems, infrastructure management and maintenance can be optimised, leading to improvements across economic, environmental, and social sustainability pillars.

From an economic sustainability perspective, Big Data analytics enhance resource efficiency by optimizing traffic management, construction quality, and maintenance planning. For instance, integrating Big Data and Building Information Modelling (BIM) for lifecycle data management in highways has been shown to improve resource allocation, reduce costs, and minimise delays [170]. In highway bridge construction, real-time data monitoring and analysis enhance construction efficiency, reduce resource wastage, and improve cost estimation accuracy, thereby minimizing cost overruns [171]. These applications contribute to long-term financial sustainability by ensuring that infrastructure assets are built and maintained efficiently.

From an environmental sustainability standpoint, Big Data analytics play a crucial role in reducing carbon emissions and optimizing energy use. Studies have demonstrated the effectiveness of AI-driven Structural Health Monitoring (SHM) in predicting maintenance needs and reducing material consumption for repairs, thus lowering the environmental impact [172]. Furthermore, IoT-enabled Big Data applications in smart, sustainable cities contribute to reduced energy consumption and improved air quality through real-time monitoring of traffic and environmental conditions. The use of Digital Twins and Big Data analytics in airport operations has led to the creation of zero-emission airport systems, incorporating sustainable practices into infrastructure management [170].

In terms of social sustainability, Big Data analytics enhance safety and reliability in transportation infrastructure by leveraging AI, ICT, and BIM for real-time monitoring, predictive maintenance, and efficient facility management. AI-powered Structural Health Monitoring (SHM) systems use Big Data from sensors and historical records to detect structural weaknesses in bridges early, reducing the risk of catastrophic failures and improving public safety [172]. Similarly, Information and Communication Technology (ICT) facilitates the collection, integration, and analysis of large datasets for facility management, optimizing infrastructure operations and minimizing disruptions [170]. When combined with BIM, Big Data analytics enable predictive maintenance strategies, allowing facility managers to make informed decisions based on real-time performance data, ultimately improving infrastructure reliability and longevity. Table 10 presents the contributions of Big Data to sustainability in transportation infrastructure projects.

Table 10. The contributions of Big Data analytics to the three pillars of sustainability based on the reviewed studies.

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
Highway Bridge Construction	Real-time data monitoring for construction quality and progress tracking.	Enhances construction efficiency and reduces resource waste through real-time data monitoring. Improves project timelines and cost estimation, minimizing delays and overruns.	[173]
Bridge Infrastructure	AI-driven SHM for early structural weakness detection and predictive maintenance.	AI-driven SHM detects structural weaknesses early, enhancing safety and preventing failures. Predictive maintenance reduces material consumption, lowering environmental impact.	[90]
Smart Sustainable Cities (Transport)	Integration with IoT-based sensors for real-time traffic and environmental monitoring.	IoT-based monitoring optimises energy use and cuts carbon emissions in transport systems. Enhances air quality and reduces noise pollution.	[174]

Table 10. *Cont.*

Infrastructure Type	Sustainability Measures	Contribution to Sustainability	Reference
Highways	Big Data and BIM integration for lifecycle data management and optimised traffic planning.	Improves resource efficiency and cost savings through optimised traffic and maintenance planning. Enhances asset lifecycle management, reducing waste and maximizing resource utilisation.	[71]
General Civil Engineering Projects	Integration with BIM and ICT integration for facility management and data-driven decision-making.	Enhances operational efficiency and resource management, reducing costs and energy use. BIM-ICT integration improves data-driven decision-making, minimizing environmental impact over the facility lifecycle.	[75]

Integrated Approach of Technologies

The analysis of the reviewed literature reveals that a significant proportion of the studies employed an integrated application of technologies, where two or more technologies were used in conjunction to enhance the pillars of sustainability. These combinations suggest that researchers and practitioners are exploring ways to leverage the strengths of each technology to create more comprehensive and effective solutions for sustainability challenges in the built environment. Among the studies that featured integrated technology use, several recurring themes emerged. The most prominent themes included the integration of BIM and IoT, BIM and AI, and IoT and AI. Table 11 presents a summary of findings on technology integration by project type and sustainability contributions.

