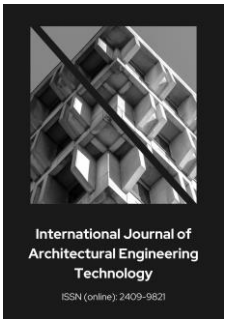
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The Digitalisation of Construction (2016–2025): A Critical Narrative Review of BIM, AI, Robotics and Digital Twins: Evidence Maturity, Circular Economy Disconnect and a Research Agenda

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ABSTRACT

Research on construction digitalisation has grown quickly but remains fragmented. This narrative review examines Scopus-indexed journal articles published between 2016 and 2025 on Building Information Modelling (BIM), artificial intelligence (AI), robotics, digital twins and related automation. A pool of 494 records was screened by title, abstract and keywords, and 89 articles were retained. An eligibility audit then separated 78 core studies from 11 records in which digital technology was contextual. The review combines a descriptive profile of the literature with an explicit, criteria based assessment of evidence maturity and of circular economy linkage. This narrative review used a single database and screening by one reviewer. Exclusion followed a construct based relevance test and not study quality. The exact date of the Scopus search was not recorded. Output accelerated after 2022 (74.2% of the 89 articles appeared from 2023 to 2025), 77.5% appeared in two MDPI journals, and author affiliations were concentrated in China and the United Kingdom. Nine overlapping themes emerged, led by BIM for design, coordination and compliance (39 core studies), robotics, automation and additive manufacturing (30), and AI and machine learning (24). Six records addressed circularity or waste reduction, and only two applied a digital tool to a material recovery or waste outcome. Within the retrieved sample, the link to the circular economy is therefore a thin evidence base and not an established finding, and the low count may partly reflect the search strategy. Case studies, pilots and cross sectional surveys are common (19 and 16 of the 89 screened records, respectively), whereas longitudinal studies and multisite validation appear limited. Blockchain evidence in the sample is minimal. A research agenda is proposed for validated, integrated and context-sensitive studies.

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1. Introduction

1.1. Background and Rationale

The construction industry is among the least digitalised sectors of the economy, yet it is under pressure to raise productivity, reduce waste and limit its environmental impact [1]. Over the past decade, research and policy have converged on Construction 4.0, a label that covers Building Information Modelling (BIM), artificial intelligence (AI), robotics, the Internet of Things (IoT), digital twins and automation. Akinade *et al*. [2] and Alwan *et al*. [3] presented BIM as a vehicle for waste reduction and sustainable development, while Selçuk Çıdık *et al*. [4] argued that its innovative potential is held back by slow organisational uptake. Reviews of AI in construction report broad application potential alongside persistent adoption challenges [5-7], and reviews of BIM point to unresolved interoperability and integration problems [8]. Digital tools are also expected to support sustainability and circular economy goals, including waste minimisation and whole life carbon reduction [9-11].

The evidence behind this narrative is scattered across a fast-growing and loosely organised literature. Three difficulties stand out. First, key terms are used inconsistently, and “digital transformation”, “smart construction” and “Construction 4.0” are often treated as interchangeable. Second, methodological rigour varies widely, from international Delphi surveys of experts [12] to single-site engineering prototypes [13]. Third, existing mappings of AI and machine learning in construction describe publication volume and keywords [14-16] but rarely test how strong the underlying evidence is. Studies of adoption also show that technologies that are technically feasible are not widely used in practice [17, 18], and context-specific work in developing economies suggests that barriers differ across settings [19-21]. This review responds to these gaps. It screens a defined sample of Scopus records with a documented protocol and assesses what that sample can and cannot support. It is a narrative synthesis and not a full systematic review.

1.2. Review Questions

This review addresses four questions:

- **RQ1:** What is the volume, growth trajectory, and publication profile of peer-reviewed research on digital technologies (BIM, AI, robotics, automation, digital twins) in construction?
- **RQ2:** What are the principal thematic strands of this literature, and how mature is the evidence underpinning each, judged against the explicit indicators set out in Section 6.1?
- **RQ3:** To what extent does this literature substantively connect digital technology adoption to circular economy outcomes, as distinct from broader sustainability, life cycle assessment (LCA) and Sustainable Development Goal (SDG) discussion?
- **RQ4:** What methodological, geographic, and structural limitations characterise the current evidence base, and what does this imply for a future research agenda?

1.3. Scope and Contribution

This review draws on a pool of 494 Scopus records retrieved with a general query on sustainable construction and construction innovation (Section 3.1). The query was not designed to capture the whole digital construction literature. Conclusions therefore describe the retrieved sample and should not be read as statements about the field as a whole, a limitation that is discussed in Section 8. Appraisal of the pool showed that only a minority of records addressed digital technology substantively and that fewer still connected it to circular economy outcomes, as claimed, for example, by Ghobadi and Sepasgozar [9]. The review therefore restricts its synthesis to the digital technology literature that the data can support (core set, n = 78) and reports in Section 6.2 how thin the circular economy linkage is within it. The contribution is deliberately modest and has four parts: a documented search and screening protocol, an explicit eligibility audit, indicator-based statements of evidence maturity, and a reproducible classification of circular economy linkage. Together, these separate what the sampled literature demonstrates from what policy discourse assumes.

2. Literature Review

2.1. The Evolution and Adoption of Building Information Modelling in Construction

BIM has anchored research on construction digitalisation for more than a decade. Selçuk Çıdık *et al*. [4] framed it as a social and organisational challenge more than a technical one, and later adoption studies support this view [12, 22]. Adoption research has since diversified. Deng *et al*. [23] modelled drivers of BIM uptake with system dynamics, Rui *et al*. [24] compared adoption in China and Japan, Ma *et al*. [25] applied the Theory of Planned Behaviour to BIM outsourcing decisions, Mujahed *et al*. [26] examined platform approaches to diffusion, and El Hajj and Martínez Montes [27] linked green building practices to the diffusion of BIM functions. At the strategic level, Alwan *et al*. [3] tied BIM to UK zero carbon building targets, and He *et al*. [28] extended it from design to procurement through a BIM and linked data platform for industrialised construction supply chains.

A second body of work links BIM to sustainability and waste outcomes. Akinade *et al*. [2] surveyed stakeholders on BIM-enabled waste minimisation and found that existing waste tools lacked adequate BIM functionality. Yardımcı and Kurucay [29] later combined LCA with the TOPSIS decision method in a BIM-based waste minimisation framework. Kaewunruen *et al*. [30] and Nabawy *et al*. [31] extended BIM dimensionality to sustainability tracking through 6D and Green BIM frameworks; Zhang *et al*. [32] offered an empirical case from China on BIM application behaviour and sustainable construction; and Ullah *et al*. [33], Piaia *et al*. [34], Llatas *et al*. [35], Cascone [36] and Asfandyar *et al*. [37] connected BIM to energy, life cycle indicators, green roofs and flood resilience.

Recent BIM research also addresses safety, cost and compliance. Rafindadi *et al*. [38] and Buhamdan *et al*. [39] used BIM for fall prevention and hazard assessment, and Amin Ranjbar *et al*. [40], Zhang *et al*. [41] and Rashidi *et al*. [42] applied it to cash flow risk, cost segregation and pre-tender estimation. Wang and Lu [43] and Wang *et al*. [44] addressed design and scheduling automation. Immersive and smart city applications were examined by Liu *et al*. [45-47], and Chen *et al*. [48], and Chen *et al*. [49] pushed compliance checking furthest by combining a large language model, deep learning and ontology reasoning. Dagou *et al*. [50] reviewed emerging technologies for project management in Chad, although their framing is contextual rather than strictly technical. Taken together, the BIM literature moves from descriptive adoption studies towards AI-augmented applications, while interoperability remains a recognised constraint [8].

2.2. Robotics, Automation and Additive Manufacturing in Construction

A parallel stream addresses physical automation. Prefabrication is treated as a policy-relevant automation route by Kirschke and Sietko [51], as a selectable method for high-rise buildings by Navaratnam [52], and as a risk landscape by Anaç *et al*. [53]. Additive manufacturing is especially active. Alhumayani *et al*. [54] showed that the environmental outcome of large-scale 3D printing depends on the material compared, and Volpe *et al*. [55] applied printing to prefabricated envelopes. Later work refines structural and material performance, with Aminpour and Memari [56] testing reinforced 3D concrete printed walls, Wang *et al*. [57] examining optimised printing paths, and Dörrie *et al*. [58] developing shotcrete printed elements for multi-storey structures in response to housing demand and emissions pressure. Li *et al*. [59] coupled construction phase LCA with performance validation in the automated assembly of timber arch shells, and Lai *et al*. [60] presented a meta model-based robotic approach that preserves traditional timber woodcraft.

Site robotics is more task-specific. Friese *et al*. [61] developed robot-assisted manufacturing of non-metallic reinforcement, and Feng *et al*. [13] designed a target recognition system for a rebar tying robot. Reviews of AI-driven robotics and automated planning describe the same direction, with gains in precision and safety but limited field evidence [62, 63]. Bühler *et al*. [1] proposed a hierarchical framework that links automation, robotics and AI to the productivity gap, which makes it one of the more integrative contributions in the sample. Baghi *et al*. [64] reviewed technologies in Solar Decathlon houses, including home automation, and Awosode *et al*. [65] examined automation in facility management in Lagos, which extends the literature into West Africa. Tajs-Zielińska and Bochenek [66] used topology optimisation, a computational rather than physical form of automation, which shows that “automation” carries both computational and robotic meanings in this field.

2.3. Artificial Intelligence and Machine Learning Applications in the Built Environment

AI research in this literature predates the recent BIM and robotics growth. Zhao *et al*. [67], the earliest AI-themed study in the sample, built a knowledge-based decision support system for enterprise risk management in Chinese construction firms. Since then, applications have spread across domains. In structures and materials, Razveeva *et al*. [68] applied convolutional neural networks to cracking in aerated concrete, Alhusban *et al*. [69] evaluated machine learning for fibre-reinforced polymer applications, Abed and Mehryaar [70] predicted the residual strength of recycled aggregate concrete after heat exposure, Trinh *et al*. [71] linked a neural network to embodied carbon optimisation, and Li *et al*. [72] coupled response surface methodology with a neural network for geopolymer grouting materials. Recognition and monitoring tasks include rebar counting from UAV imagery [73], point cloud segmentation with synthetic BIM and mixed reality data [74], and dataset generation for object detection through robotic process automation [75]. Liu *et al*. [76] and Lystbæk *et al*. [77] addressed building diagnosis and floor plan generation.

Broader reviews describe a similar breadth, together with persistent barriers in adoption, data readiness, ethics and trust [5, 6, 78-82]. A policy economics strand is also present. Li and Tang [83] examined how the digital economy affects green total factor productivity in the construction industry, a framing largely separate from the applied engineering studies. Smaller groups of studies relate AI to sustainability and circularity. Ghobadi and Sepasgozar [9] argued that AI is an under-realised enabler of circular practice in timber construction, Emad *et al*. [84] reviewed AI in tall building design, Kim [85] applied regression and case-based reasoning to environmental load and cost estimation in road construction, and Yoon and Hwang [86] analysed land shape typologies of apartment complexes with machine learning. Reported accuracy is often traded against interpretability [87], which matters for adoption.

