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Systematic Review

Additive Manufacturing for Sustainable Construction 4.0: Trends, Opportunities, and Future Directions

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Abstract

Additive manufacturing (AM) is applied in sustainable architecture and Construction 4.0 because it can support design flexibility, mass customization, material efficiency, and reduced reliance on conventional formwork. Prior reviews often addressed either construction applications or broader digital transformation, leaving the intersection of AM, construction sustainability, digital technologies, and lifecycle performance underexplored. This study conducts a systematic and bibliometric review of literature retrieved from Scopus and Web of Science covering the period from January 2016 to January 2026. The review protocol followed SPAR-4-SLR principles and PRISMA 2020 guidelines, with 58 records retained for analysis. Bibliometric and thematic analyses identified a marked rise in publication activity after 2021 with four major research themes: material development and innovation, digital fabrication and process control, lifecycle assessment and circularity, and digital integration and project implementation. Construction 4.0 technologies, including BIM, digital twins, automation, and robotics, were the most frequently represented digital enablers. The review further identifies future research opportunities and outlines a proposed conceptual pathway toward Construction 5.0. This pathway connects materials, robotics, lifecycle performance, and human-centered priorities as a future research agenda. Overall, this study contributes to a more integrated understanding of how AM can advance sustainable, digitally enabled, and human-centered construction practice.

Keywords: additive manufacturing; 3D concrete printing; sustainable architecture; Construction 4.0; Construction 5.0; digital fabrication; bibliometric review; built environment; circular economy; building information modeling

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Academic Editor: Hwang Yi

Received: 14 May 2026
Revised: 29 June 2026
Accepted: 6 July 2026
Published: 10 July 2026

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1. Introduction

The construction industry is widely known as one of the most resource-intensive and environmentally impactful industries in the world [1]. The construction sector accounts for approximately 37–40% of global energy-related CO_2 emissions and more than one-third of global energy consumption, which demonstrates its significant contribution to climate and energy challenges [2]. Beyond emissions and energy use, the sector also contributes substantially to global waste generation and accounts for roughly 40% of raw material consumption worldwide [3]. These environmental pressures are expected to intensify as rapid urbanization and population growth continue to increase demand for new infrastructure and buildings. The Global Status Report projected that global building

floor area would double by 2060, adding approximately 230 billion m^2 of new floor area [4]. More recent Global Status Report data indicate that global building floor area reached 273 billion m^2 in 2024 and continued to expand by 1.7% in that year [2]. In response to these challenges, sustainable, low-carbon, and digitally enabled construction approaches are receiving growing attention. Within this context, Construction 4.0, enabled by data, digital technologies, and automation, has emerged as a transformative framework that integrates cyber-physical systems, digital modeling, data analytics, and intelligent control into construction processes [3,5].

Among emerging technologies, additive manufacturing (AM), commonly referred to as 3D printing, is a promising approach for transforming construction practice and advancing sustainability [6]. In construction, AM refers to the layer-by-layer fabrication of building elements directly from digital models, including walls, housing units, structural components, formwork, and customized architectural features. As a digital fabrication method, AM supports geometric flexibility, automation, reduced formwork dependency, and improved material efficiency [7–9]. AM capabilities can address long-standing construction inefficiencies by reducing conventional wooden or metal formwork. As a result, AM may lower material use, labor requirements, costs, and construction waste [10]. Case-study and review evidence suggests that AM can reduce cost, construction time, waste, and emissions in specific construction contexts; however, AM-related benefits depend on material type, printing system, project scale, site conditions, and assessment boundary [11,12]. The broader significance of AM lies in the potential to work with Construction 4.0 technologies. Integration with Construction 4.0 technologies can improve design coordination, construction automation, quality control, logistics planning, operational performance, and lifecycle management. When integrated with Building Information Modeling (BIM), digital twins, construction automation and robotics, the Internet of Things (IoT), artificial intelligence (AI), and lean construction principles, AM can support data-informed design optimization, automated workflows, real-time monitoring, logistics coordination, lifecycle assessment, and circular material use [12]. Therefore, AM can be viewed as both a construction method and a component of a digitally connected system for sustainable construction across the project lifecycle.

For architecture and the built environment, AM can expand design flexibility for free-form, customized, and topology-optimized components when material, structural, scale, and regulatory constraints are considered [13–17]. Large-scale printing studies show how digital design intent can be translated into inhabitable built form. Large-scale AM applications also require evaluation as design-stage technologies connected to parametric modeling, BIM, digital twins, material specification, and sustainable built-environment performance [16,18–21].

Despite increasing scholarly attention to AM for sustainable construction, the review literature remains fragmented. Existing studies offer limited explanation of how AM can be integrated with Construction 4.0 technologies across the construction lifecycle. Reviews on Industry 4.0 and sustainability have examined digital transformation at the construction-sector level [3,22]. However, such reviews generally position AM as one technology within a broader digital-technology portfolio. Consequently, limited attention has been given to AM-specific sustainability outcomes in construction practice. In contrast, AM-focused reviews have primarily examined applications, printable materials, process parameters, structural performance, and technical feasibility [6]. Lifecycle sustainability and digital workflow integration have received comparatively less attention. Therefore, the present review conceptualizes AM as a BIM-enabled digital construction process. Under this perspective, sustainability performance depends on continuous information flow across design, simulation, fabrication, monitoring, lifecycle assessment, and project delivery.

Table 1 compares the scope of the present review with representative recent reviews and clarifies the specific novelty of this study.

Table 1. Scope comparison and novelty of the present review relative to representative recent reviews.

Review Stream with Representative Sources	Focus of Prior Reviews	Gap Addressed by the Present Review
AM in construction (Forcael et al. [6])	AM applications, materials, processes, technical feasibility, and construction research trends	Integrates AM with lifecycle sustainability, BIM-enabled workflows, implementation readiness, and a proposed Construction 5.0 pathway
3D printing in architecture and construction (Žujović et al. [15]; Tabassum and Mir [23])	3D printing technologies, architectural design potential, and sustainable construction applications.	Extends beyond 3D printing applications to the broader AM-digital-construction ecosystem, including circularity, lifecycle performance, and project delivery
Sustainable/non-conventional concrete 3D printing (Singh et al. [24])	Concrete 3D printing, printable cementitious materials, non-conventional mixtures, sustainability benefits, and implementation challenges	Links material development with digital fabrication, quality control, lifecycle assessment, regulation, and supply-chain implications
Construction 4.0 and sustainable construction reviews (Wang and Guo [25]; Forcael et al. [26])	Industry-level digital transformation, Construction 4.0 technologies, and sustainability.	Positions AM as a central digital fabrication pathway within sustainable Construction 4.0 and assesses technology-integration patterns.
Digital fabrication and AM in construction (Tuvayanond and Prasittisopin [27])	Design for manufacturing/assembly, digital fabrication, and construction AM processes.	Connects process, digital workflow, sustainability assessment, implementation barriers, and future research needs
Construction 5.0 reviews (Akhavan et al. [28]; Pal et al. [29])	Human-centered, resilient, and sustainable construction transformation.	Frames Construction 5.0 only as a proposed future pathway derived from AM-specific gaps, not as an already proven outcome.

To address this gap, this study conducts a systematic and bibliometric review of peer-reviewed publications retrieved from Scopus and Web of Science. The review examines publication trends, collaboration patterns, thematic developments, and technology-oriented applications of AM in sustainable construction. In addition to bibliometric analysis, a qualitative thematic synthesis is conducted to organize the literature into major research areas, including material development and innovation, digital fabrication and process control, lifecycle assessment and circularity, and digital integration and project implementation. The findings provide a structured understanding of the current research landscape and identify opportunities for developing a proposed future pathway for sustainable AM toward Construction 5.0. Compared with existing systematic review papers that broadly review AM in construction [6] or focus on 3D printing as a sustainable construction technology [23], this review explicitly combines bibliometric mapping with thematic synthesis at the intersection of AM, sustainability, Construction 4.0, and digital integration. It also contributes by identifying future research opportunities that connect AM research trends to a construction 5.0-oriented research agenda.

In this review, sustainable AM toward Construction 5.0 refers to the development of additive manufacturing as a digitally connected, lifecycle-oriented, human-centered, and implementation-ready construction approach. Construction 4.0 provides the digital foundation through BIM, robotics, automation, IoT, AI, and data-driven workflows, whereas Construction 5.0 extends this foundation by emphasizing human-centered innovation, resilience, sustainability verification, regulatory readiness, and societal value. This progression is important because the sustainability potential of AM cannot be assessed through

printing efficiency alone; it also depends on material performance, lifecycle evidence, workforce capability, project delivery, policy support, and social outcomes.

2. Research Background

2.1. Additive Manufacturing in the Construction Industry

Within the construction context, AM is commonly discussed in relation to process selection, material compatibility, build scale, and digital workflow requirements. In the broader manufacturing literature, AM technologies are classified by material type, feedstock form, and processing mechanism [30–32]. Using ISO/ASTM 52900 terminology, AM processes are categorized into seven process types: material extrusion, binder jetting, powder bed fusion, vat photopolymerization, directed energy deposition, material jetting, and sheet lamination [33]. Figure 1 summarizes these ISO/ASTM process categories. These categories differ in compatible materials, production scale, geometric flexibility, surface quality, and industrial applicability [18,25,34].