In existing studies, bridge infrastructure primarily employs AI-enhanced BIM and IoT systems for structural health monitoring, enabling predictive maintenance and extended service life. Road networks benefit most from the AI-IoT combination, supporting intelligent traffic management systems that reduce congestion and emissions. Railways show a strong preference for immersive reality technologies (AR/VR) combined with AI for specialised maintenance training and operations. Tunnels uniquely leverage robotics with advanced sensing technologies like 3D LiDAR, addressing the safety challenges of confined spaces through autonomous inspection systems. The main focus of studies on airport facilities primarily centres on the integration of BIM, IoT, robotics, and VR technologies to optimise the management of complex building systems, airport road pavements, and fire escape training and simulation. Additionally, the research explores the application of path-planning algorithms in intelligent mowing robots, contributing to sustainability by reducing energy consumption, minimizing operational costs, and improving resource management. Port infrastructure leverages the most diverse technology combinations, incorporating Digital Twins, drones, AI, and Big Data analytics with IoT to enhance debris tracking, structural health monitoring, safety improvements, and emissions reduction. Well-known ports like Hamburg and Rotterdam have integrated I4.0 technologies, including Digital Twins, IoT, and AI, to enhance their sustainability pillars [175].

Environmental sustainability benefits particularly from AI-IoT integrations, enabling intelligent resource monitoring systems that optimise energy consumption and reduce emissions through real-time data analytics. Economic sustainability shows balanced technology preferences, with BIM-Blockchain and BIM-IoT combinations supporting transparent resource allocation and predictive maintenance strategies that extend asset lifecycles while reducing operational costs. Social sustainability demonstrates the strongest connection to immersive reality technologies, with AI-AR and AR-VR combinations facilitating improved worker safety training, emergency response simulation, and public engagement. This suggests that addressing human factors and safety concerns relies significantly more on visualisation and simulation capabilities than purely data-driven approaches.

Application-specific technology integrations also reveal how different project phases benefit from particular technology combinations, as identified in the reviewed studies. Construction activities predominantly leverage AI-BIM integration for automated design validation and clash detection, significantly reducing costly errors and material waste. The design and planning phase demonstrates a strong preference for AI-AR combinations, enhancing collaborative design processes through contextualised visualisation that improves stakeholder engagement and decision-making. Maintenance and repair operations benefit most from BIM-IoT integration, creating Digital Twin systems that enable predictive maintenance strategies that extend infrastructure lifecycles while reducing operational disruptions. Monitoring and inspection applications uniquely leverage LiDAR-UAV combinations to create comprehensive digital records of infrastructure conditions, especially in hazardous or difficult-to-access locations. Operations and control systems show a preference for BIM-IoT integration, creating smart infrastructure systems that automatically optimise resource usage patterns and respond to changing environmental conditions.

These integrated technology applications, particularly in the operation and maintenance phase, are transforming infrastructure monitoring from periodic interventions to continuous real-time systems. For instance, the IoT sensor networks discussed above, when combined with AI analytics, provide continuous structural health monitoring that can detect early signs of deterioration, as demonstrated in bridge applications [90,91]. The previously mentioned BIM-IoT integration creates Digital Twins that not only reflect current infrastructure conditions but can predict behaviour, allowing for both immediate intervention and long-term optimisation [51]. This shift toward real-time capability transforms infrastructure management from reactive to predictive approaches, directly enhancing sustainability by optimizing resource utilisation and reducing environmental impacts. The implementation of IoT-enabled monitoring systems in port infrastructure further exemplifies how continuous data collection and analysis enhance both maintenance efficiency and operational safety [94].

Table 11. Summary of reviewed studies on technology integrations for sustainable transport infrastructure.

Infrastructure Type	Primary Technology Integrations	Key Sustainability Applications	References
Bridges	AI + BIM	Structural monitoring, lifecycle management.	[94,104,176]
	AI + IoT	Real-time condition assessment, structural monitoring and crack detection.	[90,91,177]
Roads	AI + IoT	Traffic optimisation, safety management, energy efficiency, emergency management.	[95,178,179]
	AI + AR	Enhancing worker safety through improved visualisation.	[102]
	AI + Blockchain	Transparent cost management and resource tracking.	[103]
Railways	AI + AR/VR	Asset management, maintenance training, simulation, and safety procedures.	[101]
	Autonomous robots + IoT	Enhancing safety through automated inspection systems.	[180]
Tunnels	3D LiDAR + Robotics	Automated inspection and safety improvement.	[181]
	AI + Robotics	Autonomous monitoring and damage detection.	[107]
	BIM + IoT	Planning the implementation of environmental protection in utility tunnels.	[182]
Airports	BIM + IoT	Energy management, operational efficiency of airport road pavements, improving delivery performance in terms of costs and safety.	[92,93]
	AI + VR	Emergency training and simulation for fire escape and passenger flow optimisation.	[111]