2.4. Digital Twins, IoT, and the Convergence of Digital Construction Technologies

Digital twin and IoT research is the most recent strand in the sample. Lauria and Azzalin [88] proposed a digital twin for seismic safety across a building life cycle and presented it as an evolution of BIM. Abdelalim *et al*. [89] combined agent-based modelling, BIM and Bluetooth Low Energy sensing for resource positioning, which illustrates how digital twin work integrates several constructs at once. Ning *et al*. [90] examined digital twin technology in engineering education, and Tian and Wang [91] proposed a collaborative governance framework for smart communities. Wider reviews and surveys describe IoT- and AI-enabled twins as promising but unevenly implemented, particularly in developing economies [19, 20, 92, 93].

Deconstruction and end-of-life material recovery are core circular economy activities. Cabral *et al*. [94] developed a contactless multimodal sensing approach for material assessment and recovery during deconstruction. Studies outside the retrieved sample show that digital tools are being linked to demolition waste and life cycle impacts, for example, a BIM-driven digital twin for demolition waste management [95] and digital twins for dynamic LCA [96]. The circular economy evidence inside the sample is analysed in Section 6.2. Blockchain-enabled traceability is almost absent from the sampled construction literature. The only example, Zhang *et al*. [97], describes a smart water conservancy platform, which is civil water infrastructure rather than building construction. Studies outside the sample, however, have proposed BIM and blockchain frameworks for smart contracts and transparency [98, 99], so the thinness of this strand reflects the sample at least as much as the field.

3. Methodology

3.1. Data Source and Search Strategy

Bibliographic records were retrieved from Scopus for the period 2016 to 2025. The 2025 data reflect database coverage at the time of retrieval in 2025 and therefore represent a partial year. The exact date of the Scopus search was not recorded, so only the retrieval year can be reported. Because Scopus indexing is updated over time, a repeated search may not return an identical set of records. Scopus was chosen as the single database

because of its broad multidisciplinary coverage and its structured, exportable metadata (author, affiliation, abstract, citation count and keywords), which the screening and bibliometric analysis in Sections 4 and 5 required. Single database reviews with a fixed window are common in construction sustainability research, for example, the review by Wahab *et al*. [100] of agricultural ash supplementary cementitious materials from 2005 to 2025. That study is cited only as a methodological precedent. The pool of 494 records analysed here comes from a separate query and was not derived from the dataset of that review. The window 2016 to 2025 covers the period in which BIM moved from a niche coordination tool to a mainstream research theme [4] and in which AI, robotics and digital twin research accelerated (Section 4.1).

Table **1** reports the search protocol. The query combined the phrases “sustainable construction” and “construction innovation” and was limited to articles. It was not designed as a digital construction query. Two consequences follow. The pool probably underrepresents digital construction studies that do not use these phrases, such as work indexed only under building information modelling or digital twin. The conclusions also describe the retrieved sample and not the whole field. The review is therefore a secondary, targeted screening of the pool for digital technology content (Section 3.3), and the limitation is discussed in Section 8.

Table 1: Scopus search protocol used to build the pool of 494 records

Item	Specification
Database	Scopus (single database)
Search fields	Title, abstract and keywords (TITLE-ABS-KEY)
Search string	TITLE-ABS-KEY ("sustainable construction" OR "construction innovation") AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND DOCTYPE (ar)
Filters	Document type: Article; publication years: 2016 to 2025
Retrieval	2025 (exact date not recorded; 2025 is a partial year)
Records retrieved	494
Exported fields	Author, affiliation, abstract, citation count, keywords and source title

3.2. Eligibility Criteria

A record was eligible when its title, abstract or author and index keywords showed that at least one of the following constructs was a substantive element of the study, meaning its object, its analytical method or the enabling tool of its main contribution, in a context of buildings, the built environment or civil infrastructure: Building Information Modelling (BIM); artificial intelligence, machine learning or deep learning; robotics or automation; additive manufacturing, 3D printing or off site prefabrication; digital twins, IoT or smart building and smart city sensing; computer vision, UAV based monitoring or point cloud and SLAM monitoring; and blockchain enabled digital trust systems. Incidental mention of a construct was not sufficient. This construct-based approach is similar to that used by Anaç *et al*. [53] to bound the prefabricated construction risk literature and by Wahab *et al*. [100] to bound the literature on agricultural ash materials. Records were omitted when the keyword matched outside a construction context (for example, general industrial policy or non-construction robotics), and when the substantive focus was structural or seismic mechanics, real estate finance, urban social policy or materials chemistry without a digital technology component. Construction materials science is outside the scope of this review and is addressed in separate reviews, for example by Wahab *et al*. [100].

3.3. Screening and Selection Process

Screening followed four steps (Fig. **1**), adapting the logic of the PRISMA reporting framework for identification, screening, eligibility and inclusion, as in the construction focused review of Wahab *et al*. [100]. All 494 records were checked for duplicates by title and DOI, and none were found. The 494 records were then screened by title, abstract and keywords against the criteria in Section 3.2. This excluded 403 records and left 91 as potentially eligible. Each matched keyword in the 91 records was then verified in its context, following the practice of Anaç *et*

al. [53]. This verification found two false matches: a record in which "automation" belonged to an unrelated industrial policy paper, and a record on a desert greening tree planting vehicle in which "automatic" was unrelated to construction. Both were removed, leaving 89.

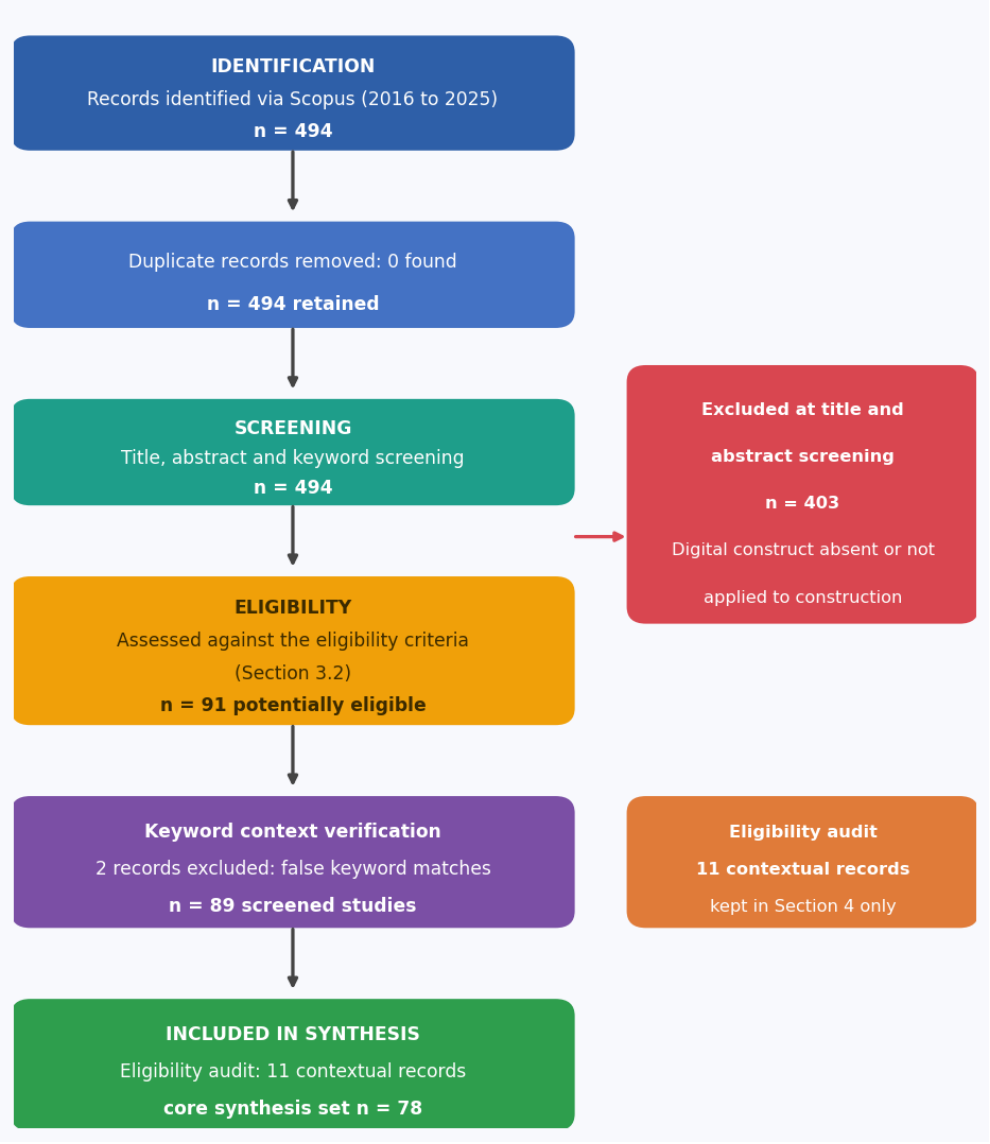


Figure 1: PRISMA flow diagram of record identification, screening, eligibility audit and inclusion.

Screening was performed by a single reviewer. The 403 exclusions (81.6% of the pool) have three scientific grounds. First, they follow from the design of the retrieval query. The query in Table **1** contained no digital technology term (Section 3.1), so records matched only on the phrases "sustainable construction" or "construction innovation", and a large share of the pool was expected to fall outside the scope of this review. Second, exclusion applied the construct based relevance test in Section 3.2, which asks whether a digital construct is a substantive element of a study in a built environment context. This is a test of relevance and construct validity. It was applied without reference to study quality, outcomes or the direction of findings, which limits selection bias linked to results. Third, the domains named in Table **2** are separate research fields with their own literatures and methods. Structural and seismic mechanics, real estate finance, urban social policy and materials chemistry address different research questions from those of digital technology adoption and application, and including them would have diluted the thematic synthesis and the maturity assessment. The pool did contain such material. Among the 11 contextual records that passed screening, the audit found studies on regional innovation ecosystems, college teaching innovation, aerated concrete properties and the seismic behaviour of precast walls (Section 3.4). Bounding a review by a substantive construct test is consistent with Anaç *et al*. [53] and Wahab *et al*. [100].

Two checks followed title and abstract screening: keyword context verification of the 91 potentially eligible records (Table **2**) and the eligibility audit of the 89 screened records (Section 3.4). Together they tested the retained records against the rules a second time and moved 13 of the 91 records out of the core synthesis (2 removed and 11 contextual), which leaves the 78 core studies. These checks address false inclusions. The exclusion decisions were made by one reviewer, and no independent check of the 403 excluded records was made, so the rate of wrongly excluded records is unknown. Only the include or exclude decision for each of the 494 records was retained, and it can be provided on request (Availability of Data and Materials). The exclusions are therefore justified at the level of the decision rules and cannot be audited record by record. This limitation is discussed in Section 8, together with the absence of independent dual screening.

