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Original Article

Advances, Gaps and Perspectives of Concrete Additive Manufacturing in Construction 4.0: A Systematic Review

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Abstract *- This systematic review article on Concrete Additive Manufacturing (3DCP) within the framework of Construction 4.0 aims to synthesize the available scientific knowledge, focusing on technological advances, research gaps and future perspectives. This research, according to its purpose, is applied, it is descriptive-explanatory according to its level, it is non-experimental-cross-sectional according to the research design and has a qualitative approach. The research is developed following the guidelines of the PRISMA 2020 statement and the SPAR-4-SLR protocol, for this purpose, a group of 896 articles related to the study has been identified, of which only 90 are included for the synthesis of information, since they meet the identification, screening and eligibility criteria. The results highlight the technological advances of the mechanical properties, especially deepening in the anisotropic behavior that is inherent to layer printing and defines the integrity of the structures, however, the industrial objective still faces challenges, with the main research gaps being experimental validation and methodological reproducibility under various scenarios and finally looking towards future perspectives, the horizon of the industry focuses on structural optimization, seeking superior mechanical performance that allows additive manufacturing to compete directly with traditional construction methods.*

Keywords *- Construction 4.0, Concrete additive manufacturing, 3D concrete printing, Prefabrication, Digital technologies.*

1. Introduction

At a global level, the construction industry is driven to decarbonize its processes, overcome the stagnation of its productivity and solve the shortage of qualified labor. In this scenario, the Construction 4.0 paradigm emerges as the strategic convergence between digital and industrial automation technologies, such as proposals of digital interoperability models, a clear example is the technological triad of Building Information Modeling (BIM), Artificial Intelligence (AI) and Big Data in robotic systems. Within this ecosystem, Concrete Additive Manufacturing (3DCP) stands out as one of the most relevant innovations on a global scale, by allowing the automated construction of complex structures through the continuous deposition of cementitious mixtures layer by layer directly from a digital model, with potential to reduce the construction schedule and eliminate the need for traditional formwork [1].

In the context of Latin America, this technology is not unrelated to the concern in the construction sector, the incorporation of this technology has advanced progressively from experimentation in laboratories and academic offices toward real industrial applications in countries such as Mexico and Colombia, led by large cement consortia [2]. Nevertheless, it faces critical barriers due to the high initial cost of importing robotic machinery, the main ones being articulated arms and gantry systems, supply of provisions and additives [3].

Previous research has identified economic, technical and work-culture barriers to the adoption of robotic and automated systems in construction [4]. In Peru, the WasiTek project, shown in Figure 1, illustrates research on robotic additive construction for post-disaster housing. Developed with the participation of the Pontifical Catholic University of Peru (PUCP), the initiative investigated local earth-based materials modified with natural polymers extracted from industrial waste [5, 6]. This project provides regional context for the exploration of automated construction using locally available materials. Its earth-based material system differs from the cementitious mixtures examined in the present review, which focuses on concrete additive manufacturing within Construction 4.0. In regions such as Huancayo, concrete additive manufacturing represents a potential research opportunity for developing housing and infrastructure solutions adapted to local raw materials and construction

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conditions. International evidence on the rheological requirements of printable cementitious mixtures [7] can inform future studies on the use of local aggregates, mixture stability and compatibility with automated printing processes. Examining this evidence can help identify technological advances with potential regional applications, as well as limitations requiring further experimental validation. Accordingly, the present review focuses on international advances, gaps and perspectives in concrete additive manufacturing within Construction 4.0, providing a basis for future research and technological transfer to contexts such as the Peruvian central highlands. The most relevant contribution of this research consists of providing a comprehensive and updated vision of the state of the art on concrete additive manufacturing as an enabling technology of Construction 4.0, integrating evidence coming from different disciplines related to cementitious materials, automation, robotics, artificial intelligence, Internet of Things, BIM and digital twins. Building on previous reviews linking concrete additive manufacturing with Construction 4.0 [19], this study provides a structured synthesis of 90 articles, organizing the evidence into thematic trends, technological advances, technological integration, research gaps and future perspectives.

The obtained results constitute a record of scientific data to guide future studies, support the development of technical standards and streamline the decision-making processes of researchers, construction companies and organizations responsible for the digital transformation of the sector.