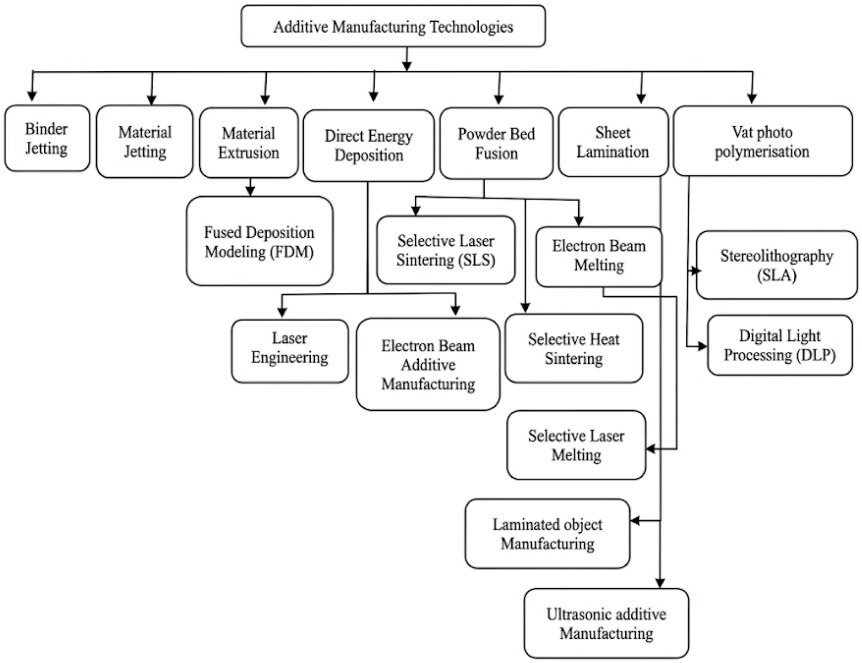


Figure 1. ISO/ASTM-based classification of additive manufacturing (AM) process categories, adapted from [31,35].

Although AM encompasses several process categories, its application in construction is primarily associated with large-scale material extrusion, particularly 3D concrete printing (3DCP), in which cementitious or earth-based materials are extruded through a nozzle and deposited layer by layer under computer control [13]. Robotic arms, gantry-based systems, and contour-crafting configurations have been investigated for printing walls, structural components, formwork, and housing units [14,18,36]. Compared with conventional construction, this approach enables automated fabrication, reduces formwork dependency, improves geometric flexibility by enabling free-form, curved, and customized building components, and supports more direct translation of digital models into physical building components [15,23,37]. Other AM processes, such as binder jetting, powder-based printing, and directed energy deposition, can support construction through specialized applications, including architectural components, molds, prototypes, connectors, or repair elements; however, they are less prevalent than large-scale cementitious material extrusion for full-scale structural building applications [15,33].

Despite its growing adoption, AM in construction faces significant technical challenges. Material rheology, extrusion stability, curing behavior, dimensional precision, reinforcement integration, and process control all affect printing performance and reliability [24,38,39]. These challenges highlight a clear gap between the capabilities of AM in controlled settings and its consistent implementation in real construction environments. Addressing these challenges requires positioning AM as a digitally enabled building process rather than only a fabrication method, with coordination needed across design, materials, equipment, monitoring, and structural performance.

2.2. Additive Manufacturing for Sustainable Construction

Sustainable construction aims to reduce the environmental, economic, and social impacts of the built environment across the project lifecycle, with emphasis on persistent challenges such as high material consumption, waste generation, energy use, and carbon emissions [1,2,40]. AM has gained increasing attention in this context through its ability to support construction sustainability via material efficiency, circular resource use, lifecycle performance, and digitally enabled decision-making.

A major sustainability contribution of AM lies in its potential to improve material efficiency and reduce unnecessary resource consumption. AM enables material-efficient geometries through layer-by-layer deposition, and when combined with topology optimization and manufacturing-constraint-based design, it can further minimize material use while maintaining structural performance [16,41]. However, the actual environmental and practical benefits of AM extend beyond the printing process itself. Material composition, equipment energy consumption, construction logistics, structural performance, and durability all influence its overall sustainability value. AM should therefore be assessed as part of an integrated construction system rather than solely as an automated fabrication technique. Material selection plays a particularly critical role in determining the sustainability performance of AM. Cementitious materials remain dominant in 3DCP due to their structural relevance; however, cement-rich printable mixtures may limit environmental benefits given the high carbon intensity of cement production [34]. To improve circularity and reduce environmental impact, recent studies have explored recycled aggregates, low-carbon binders, recycled high-density polyethylene (HDPE), and other alternative feedstocks [42,43]. Beyond environmental criteria, sustainable printing materials must simultaneously satisfy technical requirements, including pumpability, extrudability, buildability, interlayer bond strength, durability, and structural reliability, which positions material development as one of the central challenges in sustainable AM for construction.

The sustainability potential of AM can be further expanded through integration with digital construction technologies, including automation, cyber-physical systems, BIM, digital twins, IoT, robotics, and artificial intelligence. These technologies can support lifecycle simulation, process monitoring, quality management, circular material use, and data-informed decision-making [3,19,25,26]. However, sustainability benefits of AM are conditional rather than automatic. Fully realizing this potential requires moving beyond a narrow focus on construction processes and methods to evaluate AM as part of a broader digital construction ecosystem, one in which sustainable materials, optimized design, monitoring systems, structural performance, and lifecycle assessment are effectively integrated.

For the target field of next-generation digital construction, BIM is especially important because it can connect AM design intent, geometric constraints, material information, toolpath planning, process monitoring, quality records, and lifecycle assessment data [20,21,44]. This information continuity is necessary if AM is to move from isolated printing demonstrations toward interoperable, BIM-centered project delivery workflows.

3. Methodology

3.1. Review Protocol and Research Questions

This study followed the SPAR-4-SLR framework to conduct a systematic review of AM for sustainable Construction 4.0 [45]. This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [46]. A completed PRISMA 2020 checklist is provided as Supplementary Material. The review protocol was not registered. The SPAR-4-SLR protocol structures the review process through three major stages: assembling, arranging, and assessing. In the assembling stage, the review scope, research questions, search strategy, databases, and eligibility criteria were defined. In the arranging stage, records retrieved from Scopus and Web of Science were merged, duplicate records were removed, and studies were screened based on predefined inclusion and exclusion criteria. In the assessing stage, the final dataset was analyzed through bibliometric and thematic methods to identify publication trends, collaboration patterns, thematic clusters, technology-oriented integrations, research gaps, and future opportunities.

The review was guided by the following research questions:

RQ1: What are the publication trends and bibliometric patterns in AM for sustainable Construction 4.0?
RQ2: What thematic clusters and digital-technology integration patterns structure the literature on BIM-enabled AM for sustainable construction?
RQ3: What research gaps and future opportunities remain for advancing AM from Construction 4.0 toward BIM-enabled, human-centered, and sustainable Construction 5.0?

3.2. Identification and Screening

A systematic literature search was conducted using Scopus and Web of Science. These databases were selected because they provide broad coverage of peer-reviewed engineering, construction, sustainability, and technology-management research. The search covered publications from January 2016 to January 2026 and was limited to English-language journal articles, review papers, and conference papers. The review period was selected to capture a critical decade in which AM research in construction advanced beyond early feasibility-oriented studies toward integrated investigations of sustainability assessment, BIM-enabled workflows, digital twins, robotics, artificial intelligence, and Construction 4.0-based project delivery [3,6,22]. Database-specific field tags, search syntax, filters, and the final search/export date are reported in Table 2. The identification, screening, eligibility, and inclusion processes are summarized in Figure 2.

Figure 2 reports the PRISMA 2020 study selection process used for identification, screening, eligibility assessment, and inclusion. After 702 records were retrieved from Scopus and Web of Science, 2 records were removed before screening because they were manually identified as ineligible or irrelevant. The remaining 700 records were screened by subject area, document type, keywords, and relevance, excluding 579 records. The remaining 121 records were assessed by title and abstract, with 45 excluded for falling outside the review scope. Full-text retrieval was sought for the remaining 76 reports, and no reports were unavailable for retrieval. Full-text review of these 76 reports led to the exclusion of 18 reports focused on non-construction AM topics, general robotics without AM relevance, non-construction extrusion processes, or laboratory-only experiments with limited construction implications. The final set of 58 studies was selected for detailed bibliometric and qualitative analysis.

Table 2. Database-specific search strings and filters.

Database	Field Tag/Syntax	Exact Search String	Filters and Search Date
Scopus	TITLE-ABS-KEY	TITLE-ABS-KEY((“additive manufacturing” OR “3D printing” OR “3D concrete printing” OR “digital fabrication”) AND (“sustainable” OR “low-carbon” OR “circular economy” OR “life cycle” OR “lifecycle”) AND (“construction” OR “construction industry” OR “building” OR “built environment” OR “Construction 4.0” OR “digital construction”))	Publication years: 2016–2026; language: English; document types: article, review, conference paper; final search/export date: 3 March 2026.
Web of Science	Topic Search (TS=)	TS= ((“additive manufacturing” OR “3D printing” OR “3D concrete printing” OR “digital fabrication”) AND (“sustainable” OR “low-carbon” OR “circular economy” OR “life cycle” OR “lifecycle”) AND (“construction” OR “construction industry” OR “building” OR “built environment” OR “Construction 4.0” OR “digital construction”))	Publication years: 2016–2026; language: English; document types: article, review, proceedings paper; final search/export date: 3 March 2026.