Table 2: Screening stages, record counts and decision rules

Stage	Records	Decision rule
Identification	494	Scopus query in Table 1; articles only
Duplicate check	494 retained (0 removed)	Duplicates sought by title and DOI; none found
Title, abstract and keyword screening	91 retained; 403 excluded	Exclude when no construct from Section 3.2 is a substantive element in a construction or built environment context, or when the focus is structural or seismic mechanics, real estate finance, urban social policy or materials chemistry without a digital component.
Keyword context verification	89 retained; 2 excluded	Exclude keyword matches that are unrelated to construction (an industrial policy paper and a desert greening tree planting vehicle)
Eligibility audit (Section 3.4)	78 core; 11 contextual	Retain for synthesis only when a digital construct is the object, method or enabling tool of the main contribution; contextual records stay in Section 4 only.

3.4. Eligibility Audit and Core Synthesis Set

After screening, all 89 records were re-examined against Section 3.2 with one test: whether a digital construct is the object, the method or the enabling tool of the study's main contribution within a construction or built environment context. The audit used titles and the thematic codes in Appendix A. Eleven records did not meet the test. They are Hu *et al*. [101], on regional innovation ecosystems; Li *et al*. [102], on college teaching innovation, in which BIM is peripheral; Li *et al*. [103], on regional economic development; Wang *et al*. [104], on pilot zone policy and carbon emissions intensity; Yang *et al*. [105], on rural disaster emergency management; Jiang *et al*. [106], on furniture structures; Rudenko *et al*. [107], on aerated concrete properties; Zhong *et al*. [108], on seismic behaviour of precast walls; Zhao *et al*. [109], on fibre reinforcement materials; Böhm *et al*. [110], on the physical reuse of salvaged timber; and Giorgi *et al*. [111], on reuse and remanufacturing pilots. Table A2 gives the reason for each record, together with six borderline records that were retained because they met the test through computational automation, home automation, digital economy analysis in the construction industry, smart community sensing, digital twin teaching or machine learning applied to the built environment.

The 11 contextual records stay in the descriptive profile of the screened sample (Section 4), for which metadata were extracted, but they are excluded from the thematic synthesis, the maturity assessment and the gap analysis (Sections 5 to 7), which use the core set of 78 studies. Where an indicator in Section 4 can be recomputed from Appendix A, the core set value is given alongside the value for the 89 screened studies. Author affiliations were not re-extracted for the core set, so Section 4.4 refers to the 89 screened studies. Böhm *et al*. [110] and Giorgi *et al*. [111] remain in the circular economy classification (Section 3.6), because they are relevant as circularity evidence that does not involve a digital tool.

3.5. Thematic Classification Approach

Studies were coded on a non exclusive, multi label basis into nine thematic categories that were developed inductively from titles, abstracts and keywords: (1) BIM for design, coordination and compliance; (2) robotics, automation and additive manufacturing or prefabrication; (3) AI, machine learning and deep learning applications; (4) BIM for sustainability, energy and life cycle assessment; (5) digital twins, IoT and smart monitoring; (6)

computer vision, UAV and point cloud or SLAM based monitoring; (7) adoption, barriers and institutional or behavioural studies; (8) digital risk, cost and decision support; and (9) blockchain and digital trust or traceability. A label was assigned when the construct was a substantive element of the title, abstract or keywords, using the same test as in Section 3.2. Labels therefore record the presence of a construct and not the depth of its treatment, and the category counts are upper bounds on each theme's primary focus. For example, Zhao *et al*. [67] carries the AI and the risk and decision support labels because it combines knowledge-based reasoning with enterprise risk management. Vassena *et al*. [112] carries the BIM and the computer vision and SLAM labels because it integrates 4D BIM with SLAM-based mapping devices.

In total, 45 of the 89 screened studies (50.6%) and 43 of the 78 core studies (55.1%) carry more than one label. Multi labelling is therefore common but not universal. The approach is consistent with bibliometric and content analytic methods used in the reviewed literature [53, 64, 84] and with the category-based synthesis of Wahab *et al*. [100].

3.6. Circular Economy Classification

A record was classed as circular economy related if its title, abstract or keywords explicitly addressed circular economy, reuse, remanufacturing, material recovery, deconstruction or waste minimisation. General sustainability, LCA, energy performance and SDG framing did not qualify on their own, because they address broader outcomes. Qualifying records were assigned one of three evidence levels. Level 1 covers a digital tool applied to a material recovery or waste outcome in an empirical or modelling design. Level 2 covers conceptual, expectation-based, or review-level treatment of digital technology and circularity or waste. Level 3 covers circularity or waste outcomes where a digital tool is not the object of study. The classification was applied to all 89 screened records so that the proportion has a reproducible basis, and the result is reported in Section 6.2.

3.7. Note on Methodological Limitations

This is a narrative review and not a fully systematic, PRISMA-compliant review. No risk of bias or study quality instrument was applied; only one database was searched, and screening was done by a single reviewer using keyword matching with verification of keyword context (Section 3.3), instead of independent dual review. Dedicated systematic reviews of a narrow technical question, such as the review by Wahab *et al*. [100], can apply a tightly structured screening protocol because their subject is consistently defined. The subject of the present review is broad and fast-moving, spanning BIM, AI, robotics, digital twins and automation (Section 3.5), which complicates an equivalent protocol and is the main reason a narrative design was chosen. These constraints are discussed in Section 8 and should be kept in mind when interpreting the synthesis.

3.8. Use of AI Tools in the Review Process

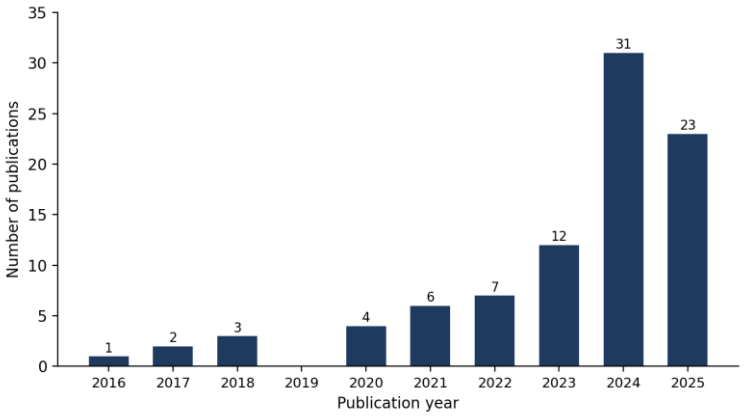
In accordance with journal policy on the disclosure of artificial intelligence (AI) tools, the authors confirm that Python (version 3.11, using the Matplotlib and Seaborn visualisation libraries) was used to process the bibliographic metadata exported from Scopus and to generate the bibliometric charts and graphical elements reported in Section 4. Python was not used to identify, screen, select or interpret the literature reviewed in Sections 2, 5 and 6; the screening decisions, thematic classification and critical synthesis were carried out by the authors, with screening done by a single reviewer (Section 3.3). Grammarly and QuillBot were used only for language editing and proofreading of text written by the authors, as stated in the Acknowledgement. No generative AI tool was used to draft the analytical or interpretive content of this manuscript.

4. Bibliometric Results

This section profiles the 89 screened studies. Where an indicator can be recomputed from Appendix A, the value for the 78 core studies (Section 3.4) is also given.

4.1. Publication Trend

Output is concentrated in the most recent years (Fig. **2**). Between 2016 and 2019, only six of the 89 studies (6.7%) were published (1, 2, 3 and 0 studies in each year). Output then rose from 2020 to 2022 (4, 6 and 7 studies) and increased sharply from 2023 onward. In all, 66 studies (74.2%) were published from 2023 to 2025, and 2024 was the largest year with 31 studies. In the core set, 57 of 78 studies (73.1%) fall in the same period. This pattern is typical of an emerging research area and not a consolidated one. It has a methodological implication that is taken up in Section 6: a young literature has had little time to accumulate citations, to be replicated or to be tested against alternative findings.



Note*:* The apparent partial decline in 2025 reflects database indexing lag and the partial year of retrieval, and not an actual reduction in research activity.

Figure 2: Annual publication trend of the screened studies (N = 89), 2016 to 2025.

4.2. Journal Distribution

Publications are clearly clustered (Fig. **3**). Buildings (37 studies, 41.6%) and Sustainability (32 studies, 36.0%) together account for 69 of 89 studies (77.5%). Both are open access journals published by MDPI. In the core set, the two journals account for 60 of 78 studies (76.9%). The remaining 20 screened studies (22.5%) are spread over six journals: Journal of Cleaner Production (6 studies, including Akinade *et al*. [2]), Journal of Building Engineering (6 studies, including Olawumi *et al*. [12]), Journal of Construction Engineering and Management (4 studies, including Wang *et al*. [73]), Engineering, Construction and Architectural Management (2 studies, including Demirkesen and Tezel [17]), and one study each in Construction and Building Materials and Construction Innovation. The implications of this concentration for editorial and disciplinary homogeneity are considered in Section 6.4.

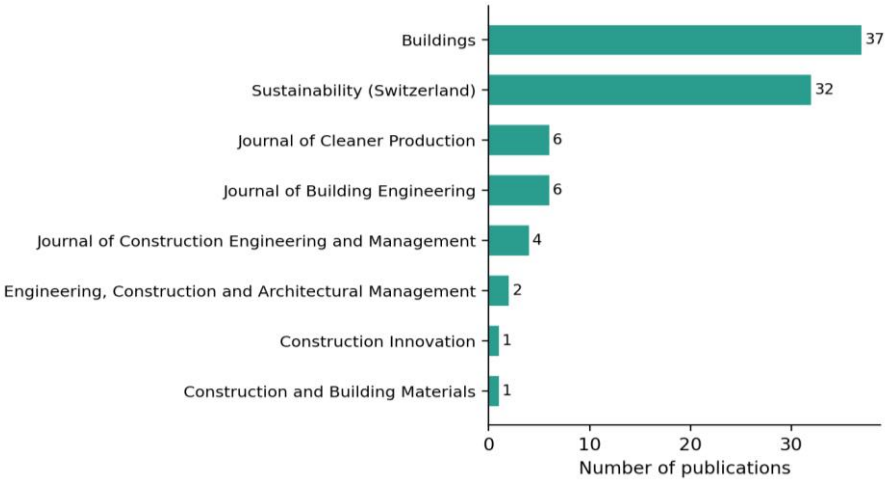


Figure 3: Leading source journals in the screened studies (N = 89).

4.3. Citation Impact

The 89 studies had accumulated 2,623 citations at the time of extraction, with a mean of 29.5 and a median of 13 citations per study. The large gap indicates a right-skewed distribution driven by a few highly cited early papers. The core set shows the same pattern (2,479 citations, mean 31.8, median 13). The most cited study was Akinade *et al*. [2] with 241 citations for its work on designing out construction waste with BIM, followed by Alwan *et al*. [3] with 235 and Alhumayani *et al*. [54] with 233. Table **3** lists the ten most cited studies. All ten belong to the core set.