The review addresses the following research questions:
RQ1. What advances in concrete additive manufacturing and its integration with Construction 4.0 technologies are reported in the reviewed literature?
RQ2. What research gaps and implementation challenges are identified for concrete additive manufacturing within Construction 4.0?
RQ3. What future research directions are identified for concrete additive manufacturing within Construction 4.0?



Fig. 1 WasiTek project, PUCP, Lima, Peru.

Source: PuntoEdu [6]. Photograph: Héctor Jara.

2. Literature Review

The literature on concrete additive manufacturing shows a progressive evolution from the first developments aimed at demonstrating technical feasibility at construction scale toward approaches more integrated with the digital transformation of the sector. Lim et al. (2012) constitute a main precedent by describing the initial advances of additive manufacturing processes applied in construction, highlighting the increase in execution speed and dependence on human capital, although they also pointed out difficulties associated with quality control, geometric precision and commercial adoption [8]. Although this work predates the main analysis period of the systematic review, it is considered relevant due to its historical value in the consolidation of the field of study.

Subsequently, Bos et al. (2016) analyzed disruptive capacity of 3D concrete printing to revolutionize traditional building systems, mainly due to its ability to dispense with formworks and mitigate waste generation. However, their study also evidenced technical limitations related to the formulation of cementitious mixtures, adhesion between layers and the lack of standardized procedures for a reliable industrial implementation [9]. In the same line, Wangler et al. (2016) introduced the concept of Digital Concrete, highlighting that 3D concrete printing does not depend only on the material, but on the coordinated interaction between computational design, robotics, automation and process control [10].

From a technological review perspective, Paolini, Kollmannsberger and Rank (2019) organized the additive manufacturing processes applied to construction, their applications in buildings and infrastructure, and the digital planning methods required for their implementation. Their work allowed recognizing the importance of integrating tools such as BIM and digital planning, although it also identified interoperability and industrial scalability as persistent challenges [11]. Complementarily, Ngo et al. (2018) reviewed materials, methods, applications and challenges of additive manufacturing in different sectors, highlighting that construction possesses high potential due to design customization, material reduction and sustainability improvement, but requires greater advances in new materials and process standardization [12].

In relation to material behavior, Roussel (2018) established that the performance of printable cementitious materials depends on specific rheological requirements, among them extrudability, dimensional stability and interlayer adhesion capacity. These parameters directly condition printing quality and the structural performance of the manufactured elements; therefore, they continue being a critical axis of research for Concrete Additive Manufacturing (3DCP) [7]. This line of study evidences that additive manufacturing cannot be evaluated only from equipment automation, but also from the interaction between fresh material, deposition process and mechanical response of the printed element. In recent years, the literature has broadened its approach toward the integration of additive manufacturing with technologies characteristic of Construction 4.0. Zhang et al. (2021) analyzed the application of artificial intelligence in construction engineering and management, with particular attention to fuzzy modeling and reasoning [13]. More recently, Jaiswal, Hunt, and Davies (2024) identified that BIM, artificial intelligence, IoT, robotics, digital twins and 3D printing form the technological core of Construction 4.0 in developing countries, although their adoption is still limited by insufficient infrastructure, specialized training and the absence of consolidated standards [14].

Overall, the reviewed background evidence that concrete additive manufacturing has gone from being studied as an experimental manufacturing technique to being understood as an enabling technology within digital construction ecosystems. Nevertheless, the literature remains fragmented among studies focused on materials, printing processes, automation, artificial intelligence, BIM, IoT or digital twins. This dispersion makes an integral understanding of the advances and of the gaps that condition its large-scale implementation difficult. Therefore, the present systematic review seeks to articulate these lines of research in a single analysis on advances, gaps and perspectives of Concrete Additive Manufacturing within the framework of Construction 4.0.

3. Methodology

This research, according to its purpose, is applied, according to its level, it is descriptive-explanatory, it is non-experimental-cross-sectional in terms of the research design and qualitative approach [15, 16]. The research was developed around a systematic literature review on the Advances, gaps and perspectives of Concrete Additive Manufacturing in Construction 4.0, the objective is to synthesize the scientific evidence related to the concept of Concrete Additive Manufacturing in the context of the other concept of Construction 4.0.

The methodological process of information collection and processing was designed combining the PRISMA 2020 statement and the SPAR-4-SLR protocol, to support transparent and systematic reporting of the search, selection, evaluation and synthesis [17, 18].