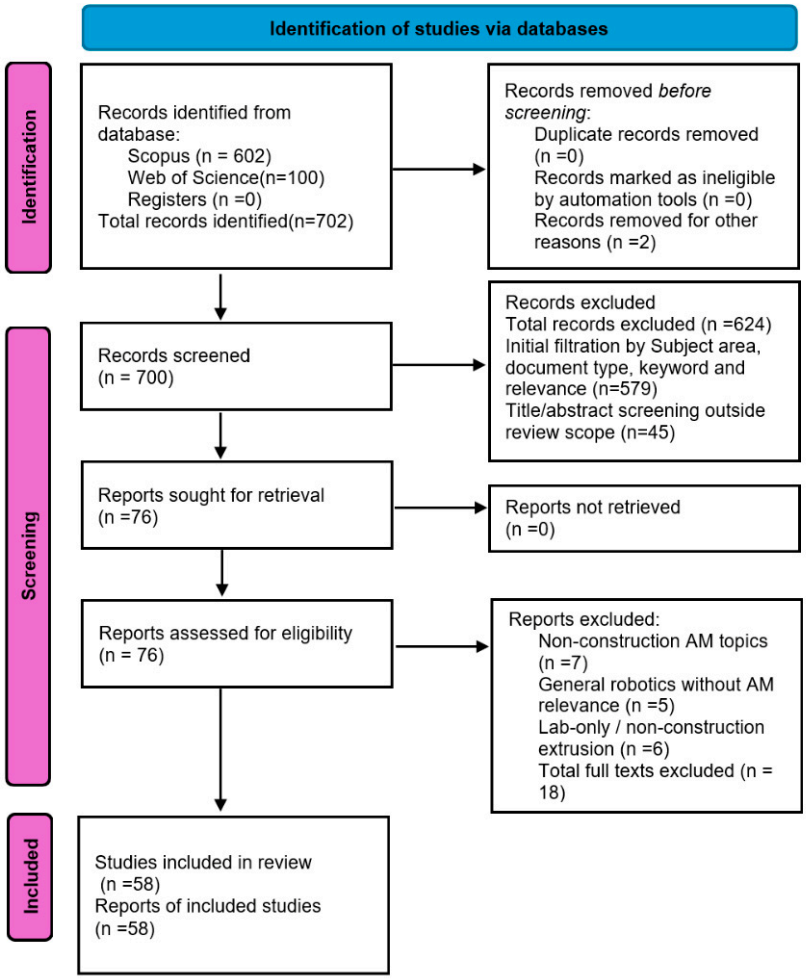


Figure 2. PRISMA 2020 flow diagram for study identification, screening, eligibility assessment, and inclusion.

To complement the PRISMA flow description, screening was organized in sequential stages. Initial screening considered titles, abstracts, keywords, subject areas, document types, and relevance. Full-text eligibility assessment was then performed for reports retained after title and abstract review. Inclusion required a focus on additive manufac-

turing or closely related digital fabrication within construction, architecture, building, or built-environment contexts, together with sustainability, lifecycle, circularity, or digital-construction dimension. Records outside the defined scope were excluded. The lead author conducted the initial screening, and coauthors checked the eligibility decisions. Uncertain cases were resolved through author consensus. Because final eligibility decisions were based on consensus checking rather than independent parallel coding, inter-rater agreement was not calculated and is acknowledged as a methodological limitation. Studies classified as "AM-related digital construction" (see Supplementary Table S1) were included only when the digital-construction focus directly supported AM-enabled sustainable construction through additive manufacturing, 3D printing, digital fabrication, or relevant Construction 4.0 technologies. Relevant links included AM workflows, lifecycle assessment, process monitoring, project implementation, and sustainability outcomes. General digital-construction studies without a clear AM-related or AM-supported sustainability connection were excluded.

3.3. Data Analysis and Thematic Synthesis

To identify key research trends and topics, the retained database records were combined into a single dataset and examined using bibliometric and thematic analysis methods.

The bibliographic records from Scopus and Web of Science were exported and loaded into R Studio for additional processing after the screening procedure was finished. RStudio (Version 2026.01.1+403) was employed as the analytical environment for data merging, preprocessing, and bibliometric analysis [47]. Both datasets were first converted into a compatible bibliographic format and merged using the bibliometrix package to remove duplicate records and ensure data consistency [48].

The bibliometrix package in R was used to perform bibliometric analysis after the combined dataset had been merged and cleaned. The R environment was primarily used for data preprocessing, merging, and initial statistical computations. Bibliometric analysis was then conducted using Biblioshiny, a web-based interface, to examine annual publication trends, source production, country contributions, institutional affiliations, co-authorship patterns, keyword co-occurrence, and thematic mapping. The complete workflow for data extraction, merging, and analysis is illustrated in Figure 3.

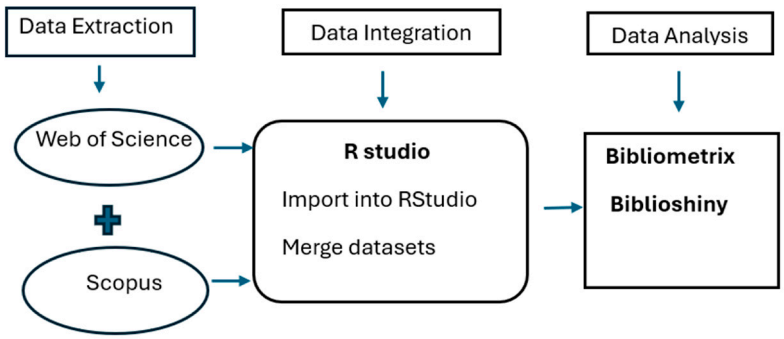


Figure 3. Data extraction and bibliometric analysis workflow.

In addition to bibliometric analysis, a qualitative thematic review was conducted to synthesize the technical content of the selected studies. Based on keyword clusters, thematic maps, and manual content review, the literature was organized into four main research areas: material development and innovation, digital fabrication and process control, lifecycle assessment and circularity, and digital integration and project implementation. This combined approach enabled the identification of quantitative research patterns and major thematic directions. The findings were further extended through a discussion of emerging digital technologies in Construction 4.0 and the identification of research gaps

and future opportunities, ultimately informing a proposed pathway for sustainable AM in Construction 5.0.

The thematic synthesis used structured coding logic rather than relying only on software outputs. Each retained study was coded for AM process/material, sustainability dimension, digital technology, method, validation scale, lifecycle boundary, and implementation relevance. The lead author completed the initial coding, and the coauthors reviewed the thematic grouping. Uncertain cases were resolved by consensus; formal inter-rater reliability was not calculated because coding was not conducted as independent parallel coding.

To strengthen traceability between the research questions and the analysis, RQ1 is addressed through bibliometric indicators, RQ2 through thematic coding and comparative interpretation of digital-technology roles, and RQ3 through maturity appraisal, implementation gaps, and future research directions.

3.4. Study Quality and Maturity Appraisal

To assess the maturity and implementation readiness of the evidence base, a descriptive quality and maturity appraisal was conducted for the 58 included studies. Each study was classified according to five dimensions: study type, validation scale, construction relevance, lifecycle boundary, and approximate technology readiness level (TRL). The appraisal was conducted after eligibility screening and was used to interpret evidence maturity rather than to exclude additional studies. The aggregated appraisal results are summarized in Table 3.

Table 3. Summary of study quality and maturity appraisal for the 58 included studies.

Appraisal Dimension	Summary of the 58 Included Studies
Study type	Literature/bibliometric review (n = 31); conceptual/framework (n = 15); case study (n = 5); research article (n = 4); experimental/technical (n = 2); conference paper (n = 1).
Validation scale	Literature-level evidence (n = 31); conceptual/framework evidence with project/building context discussed only (n = 11); project/building-scale demonstration (n = 8); conceptual/digital simulation (n = 3); laboratory/prototype validation (n = 2); material/component-scale validation or context (n = 2); not specified (n = 1).
Construction relevance	High (n = 56); medium (n = 1); low-to-medium (n = 1).
Lifecycle boundary	Most studies addressed design and/or fabrication/construction, whereas fewer studies covered monitoring/quality control, lifecycle performance, or end-of-life considerations; detailed study-level coding is provided in Supplementary Table S2.
Approximate TRL	TRL 1–3, conceptual/evidence synthesis (n = 46); TRL 3–5, laboratory/prototype validation (n = 3); TRL 6–8, pilot/project-scale demonstration (n = 8); TRL 2–4, early-stage evidence (n = 1).

The appraisal shows that the evidence base is dominated by literature/bibliometric reviews and conceptual/framework studies, whereas empirical, experimental, and case-based validation remains comparatively limited. A similar pattern is reflected in the validation scale and TRL classifications: most studies rely on literature-level or early-stage conceptual evidence, while fewer studies report laboratory/prototype validation or pilot/project-scale demonstration.

Construction relevance was generally high across the dataset, confirming alignment with construction, architecture, building, or built-environment applications. However, lifecycle coverage remained uneven, with stronger attention to design and fabrication/construction than to monitoring, quality control, lifecycle performance, or end-of-life

considerations. These findings indicate that AM research for sustainable construction has developed a substantial conceptual foundation, but field validation, lifecycle verification, regulatory readiness, and project-level implementation remain underdeveloped. Future research should therefore emphasize validated demonstrations, standardized LCA/LCC methods, code-compliant testing, and implementation-ready project evidence.

4. Results

4.1. Bibliometric Analysis

4.1.1. Publication Growth and Source Production

The trajectory of scholarly production between 2016 and 2026, as shown in Figure 4, indicates a growing interest in AM technology for sustainable construction. Based on the annual publication counts, publication activity can be described in three broad phases that correspond to the development of digital construction and sustainable AM research.

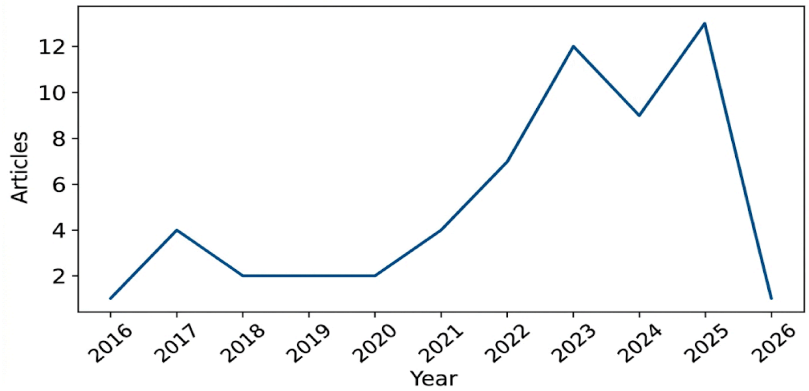


Figure 4. Annual publication growth from 2016 to 2026.