Table 3: Ten most cited studies in the screened sample, by citation count at the time of extraction

Study	Citations	Journal	Focus
Akinade *et al*. [2]	241	J. Cleaner Production	BIM for designing out construction waste
Alwan *et al*. [3]	235	J. Cleaner Production	Strategic sustainable development, UK construction
Alhumayani *et al*. [54]	233	J. Cleaner Production	Environmental assessment of large-scale 3D printing
Olawumi *et al*. [12]	209	J. Building Engineering	Barriers to integrating BIM and sustainability
Demirkesen and Tezel [17]	183	Eng., Constr. & Arch. Mgmt	Industry 4.0 adoption challenges
Kaewunruen *et al*. [30]	137	Sustainability	BIM-based life cycle management, bridge infrastructure
Jayawardana *et al*. [113]	100	J. Building Engineering	LCA of prefabricated vs traditional construction
Chen *et al*. [49]	93	Buildings	LLM-based automated BIM compliance checking
Volpe *et al*. [55]	65	Sustainability	3D printed prefabricated building envelopes
Wang *et al*. [73]	63	J. Constr. Eng. & Mgmt	Deep learning rebar counting model

4.4. Geographic Distribution

Two counting units are used in this section, and they answer different questions. The study count is the number of studies with at least one author affiliated with a given country, so each study counts once per country. The coauthorship count in Fig. (**4**) is the number of author affiliations from a country, so a study with three Chinese-affiliated authors adds three. On the study count, authors affiliated with China appear on 33 of the 89 studies (37.1%), including Zhao *et al*. [67], Deng *et al*. [23] and Ma *et al*. [25], and authors affiliated with the United Kingdom appear on 19 (21.3%), including Alwan *et al*. [3] and Akinade *et al*. [2]. On the coauthorship count, Fig. (**4**) shows 70 affiliations for China and 27 for the United Kingdom, followed by Germany (18), Australia (17) and the United States (13). Contributing institutions span 35 countries. A single multi-author, multi-country paper adds to several countries, so counts exceed the number of studies. Affiliation data refer to the 89 screened studies (Section 3.4).

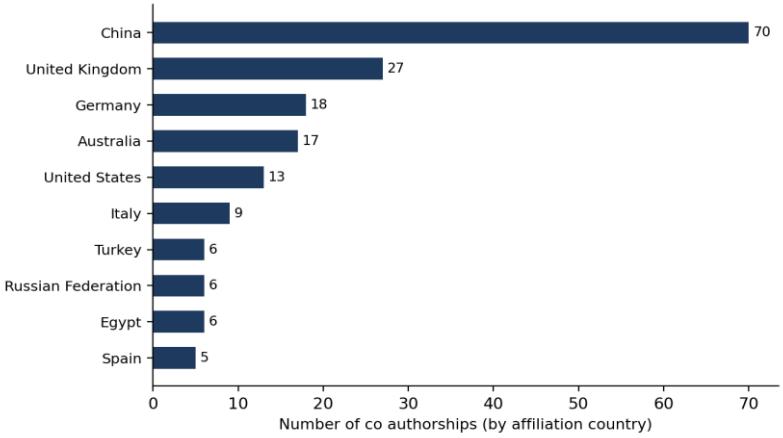


Figure 4: Geographic distribution of contributing institutions, by country of author affiliation (co-authorship counts, top 10 shown).

Author affiliation indicates where authors work and not where the buildings, firms or datasets studied are located. Study location was not coded, so affiliation is used here only as an imperfect proxy for context. The concentration is not problematic in itself. China's construction sector is large, and BIM adoption in China is the setting of several of the reviewed studies, for example Wu *et al*. [22] and Rui *et al*. [24]. This means that findings on BIM adoption barriers or robotics deployment may reflect regulatory, labour market and industry structure conditions in a few national settings. Studies with an explicit national setting outside this group, such as Oke *et al*. [114] in Nigeria, Dagou *et al*. [50] in Chad, Nabawy *et al*. [31] in Egypt, Asfandyar *et al*. [37] in Pakistan and Rashidi *et al*. [42] in Iran, are few. Work from Ghana, Rwanda, Nigeria, Indonesia, Vietnam and Mexico appears in the wider literature [19, 20, 115-119] but is largely absent from the sampled records, which suggests that the sample underrepresents these settings (Section 6.4).

5. Results: Thematic Synthesis

Nine overlapping thematic strands were identified through inductive coding of the 78 core studies (Fig. **5**, Table **4**). Because 43 of the 78 studies carry more than one label, category counts sum to 152. The three largest strands are BIM for design, coordination and compliance (39 studies), robotics, automation and additive manufacturing (30) and AI and machine learning applications (24). Blockchain-enabled applications form a single study strand (1 study). Counts record the presence of a construct in a study's metadata and not the depth of its treatment (Section 3.5). Each subsection below compares studies within a strand and states what the evidence supports.

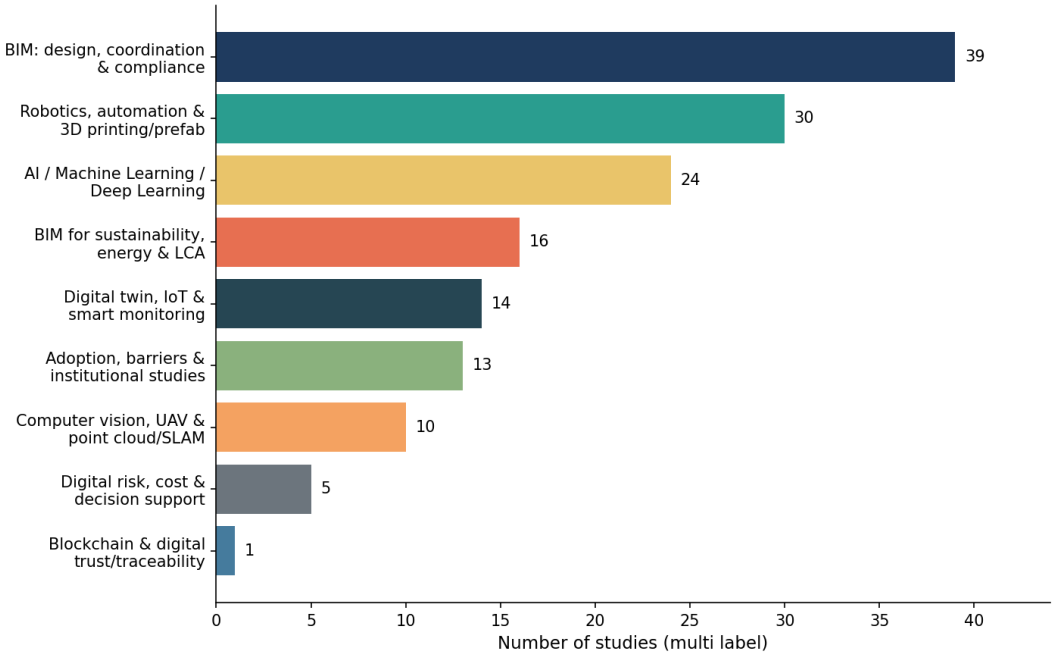


Figure 5: Thematic distribution of the core studies (n = 78; multi label coding).

5.1. BIM for Design, Coordination and Regulatory Compliance

The largest strand (39 studies) centres on BIM's traditional functions of design coordination and, more recently, automated compliance checking. Its most cited study, Akinade *et al*. [2], set an early waste reduction framing, and Alwan *et al*. [3] and He *et al*. [28] extended BIM to sustainable development policy and online procurement. Adoption studies in this strand rely on modelling or network methods, for example, system dynamics [23] and social network analysis [22]. The clearest developmental line runs from descriptive adoption research to AI-augmented BIM. Chen *et al*. [49] combined a large language model, deep learning and ontology reasoning to automate compliance checking, which shifts BIM from a coordination platform to an input for downstream reasoning. Reviews of BIM and AI note that interoperability still limits such integration [8]. The evidence is therefore mature for coordination and adoption questions and still early for automated compliance.

Table 4: Thematic Synthesis Summary Showing Category Size and Representative Studies

Theme	n	Representative studies
BIM: design, coordination & compliance	39	Akinade *et al*. [2]; Alwan *et al*. [3]; Chen *et al*. [49]
Robotics, automation & 3D printing/prefab	30	Alhumayani *et al*. [54]; Jayawardana *et al*. [113]; Volpe *et al*. [55]
AI/machine learning/deep learning	24	Wang *et al*. [73]; Zhao *et al*. [67]; Chen *et al*. [49]
BIM for sustainability, energy & LCA	16	Kaewunruen *et al*. [30]; Yardımcı and Kurucay [29]; Piaia *et al*. [34]
Digital twin, IoT & smart monitoring	14	Lauria and Azzalin [88]; Liu *et al*. [45]; Cabral *et al*. [94]
Adoption, barriers & institutional studies	13	Olawumi *et al*. [12]; Demirkesen and Tezel [17]; Oti-Sarpong *et al*. [18]
Computer vision, UAV & point cloud/SLAM	10	Vassena *et al*. [112]; Feng *et al*. [13]; Araya-Aliaga *et al*. [75]
Digital risk, cost & decision support	5	Amin Ranjbar *et al*. [40]; Zhao *et al*. [67]; Abdelalim *et al*. [89]
Blockchain & digital trust/traceability	1	Zhang *et al*. [97]

Note: Counts are multi-label, so n sums to 152, more than the 78 core studies, because many studies cover more than one construct. Counts are based on the coding record in Appendix A.

5.2. Robotics, Automation and Additive Manufacturing

The second strand (30 studies) covers construction robotics, additive manufacturing and prefabrication. A notable feature is its overlap with life cycle environmental assessment. Alhumayani *et al*. [54] compared 3D printing with cob and concrete construction, and Jayawardana *et al*. [113] compared prefabricated and traditional construction in a developing country. In both cases, the sustainability argument for automation rests mainly on environmental comparison and less on productivity or cost evidence. Volpe *et al*. [55] extended printing to building envelopes, and task-specific robotics such as the rebar tying system of Feng *et al*. [13] point to targeted solutions for labour-intensive tasks. Most of these studies are prototype or laboratory demonstrations, and full-scale multi-project deployment evidence is scarce [62,63].

5.3. Artificial Intelligence and Machine Learning Applications

Twenty-four core studies use AI, machine learning or deep learning, from component recognition to enterprise risk management. A common pattern pairs a data capture technology (UAV, sensor or point cloud) with a supervised model for a tightly defined recognition task, as in the rebar counting model of Wang *et al*. [73]. The earliest AI-themed study, Zhao *et al*. [67], shows that AI-related decision support predates the recent surge, although output has risen sharply since 2022. Broader reviews report a similar emphasis on narrow prediction and recognition tasks [5,6]. Performance in the sampled studies is typically described by accuracy or related metrics. Because no study-level appraisal was performed, this review cannot state how many AI studies include validation on independent data or comparison with non-AI baselines. The point is therefore treated as a hypothesis for future appraisal and not as a finding (Section 6.3).