The PRISMA 2020 statement provided the methodological structure to document the process constituted by four stages, adapted in this study as identification, bibliometric and documentary verification, thematic screening, and final retrieval and eligibility assessment leading to inclusion, represented in Figure 2, and simultaneously and vertically the SPAR-4-SLR protocol guided the planning of the review, in its three stages being the first of assembling, the second of organizing and the third of

evaluating, represented in Figure 5. Both frameworks allowed organizing the systematic review in such a way that it is based on explicit selection criteria and on methodological procedures widely accepted for high-quality literature reviews [17, 18].

3.1. Application of the PRISMA 2020 Statement

The PRISMA 2020 statement guided the reporting of the study selection process, as can be distinguished in Figure 2 [17].

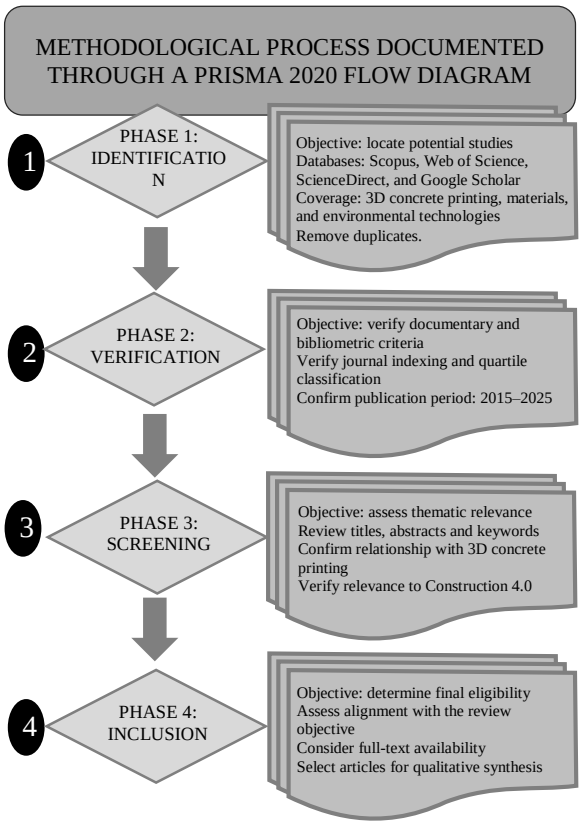

Fig. 2 Process flow diagram according to the PRISMA 2020 statement, adapted to the study [17, 19].

The diagram in Figures 2 and 3 detail the methodological process of study selection according to the combination of methodologies: the PRISMA 2020 statement hand in hand with the SPAR-4-SLR protocol. The search strategy focused on the Boolean combination of three conceptual groups: the Advances, gaps and perspectives of concrete additive manufacturing, Construction 4.0 and its application sectors.

The literature search was conducted on 12 June 2026 across Scopus, Web of Science, ScienceDirect and Google Scholar, yielding 896 records before duplicate removal. Only this aggregate figure is reported, since the number of records retrieved from each database was not preserved. These records then passed through the screening and eligibility stages described in Section 3.1.1, which resulted in 90 articles being included in the systematic review. Two aspects of this process, however, constrain its reproducibility. The lack of source-specific counts prevents the search from being fully verified, and the continual updating of Google Scholar's indexed content means that repeating the same search would likely return different results. Both are therefore acknowledged as methodological limitations.

3.1.1. Actions Recorded for Information Processing

The actions for the exclusion and inclusion of data are distinguished in these 4 levels:

Level 1 (Identification): Identification is carried out through the search of concepts: Concrete additive manufacturing) AND (Group 2: Construction 4.0) AND (Group 3: Application sector) a total of articles of n = 896 is recorded, and duplicate records that come to be 114 articles, are subtracted, resulting in 782 articles, presented in Equation (1):

$$\text{Total n° of information - level 1 filtering} = \text{remaining level 1} \quad (1)$$

$$896\text{-}114 = 782$$

Records remaining after duplicate removal: $n = 782$

Duplicate records were identified manually in Excel, primarily by comparing DOIs together with the associated bibliographic metadata. For records lacking a DOI, duplicates were detected instead by cross-checking titles, authors and publication years. Whenever a set of duplicates was found, only the most complete bibliographic record was retained. This process led to the removal of 114 duplicate records, leaving 782 unique records for screening.