The inception phase (2016–2020) was characterized by limited publication activity that ranged from one to four papers annually and focused on theoretical aspects and on the feasibility of 3D concrete printing. It was then followed by an acceleration phase (2021–2023), with an inflection point in 2023. The number of papers almost tripled by 2023 due to growing international interest in the topic, driven by the urgent need for more sustainable construction approaches and the wider implementation of Industry 4.0 through the integration of emerging technologies. Finally, the recent expansion phase (2024–2026) indicates that the subject has become a sustained area of scholarly attention, resulting in 14 publications by 2025. This pattern shows that research interest in the topic has been significantly increasing in recent years. The lower value in 2026 reflects partial-year data collection because the literature search was conducted in January 2026 and it should not be interpreted as a decline in research activity.

The bibliometric results shown in Figure 5 identify the leading publication sources over the review period. These sources represent different but complementary disciplinary orientations, such as sustainability approaches, building applications, and construction management.

From 2016 to 2026, *Sustainability* (n = 15) and *Buildings* (n = 14), both published by MDPI, showed the highest cumulative publication output among the leading sources in the processed dataset. *Automation in Construction* (n = 8) and *Engineering, Construction and Architectural Management* (n = 5) were also prominent outlets, and these four sources accounted for 42 of the 58 records, whereas the remaining 16 records were distributed across lower-frequency journals and conference outlets. The records in *Sustainability* cover topics such as circular economy strategies, recycled materials, affordable housing, resource and

energy use, carbon emission reduction, and education or awareness related to digital transformation. Papers identified from *Buildings* contributed to studies related to DfMA (Design for Manufacturing and Assembly) and DfD (Design for Deconstruction/Disassembly), digital twin applications, 3D-printed construction, technology innovation, and workforce or skill requirements. In addition to these MDPI journals, Elsevier's *Automation in Construction* has remained one of the major publication sources in recent years, with studies generally emphasizing automation, digital construction processes, computational methods, and technology-enabled construction management. Emerald's *Engineering, Construction and Architectural Management* showed steadier but more moderate growth, contributing studies on technology adoption and implementation challenges.

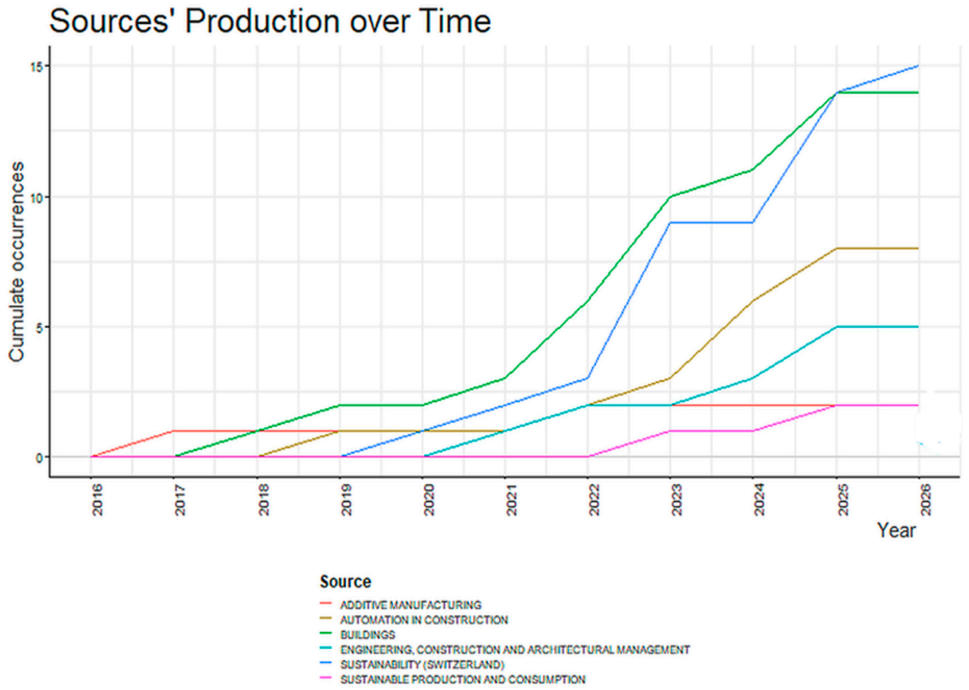


Figure 5. Publication source production during the review period.

The source distribution suggests that AM for sustainable Construction 4.0 is developing across multiple academic communities rather than within a single specialized domain. The field is also moving beyond early studies focused mainly on materials and printing processes toward broader concerns such as lifecycle performance, circular resource use, logistics, technology adoption, workforce readiness, and intelligent decision-making. This growth indicates that AM has developed from a specialized technical topic into an interdisciplinary research area with increasing relevance to the implementation of sustainable construction practices.

4.1.2. Keyword Patterns and Co-Occurrence Clustering

Using the bibliometrix R package, a word cloud and keyword co-occurrence network were generated to examine the dominant research interests in the field and thematic structure. Figure 6 illustrates keyword frequency across the selected studies. The word cloud provides a frequency-based overview of prominent keywords. As expected, the most prominent terms reflect the core keywords discussed in the Section 3, which were used to search and screen the literature, including additive manufacturing, construction, sustainability, and Construction 4.0. The prominence of these terms indicates that the reviewed literature is concentrated at the intersection of AM-enabled digital construction and sustainable development.



Figure 6. Keyword word cloud of the reviewed AM literature.

Beyond these, several thematic groupings of keywords are presented in the word cloud. Material- and process-related keywords, including concrete, cementitious materials, 3D concrete printing, digital fabrication, and architectural design, indicate that construction-scale printing applications remain an early-developed and still primary focus of the literature, consistent with the publication trend findings in the previous subsection. Digital technology keywords, such as digital twin, Internet of Things, artificial intelligence, robotics, automation, and building information modeling, suggest growing attention to the integration of AM within the Construction 4.0 ecosystem. Sustainability-related keywords, including life cycle, carbon emissions, environmental impact, circular economy, and sustainable development, indicate that environmental performance is increasingly examined through a lifecycle and circularity lens rather than through the printing process alone. Additionally, the presence of project management, technology adoption, and implementation-related keywords further indicates that the field is expanding toward implementation-oriented concerns such as adoption barriers and practical deployment.

In addition to the word cloud, Figure 7 presents the keyword co-occurrence network, in which construction industry functions as the central node around which six thematic clusters have formed, each represented by a distinct color.

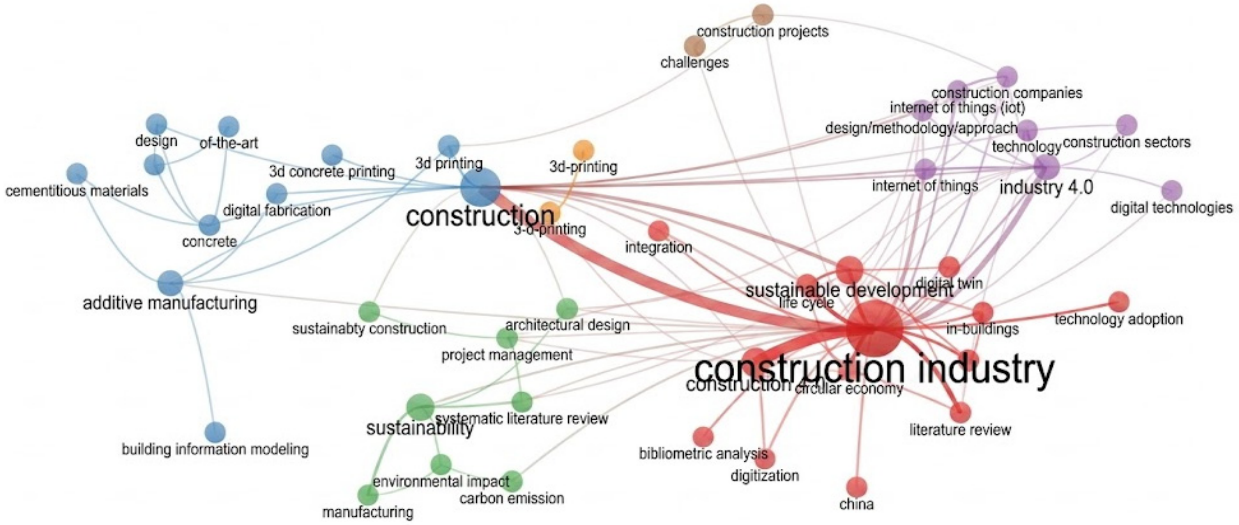


Figure 7. Keywords co-occurrence network.

The blue cluster (Cluster 1) represents the technical foundation of the field, grouping keywords such as additive manufacturing, concrete, cementitious materials, digital fabrication, 3D printing, and 3D concrete printing. The density of connections within this cluster indicates that material science and construction-scale printing applications remain the most established research area, with significant attention to adapting printable mixtures for automated construction workflows.

The green cluster (Cluster 2) and red cluster (Cluster 3) together reflect sustainability-oriented research from complementary perspectives. The green cluster focuses on environmental performance at the project and design level, encompassing terms such as sustainability, sustainable construction, environmental impact, carbon emissions, and architectural design. The red cluster extends these concerns into a broader lifecycle and industry-level context, with keywords including sustainable development, life cycle, circular economy, Construction 4.0, and digitization. These two clusters suggest that sustainability in the field is shifting from project-level environmental concern toward a more systemic discussion of circularity, digital transformation, and lifecycle thinking.