Table 11. *Cont.*

Infrastructure Type	Primary Technology Integrations	Key Sustainability Applications	References
Ports	Drone + AI	Identify and track debris formation, enabling faster response times and more efficient cleanup operations.	[183]
	Digital twin + AI	Improve monitoring of structural health, enhancing port sustainability by extending lifespan and reducing monitoring costs and failure risks.	[184]
	IoT + Big Data + AI + Blockchain	Reduce emissions through optimised operations, extend infrastructure lifespan via AI-enabled structural monitoring, minimise resource consumption, and enhance safety through early hazard detection.	[185]

Current Challenges in Technological Integration

The increasing integration of technologies indicates a clear shift toward holistic technology ecosystems in transportation infrastructure, where complementary technologies operate synergistically rather than in isolation. However, various obstacles prevent the smooth integration and optimisation of these tools to enhance project sustainability. These challenges fall into four main categories: guideline/standard misalignment, data management problems, human factors, and initial investment expenses.

Our SLR shows that there is a major problem with the alignment and coordination between sustainability assessment tools and digital technology standards. This is causing issues with implementing integrated technologies for sustainable infrastructure development. One of the main problems is the absence of comprehensive frameworks to bridge this gap. There are several sustainability standards, tools, and rating systems available to evaluate infrastructure projects, such as Greenroads, AGIC's Infrastructure Sustainability Rating Tool, and ASPIRE.

However, there is a paucity of guidance on how these resources should be fully integrated with BIM, DT, IoT, and other digital technologies in the existing literature. The fragmentation of stakeholders and industry sectors is the root cause of this issue. This lack of integration can lead to inconsistencies in data collection, analysis, and reporting, making it difficult to accurately assess the sustainability impact of technological interventions.

Data management is identified as one of the obstacles to optimizing I4.0 technologies in sustainable transportation infrastructure. Challenges related to data collection, compatibility, interoperability, formatting, and standardisation continue to impede progress. The progression of digital technologies is moving faster than the establishment of rules and regulations, resulting in regulatory and technical gaps that hinder the efficiency of these technologies. According to Costin et al. [15], the incorporation of data from platforms such as BIM, DT, GIS, and IoT is restricted by the underdeveloped IFC schema for transportation infrastructure context.

The next key factor in the successful implementation of I4.0 technologies for sustainable transportation infrastructure projects is the impact of human elements, including training and adaptation. Resistance to embracing technology-driven methods over traditional practices can hinder the adoption and optimisation of these technologies. Finally, investing in I4.0 technologies can be expensive, especially for projects that are funded by the public sector. Implementing technologies like drones, BIM, and DT comes with high initial expenses, which may hinder their widespread adoption.

4.2.3. Project Lifecycle Focus

Figure 10 presents the distribution of research studies across various project phases in the context of I4.0 applications for sustainable transportation infrastructure. A marked

concentration is observed in the Operation and Maintenance phase, with 75 studies reflecting the sector's predominant emphasis on post-construction digital applications and the retrofitting of existing assets. The Construction phase follows with 34 studies, while the Design and Project Lifecycle phases account for 19 studies each. Although some papers address multiple stages, studies adopting a lifecycle-oriented perspective remain limited—indicating opportunities to promote integrated, systems-based frameworks that enhance sustainability across the full infrastructure lifespan. Among the dual-phase combinations, Design and Construction (12 studies) and Planning and Construction (8 studies) receive relatively more attention; however, the overall decline in multi-phase studies underscores a broader tendency toward fragmented digital implementations rather than coordinated, end-to-end integration. The following section reviews the research trends towards the application of each technology in the various stages of the project lifecycle.