Level 2 (Verification): The 782 records retained from Level 1 were checked for documentary compliance, journal indexing and SJR/JCR quartile classification (Q1–Q4), without a formal assessment of individual studies' methodological quality. All records met these verification criteria and were retained for title, abstract and keyword screening, as shown in Equation (2):

$$\text{Remaining level 1 -level 2 filtering} = \text{remaining level 2} \quad (2)$$

$$782\text{-}0 = 782$$

Records retained for thematic screening: $n = 782$

Level 3 (Screening): A total of remaining articles from level 2 of 782 is recorded, and the articles that do not meet the thematic relevance requirements (Screening by title, abstract and keywords) are subtracted and are excluded for being outside the thematic, sectoral or conceptual scope (irrelevance), and come to be 369 articles resulting in 413 articles, presented in Equation (3):



Fig. 3 Diagram created according to the PRISMA 2020 and SPAR-4-SLR statements, adapted to the study

Exclusions: n = 369 records excluded for being outside the thematic, sectoral or conceptual scope (irrelevance).

Remaining level 2 -level 3 filtering=remaining level 3 (3)

782-369= 413

Records retained after screening of titles, abstracts and keywords: *n = 413*

Level 4 (Inclusion): Of the remaining 413 records from Level 3, 323 were removed due to misalignment with the research objective, such as the use of construction materials other than concrete, and the unavailability of the full text. The remaining 90 articles were included in the final synthesis, as presented in Equation (4):

Remaining level 3 -level4 filtering=Final resulting articles (4)

413-323= 90

The search and selection process narrowed the initial 896 records down to 90 scientific articles, which form the body of evidence for this systematic review. Figures 6–10 present the thematic classifications and frequencies derived from the 90 articles included in this systematic review.

Within these figures, the article served as the unit of counting, and the thematic categories were not mutually exclusive: an article could be assigned to more than one category depending on the topics it addressed. Percentages were accordingly calculated with all 90 included articles as the denominator. Because some of these articles are reviews that may draw on overlapping primary studies, the resulting frequencies should be read as indicators of coverage across publications rather than as counts of independent experimental findings. During manuscript revision, one author verified the eligibility and thematic classification of the included studies and a second author checked these decisions. Any disagreements were resolved through discussion and consensus.