The purple cluster (Cluster 4) captures the digital infrastructure supporting AM in construction, centered on Industry 4.0, Internet of Things, digital technologies, and construction sectors. The connections between this cluster and the central construction industry node indicate that AM is increasingly discussed in relation to connected, data-driven, and intelligent construction systems rather than as a standalone technology. The remaining smaller clusters and peripheral nodes, including challenges, construction projects, systematic literature review, and terminology variations such as 3D-printing and 3d printing, highlight practical implementation barriers, deployment concerns, and the ongoing standardization of field terminology. These peripheral connections suggest that while the technical and sustainability dimensions of AM are well-developed, questions of scalability, adoption, and consistent classification remain active areas of discussion.

4.1.3. Collaboration Patterns and Geographical Distribution

As shown in Figure 8, the corresponding author country analysis reveals that research on AM for sustainable construction spans 19 countries and indicates a global presence. Australia leads in total publication output, followed by China and the United States. The majority of publications across most countries are classified as single-country publications (SCP), while multiple-country publications (MCP) remain comparatively limited. This pattern suggests that although research activity in this field is growing worldwide, international collaborative research remains limited, pointing to an opportunity for greater international knowledge exchange and collaboration in areas such as research-to-practice translation and comparative policy development. The country distribution reflects corresponding-author affiliations rather than the geographical locations of applied AM projects; therefore, the bibliometric pattern should not be interpreted as a direct map of case-study implementation locations.

The institutional affiliation analysis shown in Figure 9 reveals a relatively scattered pattern of research activity across universities. Universidad del Bío-Bío appears as the most productive institution, followed by Technische Universität Braunschweig. This pattern does not fully mirror the country-level distribution because the country analysis is based on corresponding authors, while the affiliation analysis reflects institutional output. As a result, some countries may show higher overall publication activity across multiple institutions, while individual institutions from other countries may appear prominently due to concentrated contributions. The affiliation pattern suggests that research activity is internationally distributed but still relatively decentralized in numerous research institutions across the world.

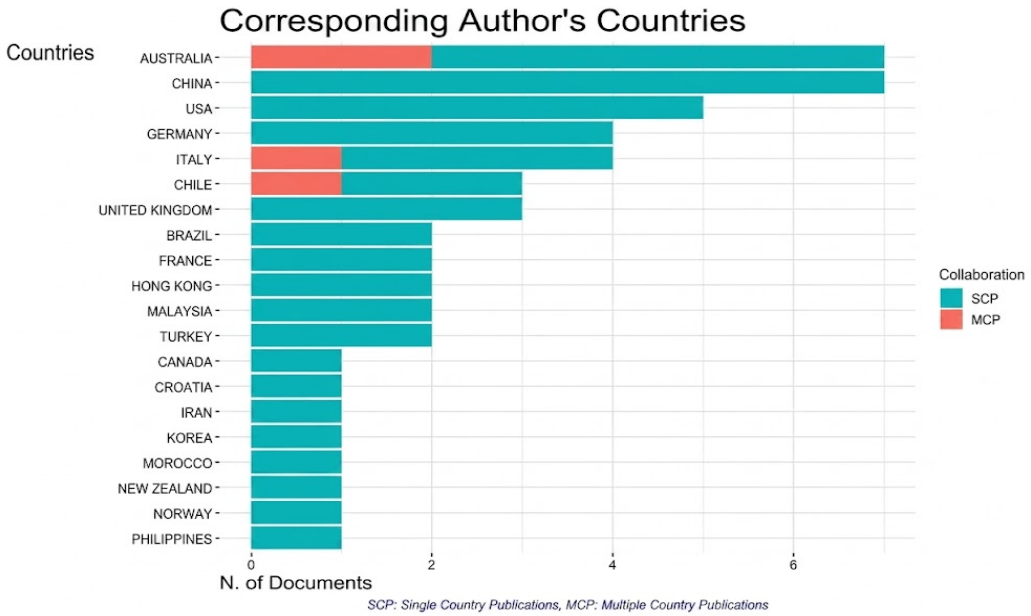


Figure 8. Corresponding-author country distribution.

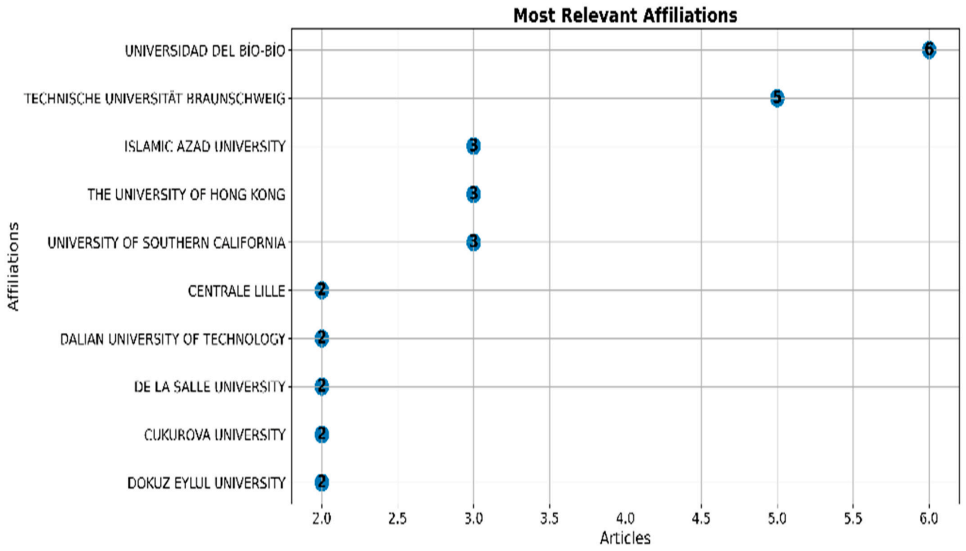


Figure 9. Affiliation of contributing institutions.

The co-authorship network shown in Figure 10 further supports the decentralized pattern observed in the institutional affiliation analysis. Sangiorgio V., Forcael E., and Opazo-Vega A. emerge as the most prominent nodes, reflecting stronger publication output and collaboration centrality within the selected review dataset. Sangiorgio's prominence is supported by contributions on lifecycle assessment of 3D printed concrete formwork and decarbonization in construction, while Forcael and Opazo-Vega are closely linked through a review of AM in the construction industry and a Construction 4.0 literature review. Beyond these central nodes, the network contains several smaller and relatively detached clusters, indicating that many research groups still collaborate within localized teams rather than through broader international networks. The co-authorship structure reflects a field in which knowledge production is distributed across multiple groups but remains only partially integrated, a pattern consistent with an emerging research area and suggesting significant scope for greater cross-institutional and international collaboration as the field evolves.

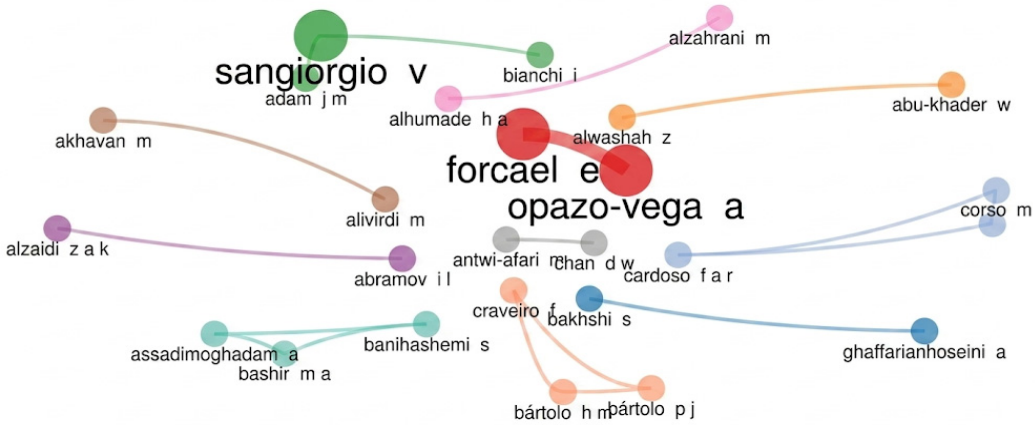


Figure 10. Collaboration network.

4.2. Thematic Analysis of Current Research Trends

The thematic analysis was conducted to identify the main research directions and emerging topics in additive manufacturing for sustainable Construction 4.0. As shown in Figure 11, centrality on the *x*-axis indicates how connected a theme is to the overall research field, while density on the *y*-axis reflects how internally developed or mature the theme is. Themes are classified into four quadrants: motor themes, which are well developed and highly connected; niche themes, which are internally developed but less connected; basic themes, which are highly connected but less internally developed; and declining or emerging themes, which are less developed and less central. Beyond the keywords used for searching and screening, the thematic clusters provide a clearer view of how Construction 4.0 technologies relate to AM across different applications for sustainable construction.

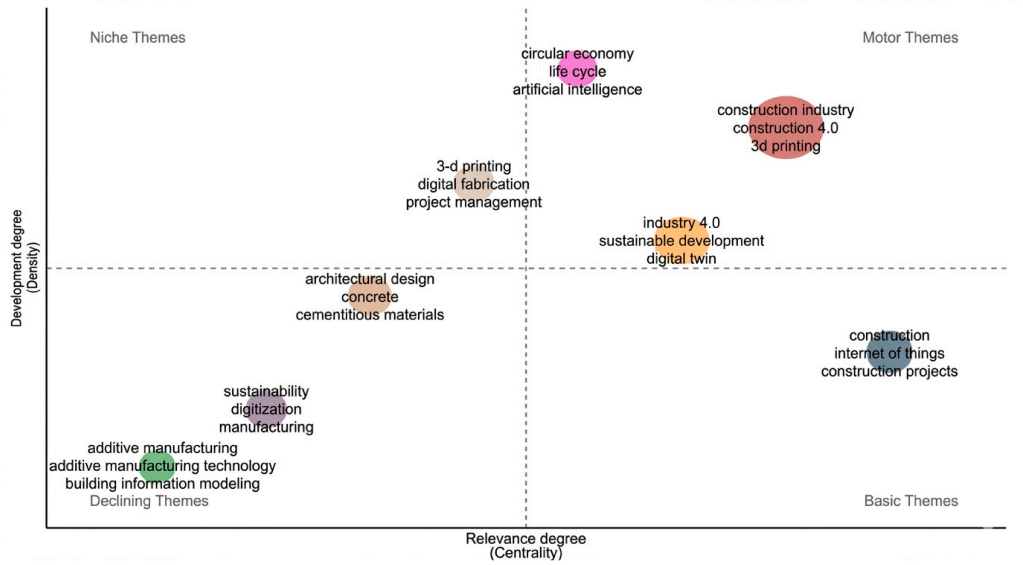


Figure 11. Thematic map of research topics.