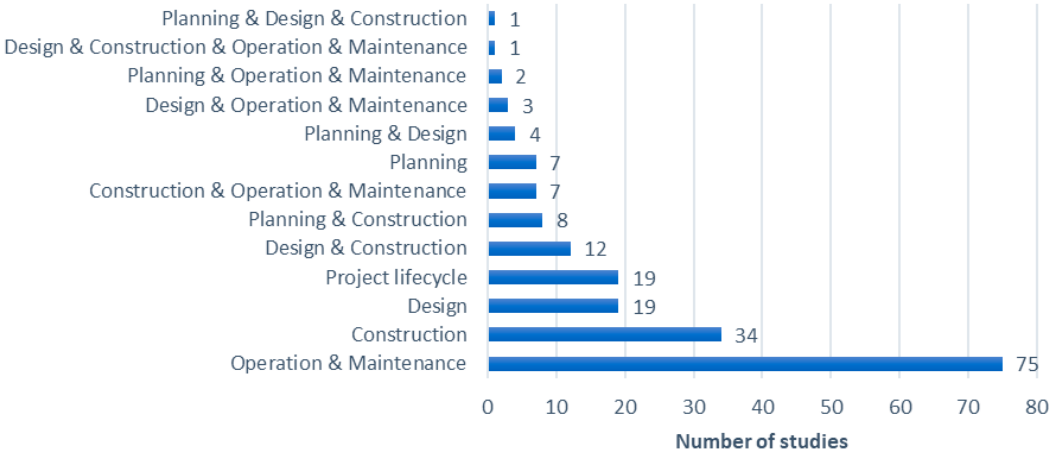


Figure 10. Distribution of papers as per project phases.

- **Planning phase**: The planning phase has received comparatively limited attention despite being a critical stage for making impactful sustainability decisions [186]. This highlights a research gap in the early-stage application of digital technologies for sustainable transportation infrastructure. This phase involves identifying infrastructure needs and setting project objectives through the use of digital technologies, which can provide information on environmental and social impacts and assist in the evaluation of various options. A study by Jangid et al. [187] used GIS and remote sensing technologies to identify suitable sites for infrastructure development, taking into account factors such as environmental constraints and social acceptability. Digital Twin, integrated with AI for roads, highways, and railway infrastructure, facilitates predictive planning and scenario testing to optimise future operations [188]. The most comprehensive approach appears in the multi-technology integration of BIM, Big Data, Blockchain and GIS for general transportation projects, which enables resource optimisation, environmental impact analysis, spatial optimisation, supply chain transparency, and material traceability, addressing all three sustainability pillars simultaneously [111].
- **Design phase**: The design phase has also seen limited research focus, even though it plays a pivotal role in embedding sustainability principles into infrastructure solutions from the outset. The incorporation of digital technologies during the design stage significantly enhances the sustainability of infrastructure projects. Designing transportation infrastructure is inherently intricate, given its vast scale and interaction with the surrounding environment. The applications of I4.0 technologies in the design phase can be categorised into distinct themes encompassing analysis and design facets, in-

cluding societal and human values, as well as health and safety considerations. Within the design stage, BIM has emerged as a paramount technological platform, often employed alongside other data modelling techniques. Furthermore, BIM is harnessed to correlate with sustainability ratings [62]. The application of long-span bridge maintenance is also addressed during the design phase [69]. Tools fostering collaboration, such as cloud-based platforms and virtual design reviews, are utilised to foster effective teamwork [50]. Design alternatives are explored through modelling to address inherent challenges, often applying degradation analysis to determine cost-effective and suitable methods for resolving design issues [189]. Moreover, risk assessment, facilitated by data-driven approaches, is employed to identify potential risks, while predictive simulation evaluates the risk levels of various design alternatives [190]. The design process further includes the facilitation of roadway optimisation by integrating visualisation, simulation, and analysis. Environmental assessments, including Life Cycle Assessment (LCA), are employed to evaluate the performance of design alternatives, considering their environmental impact [80]. Early design decisions are aimed at optimisation and may involve energy modelling [191]. The integration of Mixed Reality technologies, such as VR, is employed to create virtual environments that visualise asset conditions. Furthermore, point cloud data are harnessed for constructing 3D models of existing infrastructure assets, aiding the design phase [101]. Automated processes are leveraged to facilitate regulatory compliance, streamlining adherence to regulations [62]. Accurate georeferencing is foundational to infrastructure design as it involves the alignment of different technological platforms such as GIS and BIM. The integration of GIS and BIM enables a more efficient and accurate representation of the infrastructure design, enhancing sustainability dimensions such as cost, material waste, and advanced hazard predictions [192]. The integration of low-carbon emission materials in the design process, facilitated by BIM, can lead to reduced CO_2 emissions later during the construction phase. A study on tunnelling projects conducted by Sun and Park [193] found that the selection of low-carbon emission materials enabled by BIM resulted in decreased environmental impact. In another study, Acerra et al. [194] used BIM to optimise the design of a steel structure for a railway station, resulting in a 13% reduction in steel consumption and a 15% reduction in construction waste.