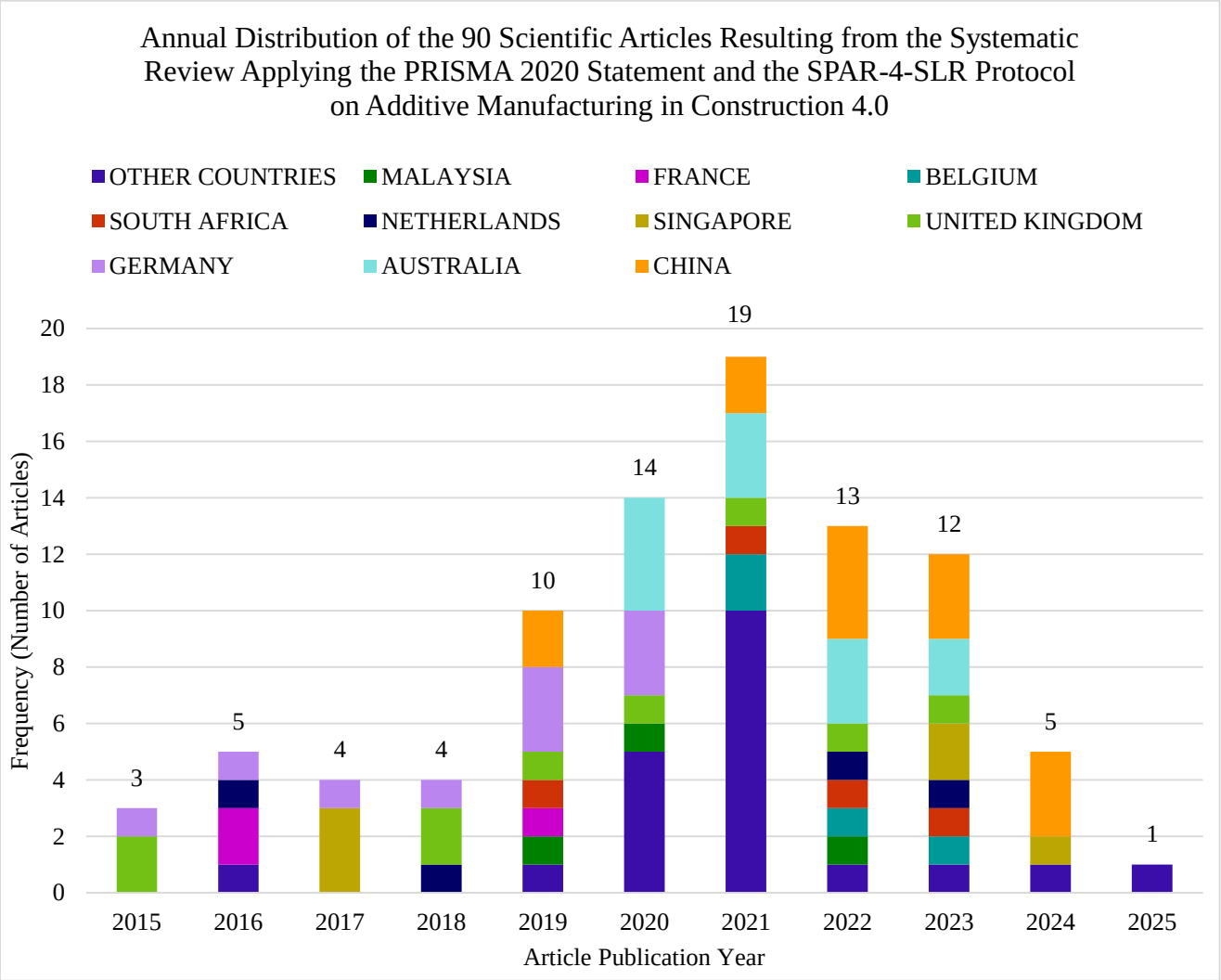

Fig. 4 Annual distribution of the articles included in the systematic review

The reported record counts were obtained from the authors' own search and selection process. PRISMA 2020 [17] and SPAR-4-SLR [18] guided the reporting and organization of the review, while Garcés et al. [19] served as a methodological reference.

The largest number of the 90 included articles was published in 2021 as shown in the histogram of Figure 4, with 19 publications in that year, followed by the year 2020 with 14 publications, followed by the year 2022 with 13 publications, then there is the year 2023 with 12 publications, followed by the year 2019 with 10 publications, after that are the years 2016 and 2024 with 5 publications each, followed by the years 2017 and 2018 with 4 publications, followed by the year 2015 with 3 publications and finally with the year 2025 with 1 publication each. Regarding the countries of origin of these articles, they are led by China, followed by Australia, Germany, United Kingdom, Singapore, Netherlands, South Africa, Belgium, France, Malaysia and Other countries. Within the selected sample, the annual number of publications decreased from 19 in 2021 to 1 in 2025, indicating a lower representation of recent publications in the review.

In Figure 4, each article was counted once under the country of the first author's first-listed institutional affiliation. For articles with international coauthors, the other countries were not counted separately.

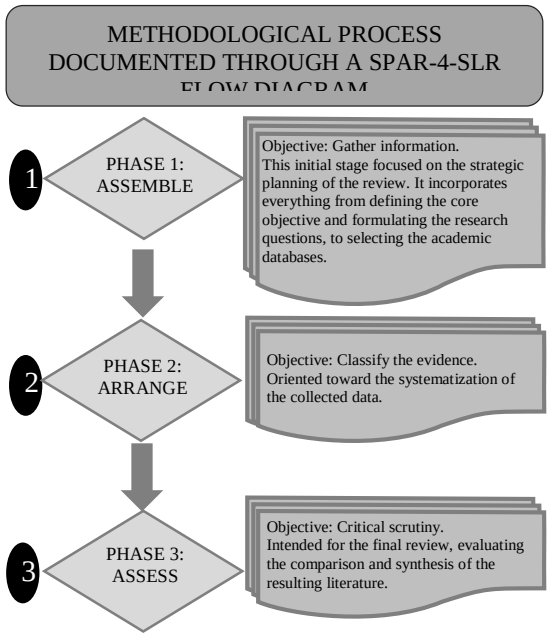

Fig. 5 Process flow diagram according to the SPAR-4-SLR protocol, adapted to the study.