A notable pattern in the map is that many themes follow a roughly diagonal distribution from the upper-right to the lower-left across the four quadrants, suggesting that the research topics in the field form a maturity gradient rather than sharply separated clusters. The exception is the basic themes cluster, where Internet of Things (IoT) and construction projects are broadly connected to the domain literature but remain less internally developed as a coherent research area. This cluster suggests a gap between the recognized relevance of IoT and project-level implementation and the current depth of research dedicated to IoT-enabled AM for sustainable construction.

Along the upper end of the diagonal, several themes reveal important current directions. Beyond the core search terms, circular economy, life cycle, and artificial intelligence appear as well-developed and highly connected themes. Their position suggests that sustainability is increasingly examined through lifecycle and circularity perspectives rather than through the printing process alone, while AI is becoming a more central topic in sustainable AM research for construction. Similarly, digital twin, sustainable development, and Industry 4.0 are positioned in the motor themes quadrant, indicating that digital integration and broader sustainability frameworks are becoming embedded in the mainstream research discussion.

In the niche quadrant, 3D printing, digital fabrication, and project management form a small cluster positioned close to the centrality axis. Their near-boundary location suggests that these topics are internally developed enough to form a coherent cluster, but they are not yet fully connected across the broader field. This may indicate that existing studies have examined how AM components can be designed and produced, but fewer have addressed how AM can be planned, coordinated, and integrated into real construction project delivery to support sustainability performance.

Toward the lower-left end of the diagonal, the declining or emerging themes include building information modeling (BIM), digitization, architectural design, concrete, and cementitious materials. The presence of BIM in this quadrant may suggest that, as one of the most important and broad concepts in construction, BIM is dispersed across multiple research contexts rather than concentrated within one mature cluster in AM for sustainable construction practices. Similarly, the positioning of concrete, cementitious materials, and architectural design suggests that material- and design-focused research remains relevant but is becoming more distributed as the field expands toward digital integration, lifecycle assessment, and implementation-oriented topics.

The thematic map suggests that current research on AM for sustainable Construction 4.0 can be organized into four trends, reflecting how the field is moving from technical feasibility and material development toward sustainability-oriented, digitally connected, and implementation-focused construction applications.

Across the four themes, the evidence shows unequal maturity. Material and process-control studies provide the strongest technical foundation, whereas lifecycle assessment, BIM-AM interoperability, data continuity, and project-level implementation remain less developed. This comparison indicates that AM is moving toward an integrated digital construction ecosystem, but the reviewed literature still provides limited empirical evidence of complete design-to-fabrication-to-lifecycle workflows.

4.2.1. Material Development and Innovation

This research trend focuses on material development and innovation in AM for sustainable construction. As identified from the thematic map, concrete and cementitious materials remain foundational because construction-scale AM still depends on materials that can satisfy both technical and sustainability requirements.

Cement-based materials remain the dominant feedstock for construction AM, especially in 3D concrete printing. Printability, pumpability, and durability are key indicators for dependable construction applications [38], while material rheology, buildability, and interlayer bonding strongly influence the structural performance of printed concrete components [34]. Cementitious composites are commonly designed to achieve extrudability, buildability, and appropriate open time [49]. However, cement-rich mixtures also raise sustainability concerns because of their high embodied carbon and energy demand. Therefore, current cementitious material for AM in construction increasingly focuses on balancing printability, structural reliability, and environmental performance.

Another major direction is the use of recycled, alternative, and bio-based materials. Recycled materials have been examined as a way to improve sustainability and resource efficiency in building applications [42], while waste recycling and embodied-carbon management have been identified as strategies for reducing reliance on natural resources [50]. Recycled high-density polyethylene, fly ash-based mixtures, recycled construction materials, and other alternative feedstocks have also been investigated for AM construction applications [11]. In parallel, cellulose fibers, wood particles, agricultural waste, and natural fibers such as hemp, flax, and bamboo have been incorporated into printable mixtures to improve rheological behavior, thermal performance, ductility, tensile strength, and crack resistance [51].

Structural and design optimization represents another important stream within material research in AM for sustainable construction. Topology optimization, finite element method simulations, and bi-directional evolutionary structural optimization are widely applied to generate lightweight structural forms and improve material distribution in 3D printing applications [16,37], directly supporting material efficiency and reduced resource consumption. These methods improve load-bearing performance while minimizing material use, reflecting a growing recognition that structural design decisions are as important as material selection in determining the sustainability outcomes of AM construction.

Material development has important implications for construction implementation. Printable mixtures require validation through pumpability, buildability, mock-up testing, and coordination among designers, contractors, equipment providers, and material suppliers. Recycled, alternative, and bio-based feedstocks may reduce resource demand, but reliable sourcing, consistent properties, and equipment compatibility remain necessary. Labor and quality-control requirements also increase because mix preparation, extrusion stability, interlayer bonding, and post-print inspection require specialized technical skills. Therefore, low-carbon and recycled printable materials should be evaluated not only for printability but also for structural performance, durability, code compliance, cost, and lifecycle benefits.

4.2.2. Digital Fabrication and Process Control

This research trend focuses on manufacturing processes and digital fabrication in AM for sustainable construction, reflecting a shift from isolated printing demonstrations toward digitally coordinated construction workflows, where process planning, toolpath control, robotic fabrication, and real-time monitoring increasingly shape both fabrication performance and sustainability outcomes. BIM, robotic fabrication, and real-time feedback have been combined to support closed-loop design and quality control [20], while computational design and digital twin monitoring have been integrated with robotic fabrication for large-scale shotcrete 3D printing [18]. AI-based methods, especially deep reinforcement learning [52], are also increasingly applied to path planning and adaptive process control [53,54], enabling more intelligent and resource-efficient manufacturing workflows.

Furthermore, research has also examined AM performance across different construction scales, from desktop-scale cementitious systems [36] and housing buildability configurations [14] to large-scale automated construction processes [55,56], while the capacity of AM to fabricate intricate and multifunctional components with high customization introduces additional considerations for process planning and material-use efficiency [17]. Design-oriented fabrication strategies, including Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD), have been emphasized as ways to improve modular construction, prefabrication efficiency, assembly coordination, and end-of-life resource recovery [16,20,57]. These approaches extend process planning beyond

the printing stage by considering how components are assembled, adapted, reused, and eventually deconstructed.

From a sustainability perspective, process-level optimization, including printing-parameter control, geometric control, and buildability analysis, has been examined to improve productivity and reduce material waste [10,14]. An integrated lean and green construction framework for AM has also shown that process-level decisions can directly influence sustainability performance [58]. Overall, digital fabrication and process control are increasingly connected to sustainability-oriented AM workflows, though the link between process-level advances and broader sustainability outcomes, including energy efficiency, systematic waste reduction, and project-level performance, remains insufficiently developed.

4.2.3. Lifecycle Assessment and Circularity

This research trend focuses on lifecycle assessment and circularity, reflected in the thematic map where life cycle and circular economy appear as well-developed and highly connected motor themes. Their prominence signals a shift from optimizing individual components toward evaluating AM's broader environmental, economic, and performance outcomes across the full construction lifecycle.

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have become the primary frameworks for evaluating AM's environmental and economic sustainability performance. Studies have applied these methods to examine recycled feedstocks for construction printing [43], evaluate the decarbonization potential of 3D-printed concrete formworks [59], and demonstrate AM's potential to support affordable housing by lowering costs while improving sustainability outcomes [11]. LCC follows a lifecycle-boundary logic similar to LCA but evaluates economic performance through cost categories such as material cost, equipment cost, labor cost, operation and maintenance cost, replacement cost, and end-of-life cost. More broadly, AM in construction digitalization has been linked to reduced energy use, lower waste generation, and improved resource efficiency across AM construction processes [10,60–62], reinforcing the connection between digital workflows and measurable environmental benefits.

However, sustainability assessment in AM remains methodologically inconsistent, as differences in functional units, system boundaries, modeling assumptions, and data quality often limit the comparability and reliability of LCA-based findings [38]. This indicates that current research is increasingly concerned not only with individual dimensions of sustainability performance, but also with how that performance is rigorously measured, compared, and verified. Overall, this trend reflects a clear shift from simple efficiency claims toward structured, lifecycle-oriented evaluation of sustainability performance of AM across the full construction process, with circular economy thinking increasingly shaping how long-term resource implications of AM are assessed and communicated.

4.2.4. Digital Integration and Project Implementation

This research trend focuses on digital integration and project implementation, connecting project management with technologies such as IoT, digital twins, and artificial intelligence. While digital integration appears as a well-developed theme in the thematic map, project-level implementation remains less internally developed, suggesting that research has increasingly recognized the technological potential of AM but has not yet fully examined its practical realization in sustainable construction projects.

Digital twins, AI-enabled systems, and Construction 4.0 technologies are increasingly used to connect AM performance with real-time monitoring, feedback control, and adaptive decision-making [21,54], supporting sustainability-oriented project delivery. The growing

presence of these technologies in the literature suggests that research is moving toward more data-driven AM systems capable of linking design, fabrication, monitoring, and evaluation within a single connected workflow. This transition is further shaped by broader industrial paradigm shifts, as Industry 4.0 adoption challenges around digitalization, BIM, and IoT have been examined through survey-based analysis [63], while Industry 5.0 perspectives have begun to emerge, reflecting interest in human-centered digital transformation for sustainable construction [61].