- **Construction phase**: The construction phase has garnered more attention in the literature than the design and planning phases. The utilisation of digital technologies during the construction stage significantly contributes to waste reduction, safety enhancement, and increased productivity. A notable illustration is a study by Song et al. [195], employing RFID and GPS technologies to enhance construction site safety by monitoring workers' locations and movements. Prominent focus areas encompass streamlined documentation procedures [196] and real-time materials management [191] for augmented efficiency and resource allocation. The construction phase further addresses environmental considerations through continuous monitoring of carbon emissions [80] and environmental surveillance facilitated by the integration of BIM and IoT [197]. The application of additive manufacturing and 3D-printing technologies [134], as well as Digital Twins, play a pivotal role in hazard identification and defect detection. Strides in supply chain management [198] and blockchain-based waste management optimisation [116]. Similar to the design phase, BIM emerges as a primary technological innovation during the construction stage, primarily manifested in clash detection, as demonstrated by Byun et al. [72]. Ershadi et al. [199] classify BIM's influence into the dimensions of integrity, collaboration, and optimisation. Another significant theme during the construction stage involves integrating BIM with UAVs and sensors. For

instance, the amalgamation of BIM and UAV technologies has been employed in infrastructure construction project management and delay and disruption analysis [200].

- **Operation and maintenance phase**: The operation and maintenance phase has received the most attention in the literature, reflecting its critical role in ensuring the long-term sustainability and performance of infrastructure through ongoing monitoring, optimisation, and the renovation and retrofitting of existing assets. Concerning maintenance, most studies concentrate on structural health monitoring (SHM), with BIM and DT emerging as a promising computational environment and an integrated digital platform for SHM. BIM and DT are primarily utilised for the integration of asset management systems to optimise maintenance operations, such as a centralised data repository and wireless SHM [72]. Preventive maintenance is also a prevalent topic in sustainable transportation infrastructure due to its proactive approach to ensuring structural sustainability throughout the service life. This includes the use of sensors for regular bridge inspection programs to identify potential issues [69], as well as the application of AR to enhance work and maintenance procedures, thereby promoting virtual training environments [201]. Additionally, the implementation of condition monitoring and the utilisation of environmentally friendly, sensor-based equipment, such as sensor-based lighting for roads, highways, and tunnels aimed at power conservation, are noteworthy. Furthermore, predictive maintenance technologies are utilised, involving the utilisation of Big Data analytics for collecting and analysing extensive datasets from diverse sources [201,202]. Flammini et al. [203] assessed drones' potential within a railway monitoring system, encompassing the detection of structural faults, security threats and the investigation of the impact of natural hazards. Shim et al. [204] proposed a maintenance information management system that integrates a 3D information model with a digital inspection system employing image processing—another key research area that aims to enhance maintenance coordination aspects. The EU-funded HERON project strives to create an integrated automated system for road infrastructure maintenance, involving the design of an autonomous ground robotic vehicle supported by autonomous drones to synchronise maintenance efforts. The incorporation of sensors, 3D mapping tools, and artificial intelligence will streamline road maintenance and optimise upgrade workflows [205].

5. Discussion and Future Research Directions

Transport infrastructure projects, such as bridges and highways, significantly impact energy consumption and the social and economic growth of the built environment. For example, in Australia, the infrastructure sector contributes 20% to the country's GDP, and considerable investment is being made in new infrastructure projects, with the 2020–2021 budget allocating over one billion AUD to transport mega projects. Given the increasing need for sustainable infrastructure to mitigate the impacts of global warming, leveraging I4.0 can enhance project sustainability. The review provides valuable insights to optimise the adoption and implementation of I4.0 technologies for sustainable transportation infrastructure projects.

- Strategic alignment of I4.0 technologies with transportation infrastructure lifecycle phases

Our review demonstrates that I4.0 technologies enhance transportation infrastructure sustainability across all dimensions, but effective implementation requires alignment with both infrastructure type and lifecycle phase. The adoption must be tailored to project-specific contexts and lifecycle requirements. Each phase demands different technological approaches. During planning and design, BIM and Digital Twin technologies enable design optimisation, while GIS provides geospatial context for environmentally sensitive decisions. AR and VR facilitate stakeholder engagement and visualisation. In construction, the focus shifts to

AR for precision guidance, while RFID, AI, and robotics enable automated processes that reduce waste and community disruption. The operation and maintenance phase—the longest and most resource-intensive period—currently receives insufficient technological attention. IoT sensor networks and data analytics show particular promise by enabling continuous monitoring and performance optimisation that extends infrastructure lifespan and enhances user experience. Challenges remain in standardizing and integrating these technologies across organisational and lifecycle boundaries. Future research should prioritise interoperability frameworks, seamless information transfer between phases, and applications specifically designed for operational sustainability, addressing the current operational phase gap while ensuring digital continuity throughout the infrastructure lifecycle.