Source: Developed based on information from Paul et al.(2021) [18].

3.2. Application of the SPAR-4-SLR Protocol

The methodological development of this review was structured simultaneously and vertically, that is, during the entire data collection phase, following the three major stages proposed by the SPAR-4-SLR protocol [18] shown in Figure 5. The sequential application of these three phases allowed structuring the review process in a logical manner, ensuring coherence between the methodological strategy and the research objectives [18]. The PRISMA 2020 statement guided the reporting of this review, while the SPAR-4-SLR protocol supported the organization of the review process [17, 18].

4. Results and Discussion

The results and discussion of this systematic review are based on an analysis and comparison of data from the 90 articles selected through the process documented in accordance with the PRISMA 2020 statement and the SPAR-4-SLR protocol. This analysis centered on descriptive thematic frequencies within the included corpus, which are presented in Figures 6–10. Accordingly, these figures report the number of articles assigned to each thematic category rather than rankings of extracted keywords. The frequencies, therefore reflect which topics the reviewed literature addresses; they do not measure the technological maturity of these topics or the extent of their industrial adoption.

4.1. Results

4.1.1. Thematic Trends Identified in Concrete Additive Manufacturing in Construction 4.0

These thematic trends are organized and classified in the histogram of Figure 6, and the following data can be distinguished: in first place, Construction applications, housing and infrastructure, leading topic with 40 mentions (44.4%). In second place, Systematic reviews, conceptual frameworks and state of the art with 30 mentions (33.3%), In third place, the topic of Mechanical properties, anisotropy and structural performance accumulates 25 contributions (27.8%), in fourth place, the topic of Construction 4.0, digitalization and industrialization with 23 articles (25.6%), followed in fifth place by Mix design, rheology and fresh behavior with 17 appearances (18.9%). This indicates that one of the outstanding topics is industrialization and the concrete mixture, which is used in additive manufacturing, thus affirming that it is in an experimental state, opening an endless number of future possibilities in topics of future interventions. Some little-mentioned topics are Advanced materials, geopolymers and cementitious composites has 16 articles (17.8%), followed by BIM, CAD/CAM, digital design and planning solutions, with 14 records (15.6%) and Automation, robotics and printing systems, with 13 publications (14.4%). Finally, Simulation, numerical modeling and prediction shares place with Parameter, path and geometry optimization (5 articles and 5.6% each), followed by Reinforcement and integration of structural reinforcement with 4 records (4.4%), Artificial intelligence and computer vision with 3 mentions (3.3%) and, closing, Monitoring, sensors, quality control and inspection with barely 2 publications (2.2%). The trends lean toward topics that enable the experimental transition to digitalization, industrialization and standardization of elements that can be replicable in different contexts.