At the project level, large-scale AM implementation depends not only on printing performance but also on logistics, workflow coordination, equipment mobility, and integration with construction schedules. Research has shown that process reliability and scalability are key implementation challenges [39] and that logistics planning directly affects the continuity and operational efficiency of 3D printing construction projects [64]. These project-level factors collectively determine whether AM can deliver expected sustainability benefits such as reduced waste, improved resource efficiency, shorter construction timelines, and lower costs.

Organizational and workforce readiness are equally critical dimensions of this trend. Organizational resistance, lack of process integration, and technology acceptance difficulties have been identified as persistent barriers to AM implementation [65], while industrialized and standardized building methods have been proposed as enablers of more productive AM-based construction [64]. Automation and process integration have been emphasized as necessary conditions for large-scale deployment [6], and workforce skills remain critical since effective digital integration depends not only on technology adoption but also on the capability to operate and manage digitally connected construction systems [66].

This trend reflects a broadening of AM research toward project-level and system-level considerations, including logistics, digital coordination, organizational readiness, and workforce capability. These dimensions are essential for realizing the sustainability potential of AM at construction scale.

Digital integration has direct implications for project delivery, supply-chain coordination, quality control, and lifecycle performance. BIM workflows, digital twins, IoT-based monitoring, and AI-enabled analytics can connect design, fabrication, installation, inspection, and operational data within a coordinated information environment. Such integration can improve material traceability, logistics planning, performance verification, code-compliance documentation, and lifecycle assessment. However, interoperability, cybersecurity, data ownership, certification, and workforce readiness remain key barriers to routine project-level adoption.

5. Discussion

5.1. Emerging Digital Technologies Supporting AM for Sustainable Construction

This discussion interprets AM through the lens of BIM-centered information continuity. AM can support sustainable construction only when digital design, material data, robotic fabrication, sensing, inspection, lifecycle assessment, and project coordination are connected through interoperable workflows. As discussed in Section 4, Industry 4.0 technologies have become important enablers of AM in sustainable construction, supporting materials development, process optimization, project implementation, and lifecycle performance. Based on the systematic review of 58 academic publications, the most frequently discussed technologies include BIM/digital twins, advanced robotics, IoT/IIoT, AI, big data and analytics, and cloud computing (Figure 12). Together, these technologies reflect an emerging trend in which AM is evolving from a primarily fabrication-focused process toward a more integrated, data-driven construction system. They support improvements in manufacturing

precision and process monitoring while also enabling data-driven decision-making across the construction project lifecycle to reduce waste, energy use, and environmental impacts.

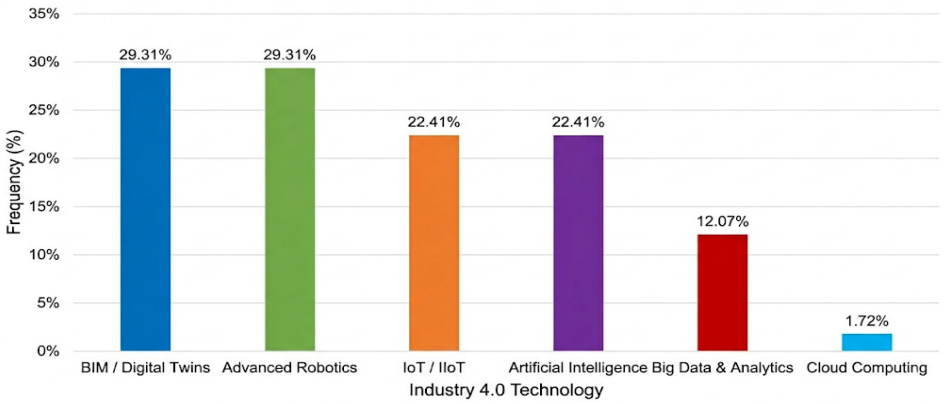


Figure 12. Distribution of Industry 4.0 technologies reported in the reviewed AM literature for sustainable construction.

As shown in Figure 12 and interpreted alongside the thematic map in Figure 11, BIM/digital twins and advanced robotics are the most frequently represented technologies, each appearing in 17 studies (29.31%). BIM/digital twins primarily support design-data integration, simulation, lifecycle modeling, and information continuity. These functions contribute to coordination, reduced rework, lifecycle tracking, and BIM-enabled lifecycle and carbon assessment [12,20,21,44]. Advanced robotics enables automated fabrication, robotic deposition, site automation, and process execution. These applications support improved precision, productivity, quality consistency, and waste reduction [14,18,53,55]. IoT/IIoT and artificial intelligence each appear in 13 studies (22.41%). IoT/IIoT provides sensor-based monitoring, real-time feedback, and process data capture for quality control, resource tracking, and performance verification [12,26,67,68]. Artificial intelligence supports path planning, optimization, predictive analytics, and decision support for adaptive control, material and process efficiency, and reduced trial-and-error [21,53,54]. Big data and analytics appear in 7 studies (12.07%) and mainly enable sustainability monitoring and evidence-based project decisions through performance analytics and multi-source data interpretation [19,21,54]. Cloud computing is the least represented at 1 study (1.72%), but it remains relevant for data sharing, remote coordination, and collaborative project-scale information management [19].

This pattern aligns with the thematic map findings and suggests that BIM has attracted broad research interest across multiple AM-related contexts rather than one specific application area. Established research has focused mainly on digital design integration, robotic fabrication, and intelligent process control, while broader data infrastructures, cloud-based coordination, and systematic integration across technologies remain less developed. Future research should move beyond isolated applications toward integrated, data-driven workflows that connect AM processes, digital construction systems, sustainability indicators, and lifecycle performance evaluation.

The identified integration pattern is interpreted as emergent rather than mature. BIM can organize design geometry, material data, toolpath information, quality records, and LCA/LCC inputs; digital twins and IoT can support feedback from fabrication and monitoring; and AI and robotics can support optimization and adaptive control. However, limited evidence demonstrates continuous interoperability across these stages in real projects. The evidence gap constrains claims regarding fully integrated AM workflows.

5.2. Current Gaps and Future Research Opportunities

Building on the bibliometric findings, thematic trends, and current digital technology applications, several critical gaps remain in advancing AM from technical feasibility toward reliable, scalable, and sustainable construction implementation. These gaps relate to process reliability, structural performance, lifecycle sustainability assessment, digital integration, standardization, and workforce readiness.

First, there is a need to advance manufacturing efficiency and process reliability in construction-scale AM. Although recent studies have demonstrated closed-loop fabrication information modeling, tower-crane-based 3D printing, and multi-functional shotcrete printing, most applications remain limited to controlled demonstrations or isolated case studies [6,14]. Current systems also rely heavily on predetermined toolpaths, which limits their ability to respond to unexpected conditions during printing [53]. The transition to real construction environments is still constrained by external variables such as temperature, humidity, material flow, curing behavior, site conditions, and equipment mobility [33]. Therefore, advancing large-scale construction deployment requires systems in which deposition quality, dimensional accuracy, layer stability, and extrusion consistency can be maintained continuously under changing site conditions.

Next, structural implementation in construction-scale AM remains challenging due to interlayer bonding, anisotropic behavior, and reinforcement placement difficulties [46]. Although material studies have examined printability, pumpability, buildability, and durability, long-term performance validation of printed structural elements remains limited [24,38]. This gap becomes more significant when recycled, alternative, or bio-based materials are used, as their field performance, moisture resistance, fire behavior, and long-term durability under real construction conditions have not yet been fully established [43,51].

Furthermore, the assessment of sustainability in AM remains fragmented and insufficiently connected to implementation practice. AM is often described as sustainable because it can reduce formwork, material waste, and construction time. However, its actual environmental performance depends on multiple factors, including binder composition, robotic energy consumption, material transportation, logistics, maintenance, service life, and end-of-life strategy. Current LCA and LCC approaches remain difficult to compare across studies because of differences in functional units, system boundaries, data assumptions, and assessment scope [59,64]. As a result, the sustainability benefits of AM are often discussed conceptually rather than verified through consistent lifecycle-based evidence. Future research should therefore develop more standardized and comparable assessment frameworks capable of evaluating AM sustainability across material, process, project, and lifecycle dimensions.

A further gap concerns the limited integration of digital technologies and the absence of industry-wide standardization needed to support sustainable AM construction on a scale. As discussed in Section 5.1, while technologies such as BIM, digital twins, IoT, AI, and robotics are widely present in the literature [44,53,54], fewer studies demonstrate how they can operate together within a closed-loop AM construction system. This lack of a unified synthesis framework and interoperability limits real-time decision-making, data continuity, quality control, lifecycle tracking, and circular material management. Economic feasibility also remains insufficiently examined because advanced robotics, sensing systems, digital twins, and AI-enabled analytics may require high initial investment, specialized expertise, software integration, and maintenance. Future studies should therefore combine LCC, cost–benefit analysis, and lifecycle performance assessment to determine whether digital AM technologies are affordable and scalable under real project conditions. This challenge is further compounded by the absence of mature standards, building codes, testing protocols, and industry-wide certification procedures, which forces many projects to

rely on case-by-case validation and undermines the efficiency gains that digital integration is expected to deliver. Beyond technology, adoption also depends on workforce readiness, digital skills, organizational acceptance, and regulatory support, and current studies indicate that future construction systems must address human and institutional readiness alongside automation [28,68]. Therefore, future research should examine how integrated digital ecosystems, supported by standardized frameworks and capable workforces, can enable sustainable AM construction across the full construction lifecycle from design and fabrication through to operation and post-construction.