5.4. BIM-Enabled Sustainability, Energy and Life Cycle Assessment

Sixteen core studies link BIM to sustainability measurement, most often through LCA embedded in or coupled with BIM models. Kaewunruen *et al*. [30] extended BIM beyond 3D, 4D and 5D into sustainability tracking through 6D BIM for bridges, a conceptual extension echoed by the Green BIM framework of Nabawy *et al*. [31]. Yardımcı and Kurucay [29] integrated LCA with TOPSIS to minimise material waste, which makes it one of the few studies that connect a digital tool to a waste outcome (Section 6.2). Piaia *et al*. [34] addressed life cycle quality assurance for nearly zero energy buildings, and Ullah *et al*. [33] applied BIM energy analysis to low carbon design in hot climates, which widens the climatic range beyond the temperate settings of much of the literature. Most studies in this strand propose or test frameworks within a single project or country, and few measure outcomes after construction.

5.5. Digital Twins, IoT and Smart Monitoring

Fourteen core studies address digital twins, IoT sensing or smart monitoring platforms. The strand is recent: 12 of the 14 studies (85.7%) were published from 2024 onward, and the earliest, Demirkesen and Tezel [17] in 2022, is an adoption study coded for IoT. Lauria and Azzalin [88] proposed a digital twin for seismic safety, Liu *et al*. [45] combined immersive technology with BIM for smart cities, and related work by Liu *et al*. [46, 47] addressed SDG-oriented business models and transport and facilities integration. Cabral *et al*. [94] linked sensing to material recovery during deconstruction. The conceptual diversity and recency suggest that this strand is still in an exploratory, framework-proposing phase. Wider surveys report IoT benefits and implementation barriers in several developing economies [19, 20, 92], which this sample does not capture.

5.6. Adoption, Barriers and Institutional and Behavioural Studies

Thirteen studies examine why digital technologies are or are not adopted. The strand contains two of the most cited studies in the sample: Olawumi *et al*. [12], a Delphi survey of international experts on barriers to integrating BIM and sustainability (209 citations), and Demirkesen and Tezel [17] on Industry 4.0 adoption challenges (183 citations). Oti-Sarpong *et al*. [18] argued from an institutional complexity perspective that barriers are as organisational and regulatory as technical. Oke *et al*. [114] extended the topic to a developing economy and found opportunities and constraints different from those in higher-income settings. Studies outside the sample report similar and context-specific barriers for AI and IoT in Rwanda, Nigeria, Indonesia and Vietnam [20, 115-118]. The prominence of this strand shows sustained interest in the adoption gap itself, which Section 6.6 examines.

5.7. Computer Vision, UAV and Point Cloud or SLAM-Based Monitoring

Ten core studies use computer vision, UAV imagery or SLAM for progress monitoring and quality inspection. Vassena *et al*. [112] integrated 4D BIM with SLAM-based mapping, which links the strand to BIM. Araya-Aliaga *et al*. [75] addressed the scarcity of labelled construction image datasets by combining AI with robotic process automation. Moohialdin *et al*. [120] extended sensor-based monitoring from progress tracking to worker exposure in hot and humid weather, and Razveeva *et al*. [68] applied convolutional neural networks to crack detection in aerated concrete, an application at the boundary with materials inspection. Reviews of AI in construction safety describe the same shift towards worker monitoring [121]. All ten studies date from 2023 or later, and most are applied prototypes tested on limited image sets.

5.8. Digital Risk, Cost and Decision Support Systems

Five core studies apply digital tools to risk and cost management. Amin Ranjbar *et al*. [40] developed a 5D BIM cash flow risk framework, Zhao *et al*. [67] combined knowledge-based reasoning with enterprise risk management, and Abdelalim *et al*. [89] used agent-based modelling with a digital twin and Bluetooth Low Energy sensing to locate resources. Although the strand is small, it shows a recurring feature: decision support applications usually combine several constructs, such as BIM, AI and IoT, and do not act as a single technology. This supports the discussion of technological convergence in Section 6.5.

6. Discussion

6.1. Technology Maturity and Evidentiary Strength

Table **5** compares the nine themes using three explicit indicators calculated from Appendix A for the core set: the number of studies, the earliest publication year, and the share of studies published from 2023 to 2025. The median citation count and the predominant evidence type (framework proposals, applied demonstrations, surveys or modelling) are added for context. Indicative stages follow a fixed rule. A theme with a single study is pre-emergent. A theme with fewer than ten studies is niche. Otherwise, a theme is established if its earliest study is from 2018 or before and fewer than 70% of its studies are from 2023 to 2025. It is growing if its earliest study is from 2020 or before and 70% or more are from 2023 to 2025. It is emergent if its earliest study is from 2022 or

later. The stages describe temporal depth and volume and are not a judgement of study quality, because no formal quality appraisal was performed (Section 3.7). Publication counts, recency and citations alone cannot establish maturity, so the evidence type and key limitation columns qualify the stage.

On these indicators, BIM for design and coordination and the adoption strand are established. Robotics and additive manufacturing, AI and machine learning, and BIM for sustainability are growing, with AI output concentrated almost entirely in the last three years (96%). Digital twins and computer vision are emergent. Digital risk and decision support are niche, and blockchain is pre-emergent with a single study.

Table 5: Comparative assessment of technology theme maturity and evidentiary characteristics (core set, n = 78)

Technology Theme	Indicators (Core Set)	Predominant Evidence Type	Indicative Stage	Key Limitation
BIM: design, coordination & compliance	n = 39; first study 2017; 69% from 2023 to 2025; median citations 13	Adoption surveys; applied case studies; recent AI-augmented tools	Established	Automated compliance checking still nascent; interoperability constraints [8]
Robotics, automation & 3D printing/prefab	n = 30; first study 2020; 80% from 2023 to 2025; median citations 12.5	Comparative LCA and environmental studies; prototype demonstrations	Growing	Few full-scale, multi-project deployments
AI/machine learning/deep learning	n = 24; first study 2016; 96% from 2023 to 2025; median citations 12.5	Single dataset model development and application studies	Growing	Validation practice not quantified at study level; treated as a hypothesis (Section 6.3)
BIM for sustainability, energy & LCA	n = 16; first study 2020; 88% from 2023 to 2025; median citations 10.5	BIM and LCA integration frameworks; regulation-aligned case studies	Growing	Few studies address waste or circularity outcomes explicitly
Digital twin, IoT & smart monitoring	n = 14; first study 2022; 93% from 2023 to 2025; median citations 10.5	Conceptual frameworks; early pilot proposals	Emergent	No mature, validated large-scale deployment evidence
Adoption, barriers & institutional studies	n = 13; first study 2018; 62% from 2023 to 2025; median citations 12	Delphi surveys; expert interviews; institutional theory analysis	Established	Barrier findings possibly context-specific (Section 6.4)
Computer vision, UAV & point cloud/SLAM	n = 10; first study 2023; 100% from 2023 to 2025; median citations 14.5	Applied prototype systems; accuracy and detection metrics	Emergent	Small, often single-site image datasets
Digital risk, cost & decision support	n = 5; first study 2016; 60% from 2023 to 2025; median citations 36	Framework and model development with illustrative case application	Niche	Very low study volume (n = 5)
Blockchain & digital trust/traceability	n = 1; first study 2020; 0% from 2023 to 2025; median citations 30	Single descriptive case (non-building infrastructure)	Pre emergent	Essentially no building construction evidence in the sample

6.2. The Circular Economy Disconnect

Circular economy outcomes are often cited as a benefit of digital technologies (Section 1.1), so the link was tested explicitly under RQ3. Applying the criteria in Table **6**.

Several other studies that touch on sustainability were not counted because they address broader outcomes. Jayawardana *et al*. [113] is an LCA comparison of prefabricated and traditional construction without an explicit circularity metric, and Liu *et al*. [47] proposes a business model oriented to the SDGs. These are adjacent to the circular economy and should not be read as evidence of measured circular outcomes. The headline finding is accordingly stated narrowly: within the retrieved sample, empirical evidence that links digital tools to measured circular economy outcomes is very limited (two studies). Two limits apply. First, the pool was retrieved with a

general query on sustainable construction and construction innovation, which was not designed to capture digital construction research (Section 3.1). The low count therefore applies to the retrieved sample and may partly reflect the search strategy, so it should not be read as a measure of the whole field. Second, studies outside the sample already connect digital twins to demolition waste and life cycle impacts [95, 96], and Ding *et al*. [11] and Elmousalami *et al*. [10] report AI applications for carbon and sustainability management. A review or policy document that presents a mature evidence base for digitally enabled circularity should therefore be read with caution, and the gap identified here is best seen as a priority for targeted searches.

Table 6: Classification of circular economy related records (screened sample, N = 89)

Study	Year and Digital Construct	Circular Economy or Waste Focus	Evidence Level
Cabral *et al*. [94]	2025; multimodal sensing	Material assessment and recovery in building deconstruction	Level 1
Yardımcı and Kurucay [29]	2024; BIM with LCA and TOPSIS	Minimising material waste	Level 1
Ghobadi and Sepasgozar [9]	2025; AI	Challenges and benefits of AI for circular economy goals in timber construction	Level 2
Akinade *et al*. [2]	2018; BIM	Designing out construction waste; stakeholder expectations	Level 2
Böhm *et al*. [110]	2025; digital tool not the object	Cascading reuse potential of salvaged timber rafters	Level 3 (contextual record)
Giorgi *et al*. [111]	2025; digital tool not the object	Reuse and remanufacturing pilot projects	Level 3 (contextual record)

6.3. Methodological Patterns and Limited External Validation

Using abstract-level coding of the 89 screened records, 16 studies (18.0%) rely mainly on surveys, questionnaires, Delphi panels or expert interviews, and these are mostly in the adoption strand (Section 5.6), for example Olawumi *et al*. [12] and Wu *et al*. [22]. A further 19 studies (21.3%) are framed as case studies or pilots, which show feasibility but rarely test generalisability across sites, contractors or regulatory settings, as in the single city or single country designs of Deng *et al*. [23] and Rashidi *et al*. [42]. These counts come from abstract-level reading and not full-text appraisal, and they should be read as approximate. Twelve studies (13.5%) are reviews or bibliometric analyses, for example Anaç *et al*. [53], Baghi *et al*. [64] and Emad *et al*. [84]. A considerable share of output is therefore synthesis of earlier work and not new primary evidence, which can make the evidence base look more mature than its primary studies are. Together, the 19 case studies or pilots and the 16 survey based studies account for 35 of the 89 screened records (39.3%). These designs are therefore common, but this share does not by itself show that they dominate the evidence base. No count of longitudinal or multisite studies is reported here, so their limited presence is an impression from abstract level reading and not a quantified finding. Full text appraisal would be needed to test it.

For AI and machine learning studies, the concern about validation could not be quantified. Because no study-level appraisal was done, the review cannot report how many AI studies use external validation or non-AI baselines, so the absence of such practices cannot be claimed as a finding. It remains a plausible hypothesis for three reasons drawn from the wider literature: reviews of AI in construction describe narrow, task-specific applications [5, 6], work on schedule prediction highlights the tension between accuracy and interpretability [87], and studies of data readiness and trustworthy AI point to weak data foundations and assurance practices [80, 82]. Formal appraisal of AI studies, using criteria such as dataset independence and baseline comparison, is a priority for future work (Section 7).