- The need for improved technical aspects among I4.0 technologies and sustainability tools

The integration of I4.0 technologies and sustainability assessment tools in infrastructure projects faces technical challenges. In the absence of a universal data exchange format, interoperability, compatibility, and data management issues are significant. Developing standards, protocols, and validation systems are necessary to overcome these challenges. Research is needed to optimise data management and analysis of I4.0-generated data for construction and sustainability. Some standardisation efforts are currently underway to establish common data formats and communication protocols that can facilitate interoperability and compatibility between different technologies. For example, efforts have been made to develop open and web service APIs (application programming interfaces) that enable easier integration of these technologies [206]. However, further research is needed to optimise data management and analysis of I4.0-generated data for construction and sustainability.

- The use of I4.0 technologies for structural health monitoring (SHM)

SHM is a prominent application of I4.0 technologies in sustainable infrastructure. There are two main approaches in SHM: model-driven and data-driven [161]. The data-driven approach relies on sensor data from both undamaged and damaged states of the structure, while the model-driven approach uses an analytical model to detect and analyse behavioural changes. SHM for sustainable infrastructure can be categorised into four areas in terms of damage level: detection, location, extent/severity, and prediction. For detection, real-time data are obtained through IoT sensors and wireless systems, enabling continuous monitoring and immediate anomaly detection. Advanced imaging tools like drones are crucial for pinpointing the precise damage locations. AI, ML, and data analytics are employed to assess damage extent and severity. These tools analyse sensor data and historical information to estimate the damage and provide quantitative measurements. ML algorithms also play a role in prediction by identifying patterns and forecasting potential future damage, allowing for timely maintenance and enhanced infrastructure resilience. However, not every ML algorithm can predict damage. The choice between model-driven or data-driven SHM systems depends on system requirements, application complexity, and the availability of relevant data and models. When using a hybrid approach, predictive accuracy relies on the performance of the physics-based model and the usability of data-driven measurements for training and validation. Future research must, therefore, integrate data analytics and machine learning to increase the accuracy of damage detection, location, severity assessment and prediction.

- Need for a more balanced consideration of sustainability pillars

Our analysis reveals a fragmented approach to sustainability in the reviewed literature, with environmental considerations appearing more frequently than others. Social aspects receive limited individual attention, and more concerning is the scarcity of studies integrating multiple sustainability pillars. This highlights a lack of the holistic approach necessary

for truly sustainable infrastructure. Environmental applications predominantly focus on energy efficiency and carbon emissions reduction through BIM and IoT implementations while largely neglecting resource conservation and ecosystem protection. Economic applications emphasise cost optimisation over lifecycle analysis and resilience considerations. Social sustainability primarily addresses safety and accessibility, overlooking community impacts, equity, and public participation. This imbalance demonstrates the need for more integrated approaches that address sustainability comprehensively rather than treating environmental, economic, and social dimensions as separate concerns. Future research should place greater emphasis on social and economic dimensions, which currently lag behind environmental considerations. Most importantly, researchers should prioritise the integration of all three sustainability pillars to develop truly holistic frameworks that can address the complex interdependencies between environmental protection, economic viability, and social equity in transportation infrastructure development.

- Gaps in infrastructure-type research coverage

Our analysis highlights significant research gaps for key infrastructure types. Maritime and port infrastructure, vital to global trade, receive limited research attention, especially when it comes to the integration of various technologies. Future studies should explore how synergistic integration of I4.0 technologies can comprehensively address sustainability pillars in maritime infrastructure. For example, combining BIM with IoT sensors, Digital Twins, and blockchain could create an environmental-economic-social framework that optimises resource utilisation during design, monitors carbon emissions during construction, and extends infrastructure lifespan through predictive maintenance. Also, airport infrastructure, despite its environmental and operational challenges, is insufficiently represented, and tunnel infrastructure, with its unique safety and energy demands, receives only moderate coverage. These gaps underscore the need for expanded research to explore how I4.0 technologies can address the specific sustainability challenges of these underrepresented systems.