5.3. Toward a Proposed Pathway for Sustainable AM in Construction 5.0

Construction 5.0 is framed in the present review as a proposed future pathway for AM in sustainable construction, rather than as a fully evidenced outcome of the reviewed literature. The findings indicate that AM research has advanced in material innovation, digital fabrication, lifecycle assessment, and digital integration; however, gaps remain in field validation, regulatory readiness, lifecycle verification, workforce capability, and project-scale implementation. Future development of AM should therefore move beyond isolated technical improvements toward an integrated construction ecosystem connecting digital systems, project workflows, practitioners, standards, policies, and community impacts. While Construction 4.0 emphasizes digitalization, automation, and data-driven construction, Construction 5.0 broadens the research agenda toward human-centered innovation, resilience, sustainability, and societal value [68].

5.3.1. Human-Centered AM and Human–Robot Collaboration

As AM systems are increasingly deployed on construction sites through robotic arms, gantry-based printing systems, mobile robots, and hybrid fabrication platforms, sustainable performance depends not only on printing efficiency but also on how workers, engineers, operators, and inspectors interact with these systems. As AI continues to transform robotics research and AM systems become more capable of acting as embodied agents on site, future research should examine how onsite practitioners engage with automated equipment across assembly, fabrication, monitoring, inspection, and quality control tasks. This includes understanding how intelligent sensing, real-time communication, operator feedback, and shared situational awareness can support safer work practices while advancing sustainable construction goals through improved safety, material quality, resource efficiency, and responsible automation.

5.3.2. Workforce Upskilling and Sustainability Readiness

The successful adoption of AM for sustainable construction depends on preparing the workforce for digitally connected and robotically assisted work environments. Education and training programs should define the competencies needed for AM-enabled construction and AI literacy across the design, fabrication, and decision-making stages. Importantly, workforce readiness should not be limited to technical skills. Future training should also embed sustainability awareness and literacy, including an understanding of material efficiency, waste reduction, lifecycle impacts, carbon implications, and circular construction strategies. This is critical for preparing the next generation of construction workers and practitioners to translate AM's sustainability potential into actual project outcomes. Without a workforce capable of integrating both digital capabilities and sustainability awareness, AM adoption may improve automation while still falling short of delivering meaningful environmental and social benefits.

5.3.3. Interdisciplinary Collaboration and Knowledge Integration

As identified from the bibliometric and thematic analyses, advancing AM for sustainable Construction 5.0 requires stronger interdisciplinary and cross-sector collaboration. The bibliometric analysis shows that while AM research for sustainable construction is globally distributed, international collaboration remains limited, with many studies concentrated within single-country publications and localized research clusters. Moving forward, broader collaboration among construction researchers, material scientists, robotics engineers, computer scientists, sustainability experts, policymakers, and industry practitioners is essential for integrating the diverse knowledge needed to address the full complexity of sustainable AM construction. Strengthening these connections can help the field move beyond fragmented technical studies toward shared frameworks, practical guidelines, and integrated AM systems that consistently deliver sustainability outcomes across material, process, project, and lifecycle dimensions.

5.3.4. Policy, Standards, and Industry Transition

Future research should contribute to AM-specific building codes, material certification standards, quality inspection protocols, and regulatory approval procedures. These mechanisms are necessary to reduce reliance on case-by-case field validation and increase industry confidence in AM-based construction. Importantly, standards and policies should not focus solely on structural safety or technical compliance, but should also support sustainability incentives and verification, encompassing lifecycle performance, material circularity, waste reduction, and long-term durability. To support research-to-practice translation, closer collaboration is needed among researchers, contractors, material suppliers, regulatory agencies, and robotics organizations, helping to align technical innovation with real project constraints, industry needs, and practical implementation pathways. In addition, policy incentives and sustainability-oriented procurement strategies may be needed to encourage the adoption of low-carbon materials, circular design practices, and lifecycle-based performance evaluation in AM construction. Together, these efforts are essential for enabling AM to demonstrate reliable environmental, economic, and social value in future construction practice.

5.3.5. Implications for Architectural Practice

For architectural practice, sustainable AM has implications for design-to-fabrication coordination rather than for architectural expression alone. Parametric modeling, BIM authoring, digital twins, material specification, fabrication constraints, and post-occupancy evaluation need to operate as an integrated workflow. Architects and design teams will also need methods for specifying low-carbon printable materials, coordinating printed components with conventional building systems, assessing surface quality and spatial performance, and verifying environmental performance after occupancy. These implications should be interpreted as opportunities for architectural practice within a broader construction ecosystem, supported by material evidence, digital workflow integration, regulatory acceptance, and lifecycle performance data [15,17,20,21].

5.3.6. Societal Value and Broader Impacts

AM should also be evaluated for its broader societal contributions toward the goals of Construction 5.0. Future research should examine how AM can support affordable housing delivery, disaster recovery, local material use, workforce inclusion, and regional construction resilience. Sustainability is not only an environmental challenge but also a social and economic one, and AM holds long-term potential to improve accessibility, strengthen local supply chains, support workers, and respond to diverse community needs.

Therefore, future AM research in construction should assess sustainability outcomes across environmental, economic, and social dimensions, ensuring that technological advancement translates into tangible benefits for broader communities and contributes meaningfully to the social goals of sustainable construction practice.

6. Conclusions

This study presented a systematic and bibliometric review of additive manufacturing within the context of sustainable Construction 4.0 and a proposed future pathway toward Construction 5.0. Based on 58 peer-reviewed publications from January 2016 to January 2026, the findings show that the field has shifted from early theoretical and feasibility-oriented studies toward broader interest in scalability, practical implementation, digital integration, lifecycle assessment, circularity, and project-level delivery. The analysis indicates a clear rise in publication activity after 2021, with growing contributions from journals focused on sustainability, buildings, automation, and construction management. The results also show strong thematic links among additive manufacturing, sustainability, Construction 4.0, concrete, digital twins, artificial intelligence, IoT, and circular economy. Among the emerging technologies, advanced robotics, BIM, and digital twin-related applications receive the greatest research attention. The thematic analysis further suggests that manufacturing-processes research is relatively more developed, whereas materials, sustainability assessment, and digital integration still require deeper incorporation into routine construction practice. These findings indicate that the future of additive manufacturing in construction will depend on closer alignment between technological innovation, sustainable material development, and BIM-centered project implementation.

Overall, the review answers RQ1 most strongly through bibliometric evidence, addresses RQ2 through thematic interpretation of AM-digital technology relationships, and addresses RQ3 by identifying gaps in interoperability, lifecycle verification, standardization, workforce readiness, and project-scale validation.

Despite these insights, this study has several limitations. First, the review was based on two major bibliographic databases, Scopus and Web of Science, and was restricted to English-language publications. Relevant studies indexed only in other databases, published in other languages, or available through industry reports, standards, and regional technical documents may therefore have been excluded. Second, the results are sensitive to the selected search strings and terminology; studies using different terms for additive manufacturing, digital fabrication, construction-scale printing, or sustainable construction may not have been retrieved. Third, bibliometric mapping and clustering are affected by citation practices, database coverage, keyword quality, indexing inconsistencies, and software settings; therefore, the clusters should be interpreted as analytical patterns rather than fixed categories. Fourth, the review protocol was not registered before the study, which limits external verification of any protocol changes. Fifth, although a structured quality and maturity appraisal was added, it remains descriptive and interpretive rather than a formal risk-of-bias assessment. Finally, citation-based indicators may favor older or highly visible publications and may underrepresent emerging work with practical relevance but limited citation history. Future reviews should consider broader databases, multilingual and grey-literature sources, registered protocols, independent coding with inter-rater agreement, and more formal quality-appraisal tools.

Building on the results and gaps identified in Sections 4 and 5, future research should prioritize integrated workflows that connect BIM-based digital design, material data, robotic feedback, process monitoring, and lifecycle assessment; validated material and structural performance under real construction conditions; standardized LCA/LCC methods for comparing AM with conventional construction; and project-level demonstrations

that evaluate cost, quality control, supply-chain coordination, labor readiness, regulation, and long-term performance. Construction 4.0 represents the current digital-construction context reviewed in this study, whereas Construction 5.0 is proposed as a future pathway because existing Construction 4.0 applications still face limitations in interoperability, lifecycle verification, regulatory readiness, workforce capability, and project-scale implementation. Construction 5.0 should therefore be understood as a proposed future research pathway for AM rather than a fully established outcome. Future studies should also compare AM with conventional construction methods using standardized LCA and LCC procedures, making the comparison a future research direction rather than an objective already completed in the present review. Advancing this pathway will require stronger collaboration among designers, engineers, contractors, material suppliers, robotics specialists, policymakers, and sustainability experts so that AM can move from isolated demonstrations toward reliable, scalable, human-centered, and sustainable digital construction practice.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/architecture6030110/s1, PRISMA 2020 checklist; Table S1: Included studies and extracted characteristics (n = 58); Table S2: Quality and maturity appraisal of included studies (n = 58). The references for the studies listed in Tables S1 and S2 have been included in the manuscript reference list [6,10,11,14,16–21,24–29,36,38,39,41–44,53–88].

Author Contributions: Conceptualization, F.Y. and Z.Z.; methodology, F.Y.; software, F.Y.; validation, F.Y., Z.Z. and A.D.; formal analysis, F.Y.; investigation, F.Y.; data curation, F.Y. and Z.Z.; writing—original draft preparation, F.Y.; writing—review and editing, F.Y., Z.Z. and A.D.; visualization, F.Y.; supervision, Z.Z. and A.D.; project administration, F.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The bibliographic records analyzed in this study are available from the authors upon request.

Acknowledgments: The authors used AI tools, including ChatGPT (GPT-5.5, OpenAI) and Claude (Fable 5 High, Anthropic), only for grammar proofreading and academic writing refinement. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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