6.4. Geographic and Editorial Concentration

Two risks arise. The first is geographic. At least one China-affiliated author appears on 37.1% of the 89 screened studies, and at least one UK-affiliated author on 21.3% (study counts; Section 4.4). Findings on adoption

barriers, regulatory drivers and institutional dynamics (Section 5.6) may therefore be shaped by a few national settings. Barrier findings from Demirkesen and Tezel [17] or Olawumi *et al*. [12] should not be assumed to transfer to sectors with different contracting norms, workforce structures or regulation, and the primary studies seldom state this caveat. Comparative studies such as Rui *et al*. [24] are exceptions. Research from African, Southeast Asian and Latin American settings exists [19, 20, 115-119], and its limited presence in the sample suggests that the retrieval route, and not only research activity, contributes to the concentration. Because affiliation is not study location, generalisability statements rest on this proxy and on the few studies with explicit national settings.

The second risk is editorial. Of the 89 screened studies, 77.5% appeared in two MDPI open access journals, Buildings and Sustainability. The visible output may therefore reflect the editorial scope, review practices and publication speed of these outlets more than a diversified venue profile would. This says nothing directly about the rigour of any single paper, but the literature is less editorially and disciplinarily diverse than the study count suggests.

6.5. Technological Fragmentation and Limited Integration Studies

Although many studies carry several labels (Section 3.5), integration studies that evaluate two or more digital technologies as one interacting system remain rare. Exceptions include Vassena *et al*. [112] (4D BIM and SLAM), Chen *et al*. [49] (BIM, a large language model and ontology reasoning), Abdelalim *et al*. [89] (digital twin, Bluetooth Low Energy and agent-based modelling) and Bühler *et al*. [1] (automation, robotics and AI in one productivity framework). Most studies address one construct largely on its own, for example, the BIM and sport facility review of Liu *et al*. [122]. Real projects, however, would need to combine BIM, sensing, AI and robotics to approach the Construction 4.0 vision in Section 1.1. This fragmentation is an important gap between what researchers publish and what policy and industry discussions describe as integrated systems.

6.6. The Innovation Adoption Gap

The adoption strand (Section 5.6) includes two of the five most cited studies in the sample (Table **3**), which indicates continued interest in why digital technologies are not adopted at scale despite more than a decade of applied research showing technical feasibility. This creates a mismatch within the literature. The applied and technical strands (Sections 5.1 to 5.3 and 5.7) mostly show that technologies work in controlled or pilot contexts, while the adoption strand reports organisational, regulatory and behavioural obstacles at scale. Few studies bridge the two by following one technology from pilot to documented industry-scale deployment. As a result, barriers identified in surveys can seldom be tested against longitudinal adoption paths. Context-specific adoption studies outside the sample, such as those on Rwanda, Nigeria and Indonesia [115-117], suggest that the barriers also vary by setting.

7. Research Gaps and Future Research Agenda

Table **7** lists six priority research gaps identified in the core set. For each gap, it gives the evidence basis and a recommendation for future work. Each gap describes the sampled literature, and the gaps on circular economy linkage and blockchain in particular should be tested with targeted searches before they are treated as gaps in the field.

Two broader methodological recommendations follow from Section 6.3. First, future primary studies should use preregistered protocols, or at least clearly justified sampling and validation designs, because case studies, pilots and single dataset model development are common in the sample (Section 6.3). Second, future systematic reviews should apply formal quality appraisal tools, for example adapted CASP or MMAT criteria, and should combine multiple databases with citation tracking, so that readers can weigh findings by methodological strength and can separate gaps in research activity from gaps in retrieval.

Table 7: Identified Research Gaps, Supporting Evidence, and Recommended Future Research Directions

Gap	Evidence from the Reviewed Literature	Recommended Future Research
Thin digital technology and circular economy linkage	Six of 89 screened records (6.7%) address circularity or waste; four involve a digital tool; two apply a digital tool to a material recovery or waste outcome (Table 6)	Empirical studies that measure material recovery, reuse or waste reduction attributable to specific digital tools, and targeted searches to test whether the gap extends beyond this sample
Validation practice in AI and machine learning not established	Reviews describe narrow, task specific AI applications [5,6]; study level validation was not appraised here	Appraisal of validation practice in AI studies; multi-site validation; comparison against non-AI methods; open benchmark datasets
Missing integration studies	Most studies address one construct on its own; multi-technology integration studies are exceptions (Section 6.5)	Field studies evaluating combined BIM, sensing, AI and robotics systems as interacting pipelines
Adoption research disconnected from deployment evidence	Adoption and barrier studies (survey- and Delphi-based) rarely follow technologies to documented industry-scale deployment	Longitudinal studies following specific technologies from pilot to scaled deployment, testing whether identified barriers predict adoption outcomes
Geographic concentration	At least one China-affiliated author on 37.1% of the 89 screened studies and one UK-affiliated author on 21.3%; sparse explicit settings in Africa, Latin America and Southeast Asia within the sample (Section 4.4)	Comparative cross-national studies that test whether adoption barriers and technology performance generalise across institutional contexts, with study location recorded separately from author affiliation
Blockchain evidence in building construction not found in the sample	One blockchain study in the sample [97], on water infrastructure; BIM and blockchain studies exist outside the sample [98,99]	Supplementary searches and citation tracking to establish field-level evidence; applied blockchain pilots in building supply chains, procurement or material traceability with reported outcomes

8. Limitations of This Review

Several limitations should be considered. Each affects how far the findings can be generalised.

Single database: Only Scopus was searched. Other sources, such as Web of Science, IEEE Xplore and regional or non-English databases, may index relevant work, and their omission could understate work from areas with less Scopus coverage.

Query design: The pool was retrieved with a query on sustainable construction and construction innovation and not with a digital construction query (Table **1**). It probably omits digital studies that do not use these phrases. Findings describe the retrieved sample, and absences such as the single blockchain study or the sparse circular economy linkage may partly reflect retrieval and not research activity. Supplementary searches and citation tracking would be needed to separate the two. In this review, related studies outside the sample were consulted only to test whether the gaps were likely to be artefacts of retrieval [95, 96, 98, 99].

Single reviewer screening: Screening and coding were done by one reviewer without independent verification, and the reasons for the 403 exclusions were not recorded. No exclusion log or other supporting documentation was kept apart from the include or exclude decision for each record, so the exclusions cannot be audited at reason level or reproduced exactly. No independent check of the excluded records was made, so the rate of wrongly excluded records is unknown. Some inclusion and exclusion decisions may therefore be subjective, although the rules in Section 3.2 were applied throughout by the same reviewer and the eligibility audit (Section 3.4) was carried out to reduce inconsistency.

Retrieval date: The exact date of the Scopus search was not recorded, and only the retrieval year (2025) is reported in Table **1**. Scopus indexing changes over time, so a repeated search may return a different set of records, and the 2025 coverage is partial.

Coding depth and appraisal: Thematic labels and study design categories were assigned from titles, abstracts and keywords and record the presence of a construct, not the depth of treatment. No quality or risk of bias appraisal was performed, and maturity stages in Table **5** describe temporal depth and volume only. Validation practice in AI studies could not be quantified.

Affiliation and timing: Affiliation is not study location, and affiliations were not re-extracted for the core set. Citation counts depend on time since publication and favour older studies, and 2025 is a partial year.

9. Conclusion

This review mapped the peer-reviewed literature on digital technologies in construction within a Scopus pool of 494 records, from which 89 articles were screened, and 78 core studies were synthesised. The sample is young and growing quickly (74.2% of screened studies from 2023 to 2025), is concentrated in two MDPI journals, and has author affiliations concentrated in China and the United Kingdom. BIM for design and coordination, robotics and additive manufacturing, and AI and machine learning are the largest strands, while digital twins and computer vision are emergent and blockchain is represented by a single study. These statements describe the retrieved sample and not the whole field. The evidence linking digital technologies to circular economy outcomes is very limited in the retrieved sample, and this may partly reflect the search strategy. Six records address circularity or waste, only four involve a digital tool, and two apply one to a measured material recovery or waste outcome. Methodologically, case studies, pilots and cross sectional surveys are common (35 of the 89 screened records), whereas longitudinal evidence and studies that integrate several technologies appear limited, and validation practice in AI studies remains to be appraised. None of this denies the real progress of the last decade. It does call for a more disciplined, integration-oriented and empirically grounded agenda that tests whether claims about circularity, scalability and transfer across contexts hold, using multiple databases, citation tracking and formal appraisal.

List of Abbreviations

AI	=	Artificial Intelligence
BIM	=	Building Information Modelling
IoT	=	Internet of Things
UAV	=	Unmanned Aerial Vehicle
SLAM	=	Simultaneous Localisation and Mapping
LCA	=	Life Cycle Assessment
TOPSIS	=	Technique for Order of Preference by Similarity to Ideal Solution
PRISMA	=	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RQ	=	Research Question
SDG	=	Sustainable Development Goal
MDPI	=	Multidisciplinary Digital Publishing Institute
CASP	=	Critical Appraisal Skills Programme
MMAT	=	Mixed Methods Appraisal Tool
DOI	=	Digital Object Identifier
LLM	=	Large Language Model
UK	=	United Kingdom

Authors' Contributions

All authors contributed to the preparation of this study. Conceptualisation, methodology, formal analysis, writing of the original draft: A.W.; Investigation, supervision, data curation, software: I.C.; Validation, visualisation: S.R.; Writing, review and editing, supervision: E.K.A. All authors have read and approved the final manuscript.

Availability of Data and Materials

The bibliographic dataset underlying this review comprises the 494 records exported from Scopus, the screening decisions for those records, the 89 screened studies with their thematic coding (Appendix A, Table A1) and the eligibility audit (Appendix A, Table A2). It is available from the corresponding author upon reasonable request.

Consent for Publication

Not applicable. This manuscript does not include any images, videos or personal details of identifiable individuals.

Conflict of Interest

The author(s) declare no conflicts of interest regarding this manuscript.

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Appendix A

The table below lists all 89 screened studies, sorted by publication year, with the assigned thematic codes and the citation counts at the time of extraction. The 11 contextual records identified in the eligibility audit (Section 3.4) are marked with a dagger (†). The reference number follows each study name, and full bibliographic details appear in the References section.