- Enhancing real-time intelligent monitoring for sustainable infrastructure management

Our analysis reveals an emerging trend toward integrated I4.0 technologies for infrastructure monitoring, yet standardisation challenges and limited cross-domain applications persist. The real-time intelligent monitoring capabilities of these integrated technologies address the fragmented approach to sustainability identified in Section 4.2.2, where environmental considerations often overshadow social and economic dimensions. By transforming traditional inspection practices from periodic assessments to continuous, data-driven processes, these systems enable more balanced sustainability outcomes. For instance, UAVs combined with AI for automated crack detection [105,177] not only enhance environmental sustainability through resource optimisation but also improve social sustainability by eliminating hazardous manual inspections. Similarly, IoT sensors with edge computing capabilities [89,207] contribute to economic sustainability through cost-effective maintenance while supporting real-time decision-making. Despite these advances, our review identifies significant gaps in standardisation and integration across different transportation infrastructure types. Future research should focus on developing standardised protocols for translating monitoring insights into sustainable maintenance actions, particularly for underrepresented infrastructure types like maritime and port facilities identified in our analysis. Additionally, research efforts should address the limited attention to social sustainability dimensions through more sophisticated predictive analytics that incorporate community impact assessments alongside other performance monitoring aspects.

- Streamlining the use of 3D printing for innovative and sustainable materials

Research indicates that 3D printing presents numerous promising avenues for enhancing material efficiency in construction infrastructure. This includes the application of recycled or biodegradable materials, the integration of robotics and automation to improve speed and precision, and the reduction in resource consumption and emissions. However, to date, few projects have implemented these technologies, with bridges being the primary focus of additive manufacturing applications. Future research should concentrate on expanding the scalability of 3D printing. This would allow for the construction of larger and more complex infrastructures, particularly when combined with sensors and AI, to optimise energy efficiency.

- Further research is needed on the application of blockchain in the context of sustainable infrastructure context

The research found that there is a significant disparity in the number of studies exploring blockchain technology applications in the AEC industry, with a focus on the building sector and limited exploration of infrastructure. Transportation infrastructure projects face complex contractual arrangements and involve multiple stakeholders, making blockchain technology appealing for enhanced transparency, traceability, and accountability. It can reduce disputes and improve contract management, supply chain efficiency, and project delivery. As previously mentioned, each infrastructure project typically utilises a distinct file format and has specific interoperability requirements. In this context, blockchain technology enhances transparency, traceability, and accountability in contract management, supply chains, and project delivery. It also enables resource tracking, certification verification, sustainability compliance, and management of intelligent systems. Future research should explore blockchain technology in diverse infrastructure projects, addressing functionality and interoperability requirements. The integration of blockchain with existing digital infrastructures, including IoT-enabled devices and cloud interactions, is essential for its widespread adoption in the infrastructure sector.

- Exploring the applicability of VR/AR technologies in transportation infrastructure projects

Future studies utilizing AR and VR to enhance sustainability in transportation infrastructure can be conducted across several domains. The first involves simulating scenarios, assessing environmental impact, and identifying sustainability opportunities. The second focuses on reducing waste, facilitating coordination, and monitoring sustainable infrastructure performance. The third category aims to educate construction workers, customers, and stakeholders about sustainable materials, practices, and design principles. The fourth addresses safety and risk management, using AR and VR to simulate hazardous situations, train workers, and monitor site safety. The fifth category focuses on stakeholder engagement, utilizing AR and VR to engage stakeholders, promote sustainable design features, simulate project outcomes, and involve communities in sustainable infrastructure planning.

- Greater emphasis is needed on synergistic technology integration

The integration of multiple I4.0 technologies demonstrates significant synergistic potential, extending beyond the sum of individual capabilities. However, the underlying mechanisms of these integrations require further investigation. For example, BIM-IoT integration establishes a bidirectional relationship where BIM provides a semantic framework for contextualizing sensor data, while IoT delivers real-time insights that dynamically update models. Similarly, UAV-AI combinations rapidly transform raw imagery into actionable structural assessments. Future research should examine these technology ecosystems through the lens of information flows, exploring how data transform across technological boundaries to achieve sustainable outcomes.