Table A1: full list of screened studies (N = 89)

Study	Year	Title	Journal	Theme(s)	Citations
Zhao *et al*. (2016) [67]	2016	An enterprise risk management knowledge-based decision support system for construction firms	Engineering, Construction and Architectural Management	AI/ML/DL; Risk/Cost DSS	37
Alwan *et al*. (2017) [3]	2017	Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using Building Information Modelling.	Journal of Cleaner Production	BIM Design/Compliance	235
Selçuk Çıdık *et al*. (2017) [4]	2017	Innovative Capability of Building Information Modelling in Construction Design	Journal of Construction Engineering and Management	BIM Design/Compliance	25
Akinade *et al*. (2018) [2]	2018	Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment	Journal of Cleaner Production	BIM Design/Compliance	241
He *et al*. (2018) [28]	2018	An e-commerce platform for industrialised construction procurement based on BIM and linked data	Sustainability (Switzerland)	BIM Design/Compliance; Adoption/Barriers	26
Olawumi *et al*. (2018) [12]	2018	Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts	Journal of Building Engineering	Adoption/Barriers	209
Alhumayani *et al*. (2020) [54]	2020	Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete	Journal of Cleaner Production	Robotics/Automation/ 3DP; BIM Sustainability/LCA	233
Kaewunruen *et al*. (2020) [30]	2020	Sustainability-based lifecycle management for bridge infrastructure using 6D BIM	Sustainability (Switzerland)	BIM Design/Compliance; BIM Sustainability/LCA	137
Zhang *et al*. (2020) [97]	2020	Construction of Chinese smart water conservancy platform based on the blockchain: Technology integration and innovation application	Sustainability (Switzerland)	Blockchain	30
Zhang *et al*. (2020) [32]	2020	Understanding the relation between BIM application behaviour and sustainable construction: A case study in China	Sustainability (Switzerland)	BIM Design/Compliance	35

Study	Year	Title	Journal	Theme(s)	Citations
Amin Ranjbar *et al*. (2021) [40]	2021	Developing a novel cash flow risk analysis framework for construction projects based on 5D BIM	Journal of Building Engineering	BIM Design/Compliance; Risk/Cost DSS	36
Baghi *et al*. (2021) [64]	2021	Innovation in sustainable solar-powered net-zero energy solar decathlon houses: A review and showcase	Buildings	Robotics/Automation/ 3DP	15
Buhamdan *et al*. (2021) [39]	2021	Developing a BIM and Simulation-Based Hazard Assessment and Visualisation Framework for CLT Construction Design	Journal of Construction Engineering and Management	BIM Design/ Compliance	12
Kirschke and Sietko (2021) [51]	2021	The function and potential of innovative reinforced concrete prefabrication technologies in achieving residential construction goals in Germany and Poland	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP	21
Tajs-Zielińska and Bochenek (2021) [66]	2021	Multi-domain and multi-material topology optimisation in design and strengthening of innovative sustainable structures	Sustainability (Switzerland)	Robotics/Automation/3DP	15
Volpe *et al*. (2021) [55]	2021	Building envelope prefabricated with 3d printing technology	Sustainability (Switzerland)	Robotics/Automation/ 3DP	65
Demirkesen and Tezel (2022) [17]	2022	Investigating major challenges for Industry 4.0 adoption among construction companies	Engineering, Construction and Architectural Management	BIM Design/Compliance; Digital Twin/IoT; Adoption/Barriers	183
Li *et al*. (2022) [102] †	2022	College Teaching Innovation from the Perspective of Sustainable Development: The Construction and Twelve-Year Practice of the 2P3E4R System	Sustainability (Switzerland)	BIM Design/Compliance	23
Li *et al*. (2022) [103] †	2022	Under the Background of AI Application, Research on the Impact of Science and Technology Innovation and Industrial Structure Upgrading on the Sustainable and High-Quality Development of Regional Economies	Sustainability (Switzerland)	AI/ML/DL	21
Navaratnam (2022) [52]	2022	Selecting a Suitable Sustainable Construction Method for Australian High-Rise Building: A Multi-Criteria Analysis	Sustainability (Switzerland)	Robotics/Automation/ 3DP	18
Oti-Sarpong *et al*. (2022) [18]	2022	Transforming the construction sector: an institutional complexity perspective	Construction Innovation	Adoption/Barriers	43
Rafindadi *et al*. (2022) [38]	2022	A Conceptual Framework for BIM Process Flow to Mitigate the Causes of Fall-Related Accidents at the Design Stage	Sustainability (Switzerland)	BIM Design/Compliance	13
Wu *et al*. (2022) [22]	2022	Investigating the Key Hindering Factors and Mechanism of BIM Applications Based on Social Network Analysis	Buildings	BIM Design/Compliance; Adoption/Barriers	8

Study	Year	Title	Journal	Theme(s)	Citations
Anaç *et al*. (2023) [53]	2023	Prefabricated Construction Risks: A Holistic Exploration through Advanced Bibliometric Tool and Content Analysis	Sustainability (Switzerland)	Robotics/Automation/ 3DP; Adoption/Barriers	22
Deng *et al*. (2023) [23]	2023	Research on Influencing Factors and Driving Path of BIM Application in Construction Projects Based on the SD Model in China	Buildings	BIM Design/Compliance	9
Friese *et al*. (2023) [61]	2023	Robot-Assisted Manufacturing Technology for 3D Non-Metallic Reinforcement Structures in the Construction Applications	Buildings	Robotics/Automation/ 3DP	8
Jayawardana *et al*. (2023) [113]	2023	A comparative life cycle assessment of prefabricated and traditional construction – A case of a developing country	Journal of Building Engineering	Robotics/Automation/ 3DP; AI/ML/DL; BIM Sustainability/LCA; Adoption/Barriers; Risk/Cost DSS	100
Jiang *et al*. (2023) [106] †	2023	A New Design Approach: Applying Optical Fibre Sensing to 3D-Printed Structures to Make Furniture Intelligent	Sustainability (Switzerland)	Robotics/Automation/ 3DP; AI/ML/DL; BIM Sustainability/LCA; Digital Twin/IoT	11
Liu *et al*. (2023) [122]	2023	Integration of Building Information Modelling with Sport and Facility: Current Status and Future Directions	Buildings	BIM Design/Compliance; AI/ML/DL; BIM Sustainability/LCA; Digital Twin/IoT	5
Moohialdin *et al*. (2023) [120]	2023	Proximity Activity Intensity Identification System in Hot and Humid Weather Conditions: Development and Implementation	Journal of Construction Engineering and Management	Robotics/Automation/ 3DP; Comp. Vision/UAV/SLAM	5
Oke *et al*. (2023) [114]	2023	Application of Digital Technologies Tools for Social and Sustainable Construction in a Developing Economy	Sustainability (Switzerland)	BIM Design/Compliance	11
Razveeva *et al*. (2023) [68]	2023	Analysis of Geometric Characteristics of Cracks and Delamination in Aerated Concrete Products Using Convolutional Neural Networks	Buildings	AI/ML/DL; Comp. Vision/UAV/SLAM	16
Vassena *et al*. (2023) [112]	2023	Construction Progress Monitoring through the Integration of 4D BIM and SLAM-Based Mapping Devices	Buildings	BIM Design/Compliance; Comp. Vision/UAV/SLAM	32
Wang *et al*. (2023) [73]	2023	The Development of a Rebar-Counting Model for Reinforced Concrete Columns: Using an Unmanned Aerial Vehicle and Deep-Learning Approach	Journal of Construction Engineering and Management	BIM Design/Compliance; Comp. Vision/UAV/SLAM	63
Zhang *et al*. (2023) [41]	2023	Development of a BIM-Enabled Automated Cost Segregation System	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP; Risk/Cost DSS	7

Study	Year	Title	Journal	Theme(s)	Citations
Abdelalim *et al*. (2024) [89]	2024	Agent-Based Modelling for Construction Resource Positioning Using Digital Twin and BLE Technologies	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP; Digital Twin/IoT; Risk/Cost DSS	13
Abed and Mehryaar (2024) [70]	2024	A Machine Learning Approach to Predict Relative Residual Strengths of Recycled Aggregate Concrete after Exposure to High Temperatures	Sustainability (Switzerland)	AI/ML/DL	21
Alhusban *et al*. (2024) [69]	2024	The Efficiency of Using Machine Learning Techniques in Fiber-Reinforced-Polymer Applications in Structural Engineering	Sustainability (Switzerland)	AI/ML/DL	19
Aminpour and Memari (2024) [56]	2024	Numerical and experimental study on reinforced 3DCP walls filled with lightweight concrete	Journal of Building Engineering	Robotics/Automation/ 3DP	4
Awosode *et al*. (2024) [65]	2024	The Relevance of Automation in the Facility Management of Selected High-Rise Buildings in Lagos, Nigeria †	Buildings	Robotics/Automation/ 3DP	3
Cascone (2024) [36]	2024	Eco-Innovative Construction: Integrating Green Roofs Design within the BIM Framework	Sustainability (Switzerland)	BIM Design/Compliance	16
Chen *et al*. (2024) [49]	2024	Automated Building Information Modelling Compliance Check through a Large Language Model Combined with Deep Learning and Ontology	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP; AI/ML/DL	93
Chen *et al*. (2024) [48]	2024	Intelligent Systems Integrating BIM and VR for Urban Subway Microenvironmental Health Risks Management	Buildings	BIM Design/Compliance; BIM Sustainability/LCA	15
Feng *et al*. (2024) [13]	2024	Research on the System Design and Target Recognition Method of the Rebar-Tying Robot	Buildings	Robotics/Automation/ 3DP; AI/ML/DL; Comp. Vision/UAV/SLAM	24
Hu *et al*. (2024) [101] †	2024	The Innovative Construction of Provinces, Regional Artificial Intelligence Development, and the Resilience of Regional Innovation Ecosystems: Quasi-Natural Experiments Based on Spatial Difference-in-Differences Models and Double Machine Learning	Sustainability (Switzerland)	AI/ML/DL	19
Lai *et al*. (2024) [60]	2024	Preserving Woodcraft in the Digital Age: A Meta-Model-Based Robotic Approach for Sustainable Timber Construction	Buildings	Robotics/Automation/ 3DP	6
Lauria and Azzalin (2024) [88]	2024	Digital Transformation in the Construction Sector: A Digital Twin for Seismic Safety in the Lifecycle of Buildings	Sustainability (Switzerland)	Digital Twin/IoT	16

Study	Year	Title	Journal	Theme(s)	Citations
Lee *et al*. (2024) [74]	2024	Innovative Point Cloud Segmentation of 3D Light Steel Framing System through Synthetic BIM and Mixed Reality Data: Advancing Construction Monitoring	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP; AI/ML/DL; Comp. Vision/UAV/SLAM	12
Li and Tang (2024) [83]	2024	Pathways of the Digital Economy's Impact on Green Total Factor Productivity in the Construction Industry	Sustainability (Switzerland)	AI/ML/DL; Digital Twin/ IoT	7
Liu *et al*. (2024) [45]	2024	Immersive Technology and Building Information Modelling (BIM) for Sustainable Smart Cities	Buildings	BIM Design/Compliance; AI/ML/DL; Digital Twin/ IoT	28
Liu *et al*. (2024) [46]	2024	Integration of Building Information Modelling (BIM) with Transportation and Facilities: Recent Applications and Future Perspectives	Buildings	BIM Design/Compliance; BIM Sustainability/LCA; Digital Twin/IoT; Comp. Vision/UAV/SLAM	9
Liu *et al*. (2024) [47]	2024	Integration of Smart Cities and Building Information Modelling (BIM) for a Sustainability-Oriented Business Model to Address Sustainable Development Goals	Buildings	BIM Design/Compliance; Digital Twin/IoT	21
Liu *et al*. (2024) [76]	2024	Research on Diagnosis and Assessment Processes and Methods for Existing Residential Buildings Based on Intelligent Assistance Models	Buildings	AI/ML/DL	9
Llatas *et al*. (2024) [35]	2024	Application of Knowledge Discovery in Databases (KDD) to environmental, economic, and social indicators used in BIM workflow to support sustainable design	Journal of Building Engineering	BIM Design/Compliance	7
Ning *et al*. (2024) [90]	2024	Exploration of the Application and Practice of Digital Twin Technology in Teaching Driven by Smart City Construction	Sustainability (Switzerland)	Digital Twin/IoT	9
Piaia *et al*. (2024) [34]	2024	Advancing the Decarbonization of the Construction Sector: Lifecycle Quality and Performance Assurance of Nearly Zero-Energy Buildings	Sustainability (Switzerland)	BIM Design/Compliance; Robotics/Automation/ 3DP; BIM Sustainability/LCA	15
Rashidi *et al*. (2024) [42]	2024	Applying Building Information Modelling (BIM) Technology in Pre-Tender Cost Estimation of Construction Projects: A Case Study in Iran	Buildings	BIM Design/Compliance	20
Trinh *et al*. (2024) [71]	2024	Assessing embodied carbon of flat slab buildings – An ANN-integrated optimisation methodology	Journal of Cleaner Production	AI/ML/DL	14

Study	Year	Title	Journal	Theme(s)	Citations
Ullah *et al*. (2024) [33]	2024	Research on Low-Carbon Design and Energy Efficiency by Harnessing Indigenous Resources through BIM-Ecotect Analysis in Hot Climates	Sustainability (Switzerland)	BIM Sustainability/LCA	7
Wang and Lu (2024) [43]	2024	Development of a BIM Platform for the Design of Single-Story Steel Structure Factories	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP	11
Wang *et al*. (2024) [44]	2024	Automatic Planning Method of Construction Schedule under Multi-Dimensional Spatial Resource Constraints	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP	9
Wang *et al*. (2024) [57]	2024	Research on Mechanical Properties of a 3D Concrete Printing Component-Optimized Path by Multimodal Analysis	Sustainability (Switzerland)	Robotics/Automation/ 3DP	10
Yang *et al*. (2024) [105] †	2024	Exploring the Intelligent Emergency Management Mode of Rural Natural Disasters in the Era of Digital Technology	Sustainability (Switzerland)	AI/ML/DL	20
Yardımcı and Kurucay (2024) [29]	2024	LCA-TOPSIS Integration for Minimising Material Waste in the Construction Sector: A BIM-Based Decision-Making	Buildings	BIM Design/Compliance; BIM Sustainability/LCA	17
Yoon and Hwang (2024) [86]	2024	Analysing Land Shape Typologies in South Korean Apartment Complexes Using Machine Learning and Deep Learning Techniques	Buildings	AI/ML/DL	1
Zhao *et al*. (2024) [109] †	2024	A novel type of mineral-impregnated fibre reinforcements based on alkaline-resistant glass fibre and magnesium oxychloride cement for enhanced sustainability in construction	Journal of Cleaner Production	Robotics/Automation/ 3DP	23
Araya-Aliaga *et al*. (2025) [75]	2025	Automating Dataset Generation for Object Detection in the Construction Industry with AI and Robotic Process Automation (RPA)	Buildings	BIM Design/Compliance; Robotics/Automation/ 3DP; AI/ML/DL; Comp. Vision/UAV/SLAM	18
Asfandyar *et al*. (2025) [37]	2025	Enhancing Sustainable Flood Resilience and Energy Efficiency in Residential Structures: Integrating Hydrological Data, BIM, and GIS in Quetta, Pakistan	Sustainability (Switzerland)	BIM Design/Compliance; Robotics/Automation/ 3DP; BIM Sustainability/LCA; Adoption/Barriers	5
Böhm *et al*. (2025) [110] †	2025	Cascading potential of salvaged rafters from building demolition and deconstruction in southern Germany	Journal of Cleaner Production	Robotics/Automation/ 3DP	11
Bühler *et al*. (2025) [1]	2025	Bridging the Construction Productivity Gap, A Hierarchical Framework for the Age of Automation, Robotics, and AI	Buildings	Robotics/Automation/ 3DP; AI/ML/DL; Digital Twin/IoT	8

Study	Year	Title	Journal	Theme(s)	Citations
Cabral *et al*. (2025) [94]	2025	A Contactless Multi-Modal Sensing Approach for Material Assessment and Recovery in Building Deconstruction	Sustainability (Switzerland)	Robotics/Automation/ 3DP; AI/ML/DL; BIM Sustainability/LCA; Digital Twin/IoT; Comp. Vision/UAV/SLAM	13
Dagou *et al*. (2025) [50]	2025	The Future of Construction: Integrating Innovative Technologies for Smarter Project Management	Sustainability (Switzerland)	BIM Design/Compliance; AI/ML/DL; Digital Twin/ IoT; Adoption/Barriers	11
Dörrie *et al*. (2025) [58]	2025	From Digital to Real: Optimised and Functionally Integrated Shotcrete 3D Printing Elements for Multi-Storey Structures	Buildings	Robotics/Automation/ 3DP; Digital Twin/IoT	9
El Hajj and Martínez Montes (2025) [27]	2025	Examining Green Building Practices: The Influence on Building Information Modelling Function Diffusion	Sustainability (Switzerland)	BIM Design/Compliance; BIM Sustainability/LCA; Adoption/Barriers	12
Emad *et al*. (2025) [84]	2025	The Role of Artificial Intelligence in Developing the Tall Buildings of Tomorrow	Buildings	AI/ML/DL; Comp. Vision/UAV/SLAM	11
Ghobadi and Sepasgozar (2025) [9]	2025	Challenges and Benefits of Implementing AI in Timber Construction for Circular Economy Goals	Buildings	AI/ML/DL	6
Giorgi *et al*. (2025) [111] †	2025	Pilot Projects to Put Reuse and Remanufacturing into Practice in the Tertiary Building Sector	Sustainability (Switzerland)	Digital Twin/IoT	1
Kim (2025) [85]	2025	Advancing Sustainable Road Construction with Multiple Regression Analysis, Regression Tree Models, and Case-Based Reasoning for Environmental Load and Cost Estimation	Buildings	AI/ML/DL	3
Li *et al*. (2025) [59]	2025	Automated Screw-Fastened Assembly of Layered Timber Arch-Shells: Construction-Phase LCA and Performance Validation	Buildings	Robotics/Automation/ 3DP; BIM Sustainability/LCA	1
Li *et al*. (2025) [72]	2025	Multi-objective optimisation of recycled fine aggregate geopolymer-based grouting materials using the response surface methodology and backpropagation neural network coupled approach	Construction and Building Materials	AI/ML/DL	5
Lystbæk *et al*. (2025) [77]	2025	Low-resource GAN-stack for high-resolution floor plan generation with enhanced evaluation and contextual validation	Journal of Building Engineering	Robotics/Automation/ 3DP; AI/ML/DL; BIM Sustainability/LCA	4
Ma *et al*. (2025) [25]	2025	Exploring Behavioural Mechanisms of BIM Outsourcing in Construction Enterprises: A TPB-Based Empirical Study from China	Buildings	BIM Design/Compliance; Adoption/Barriers	1

Study	Year	Title	Journal	Theme(s)	Citations
Mujahed *et al*. (2025) [26]	2025	Platform Approaches in the AEC Industry: Stakeholder Perspectives and Case Study	Buildings	BIM Design/Compliance; BIM Sustainability/LCA; Adoption/Barriers	6
Nabawy *et al*. (2025) [31]	2025	Green Building Information Modelling Framework for Sustainable Residential Development in Egypt	Buildings	BIM Design/Compliance; BIM Sustainability/LCA	2
Rudenko *et al*. (2025) [107] †	2025	Physical–Mechanical and Microstructural Properties of Non-Autoclaved Aerated Concrete with Ash-and-Slag Additives	Sustainability (Switzerland)	AI/ML/DL	11
Rui *et al*. (2025) [24]	2025	A Mixed-Method Comparative Analysis of BIM Technology Adoption in China's and Japan's Construction Sectors	Buildings	BIM Design/Compliance; Adoption/Barriers	3
Tian and Wang (2025) [91]	2025	Innovative Pathways for Collaborative Governance in Technology-Driven Smart Communities	Sustainability (Switzerland)	Digital Twin/IoT	10
Wang *et al*. (2025) [104] †	2025	How Does the Construction of New Generation of National AI Innovative Development Pilot Zones Affect Carbon Emissions Intensity? Empirical Evidence from China	Sustainability (Switzerland)	AI/ML/DL; BIM Sustainability/LCA	4
Zhong *et al*. (2025) [108] †	2025	Seismic Behaviour of Beam-Connected Precast Walls with Innovative Concealed Steel Bracings: Experimental Insights and Numerical Study	Buildings	Robotics/Automation/ 3DP	0

Table A2: Eligibility Audit: Contextual and Borderline Records

Study	Focus	Audit decision and reason
Hu *et al*. [101]	Regional AI development and innovation ecosystem resilience	Contextual: regional economic analysis without a construction technology application
Li *et al*. [102]	College teaching innovation	Contextual: BIM is peripheral to the teaching system
Li *et al*. [103]	AI background, innovation and industrial structure upgrading	Contextual: regional economic development
Wang *et al*. [104]	National AI pilot zones and carbon emissions intensity	Contextual: macro policy evaluation, not construction specific
Yang *et al*. [105]	Emergency management of rural natural disasters	Contextual: civil protection, not construction
Jiang *et al*. [106]	Optical fibre sensing in 3D printed furniture	Contextual: product design, not building or infrastructure construction

Study	Focus	Audit decision and reason
Rudenko *et al*. [107]	Non autoclaved aerated concrete with ash and slag additives	Contextual: materials properties, digital construct not the object
Zhong *et al*. [108]	Seismic behaviour of precast walls with steel bracings	Contextual: structural mechanics excluded by Section 3.2
Zhao *et al*. [109]	Mineral impregnated fibre reinforcement	Contextual: materials development
Böhm *et al*. [110]	Cascading reuse of salvaged timber rafters	Contextual: physical material reuse; kept as circular economy context (Section 6.2)
Giorgi *et al*. [111]	Reuse and remanufacturing pilot projects	Contextual: circularity practice; kept as circular economy context (Section 6.2)
Tajs-Zielińska and Bochenek [66]	Topology optimisation of sustainable structures	Borderline, retained: computational automation of structural design
Baghi *et al*. [64]	Solar Decathlon house innovations	Borderline, retained: review includes home automation technologies
Li and Tang [83]	Digital economy and green productivity in construction	Borderline, retained: digital economy analysed within the construction industry
Tian and Wang [91]	Governance of technology driven smart communities	Borderline, retained: smart community and sensing context
Ning *et al*. [90]	Digital twin technology in teaching	Borderline, retained: digital twin is the object, education is the setting
Yoon and Hwang [86]	Land shape typologies of apartment complexes	Borderline, retained: machine learning applied to the built environment