- Need for more research on planning, design, and project lifecycle

Despite the considerable focus on the operation and maintenance phase in the existing literature, there is a clear need for expanded research into the planning and design phases, as well as the broader project lifecycle. These early stages are pivotal for shaping the long-term sustainability of infrastructure projects, as the decisions made during planning and design have far-reaching implications on resource efficiency, environmental impact, and overall project resilience. A more holistic, systems-based approach that integrates sustainability principles across the entire lifecycle can enhance the effectiveness of digital technologies in addressing these challenges. Specifically, research aimed at bridging the gaps between these stages could foster more informed, proactive decision-making, ensuring that sustainability goals are not only considered at later stages but embedded throughout the entire project development process.

- Greater emphasis should be placed on conducting research in developing countries

The SLR reveals variations in the implementation of sustainability indicators when utilizing I4.0 technologies for infrastructure projects across diverse countries [208]. Developed countries tend to prioritise environmental indicators more heavily in infrastructure design evaluation, whereas developing countries place greater emphasis on economic and social indicators. There is a critical need for additional research into developing innovative models for assessing sustainable infrastructure in developing countries. These include the identification of suitable indicators for measuring sustainability, the creation of assessment models, the formulation of assessment frameworks, and the establishment of guidelines specifically tailored to the context of I4.0 technologies in developing countries. More specifically, future research should investigate context-specific applications of digital technologies that address the unique infrastructure challenges of diverse regions, including resource constraints, institutional capacity limitations, and different sustainability priorities. Such research efforts are essential to ensure comprehensive and inclusive approaches to sustainable infrastructure development worldwide.

6. Conclusions

This mixed-method systematic literature review has identified a significant increase in academic research on the use of I4.0 technologies in infrastructure projects to improve sustainability, with a total of 199 documents examined in this study. The thematic analysis categorised the selected publications into four main clusters: (1) Infrastructure type, (2) Technology types, (3) Project lifecycle stages, and (4) Geographic context. This granular categorisation enables researchers to identify specific areas of focus and evaluate the effectiveness of I4.0 technologies in addressing sustainability concerns.

The findings indicate that the integration of I4.0 technologies to enhance the sustainability implications of construction infrastructure has gained momentum, with a predominant focus on roads, highways, and bridges. BIM is extensively used across all transportation project types for various purposes, such as energy assessment, sustainable design, stakeholder engagement, and asset management. IoT and AI/ML are employed for real-time monitoring, predictive maintenance, and resource optimisation in bridges, highways, railways, tunnels, and ports. 3D printing is being explored for the fabrication of structural components, repair, and construction in bridges, highways, tunnels, and ports. UAVs and drones are used for inspection, monitoring, and surveying in bridges, highways, and tunnels. The review also highlights that the distinctive characteristics of transportation infrastructure projects can influence the choice and incorporation of digital technologies.

The paper examines how these technologies contribute to different aspects of sustainable transportation projects. However, the review revealed limited attention to the

social dimension of sustainability, emphasising the need for a more holistic approach to implementing I4.0 technologies in transportation infrastructure projects for sustainable development. Future research should focus on the integrated approach of various technologies and their collective impact on sustainability in transportation construction projects, considering not only the economic and environmental aspects but also the social dimension.

This paper presents a fundamental basis for ongoing research, identifies gaps, and highlights emerging technologies that are crucial for academia and industry stakeholders to develop sustainable tools and techniques for repairing, advancing, and expanding transportation infrastructure. Moving forward, policymakers and regulators can accelerate sustainable technology adoption in transportation infrastructure by updating regulatory frameworks to remove barriers in procurement, information sharing, and delivery models. Supporting standardisation ensures interoperability, data quality, and security. Sustainability performance requirements should be integrated into infrastructure funding, approval, and monitoring processes, creating incentives for technology-enabled sustainability improvements.

It is important to acknowledge that this SLR was limited to the Scopus database and a defined timeframe ending in November 2023. Consequently, some recent or relevant publications may not have been captured. To address this limitation, future research could broaden the search scope by incorporating multiple databases and extending the publication period. Such an expansion would enhance the comprehensiveness of the literature review and enable comparative analyses of emerging trends and evolving applications of I4.0 technologies in the context of sustainable transportation infrastructure—particularly from a construction-oriented perspective—by comparing future developments with the findings of the present study. Moreover, for the technology inclusions, we have utilised the framework established by Oesterreich and Teuteberg [29]. This framework is widely recognised and accepted in the field of I4.0 research, making it a reliable and comprehensive resource for identifying relevant technologies. However, it is possible that some technologies may have been missed and not considered in this study. Future studies could extend this work by investigating emerging or overlooked I4.0 technologies to enrich current analysis and capture evolving applications.

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