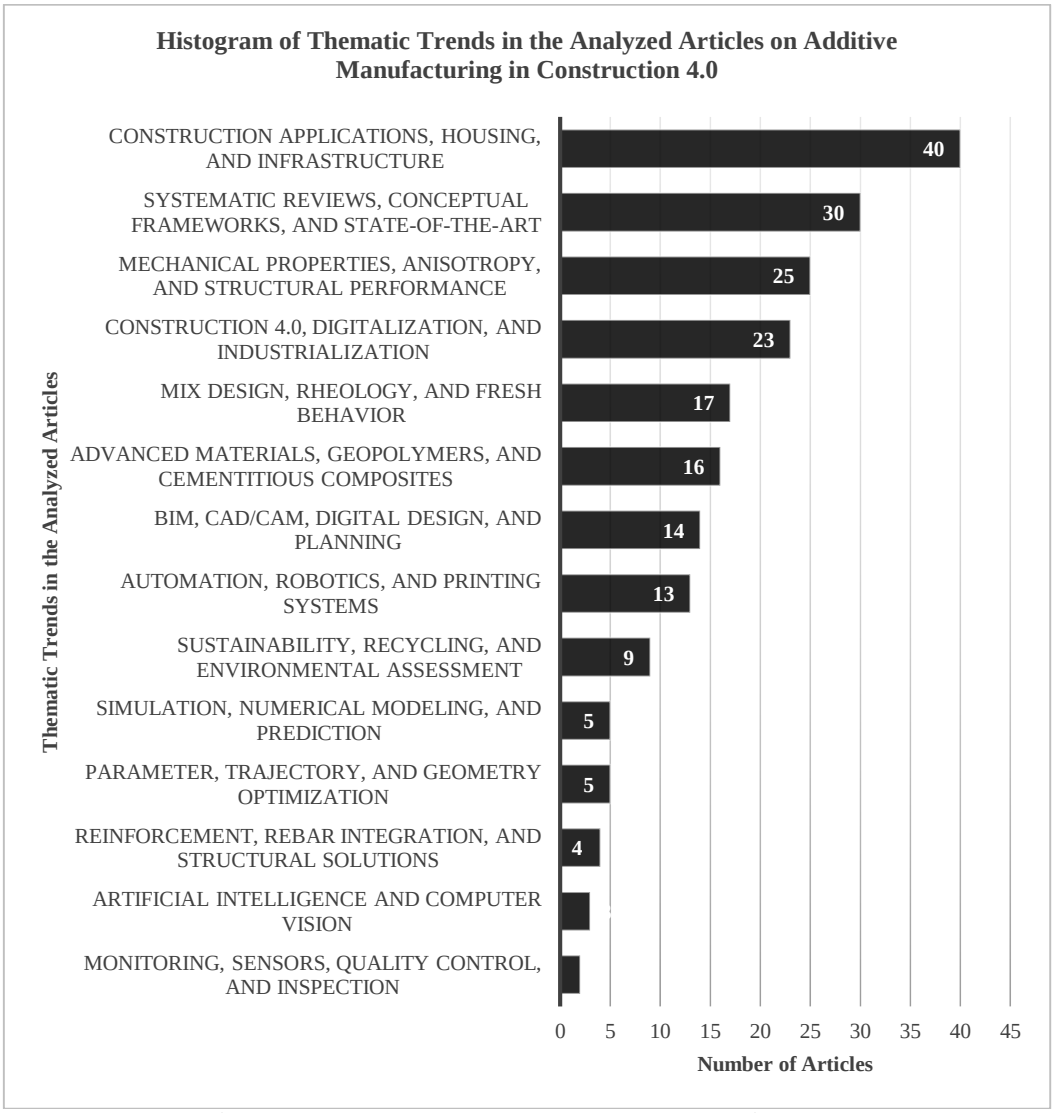

Fig. 6 Histogram of thematic trends in the analyzed articles on additive manufacturing in construction 4.0

4.1.2. Technological Advances in Concrete Additive Manufacturing in Construction 4.0

When carrying out the scrutiny of the technological advances of concrete additive manufacturing in the 90 articles, the most relevant data were organized and classified in the histogram of Figure 7. The dominant scientific advance are the Mechanical properties and anisotropic behavior, records with 22 publications (24.4%).

In second place, the development of Advanced materials, geopolymers and composites is identified accumulates 16 appearances (17.8%), while in third place, construction scaling and application on site follows with 15 records (16.7%). In fourth place: BIM/CAD/CAM Integration and digital manufacturing records 14 appearances (15.6%), closely complemented by the sixth place of Robotics, automation and printing systems, with 12 publications (13.3%) and in fifth place, Printable mix design and dosage with 13 records (14.4%).

In the decreasing zones is found the seventh place, , the technological advance of the analysis of Rheological control, extrudability and buildability records 10 articles (11.1%), followed by Sustainability, recycling and reduction of environmental impact with 9 mentions (10.0%) and Optimization of printing parameters with 6 contributions (6.7%).The technical development gap becomes even more severe at the lower end of the histogram. Simulation, numerical modeling and performance prediction has only 5 publications (5.6%); structural reinforcement and integration of reinforcements records barely 4 articles (4.4%), Applied artificial intelligence and computer vision is limited to 3 contributions (3.3%), and Monitoring, sensors and process quality control closes the count with a discreet presence of 2 records (2.2%).

Although technological advances have made an important evolution, a stagnant topic that very few authors mention are electrical and sanitary installations, enabling a broad field of Hybrid Additive Manufacturing, adding the use of other materials or reconfiguring digital systems. While global efforts have massively concentrated on the rheology of the material [10] and the optimization of the mechanical systems of robots [19], the incorporation of functional subsystems indispensable for real habitability is being a pending topic.

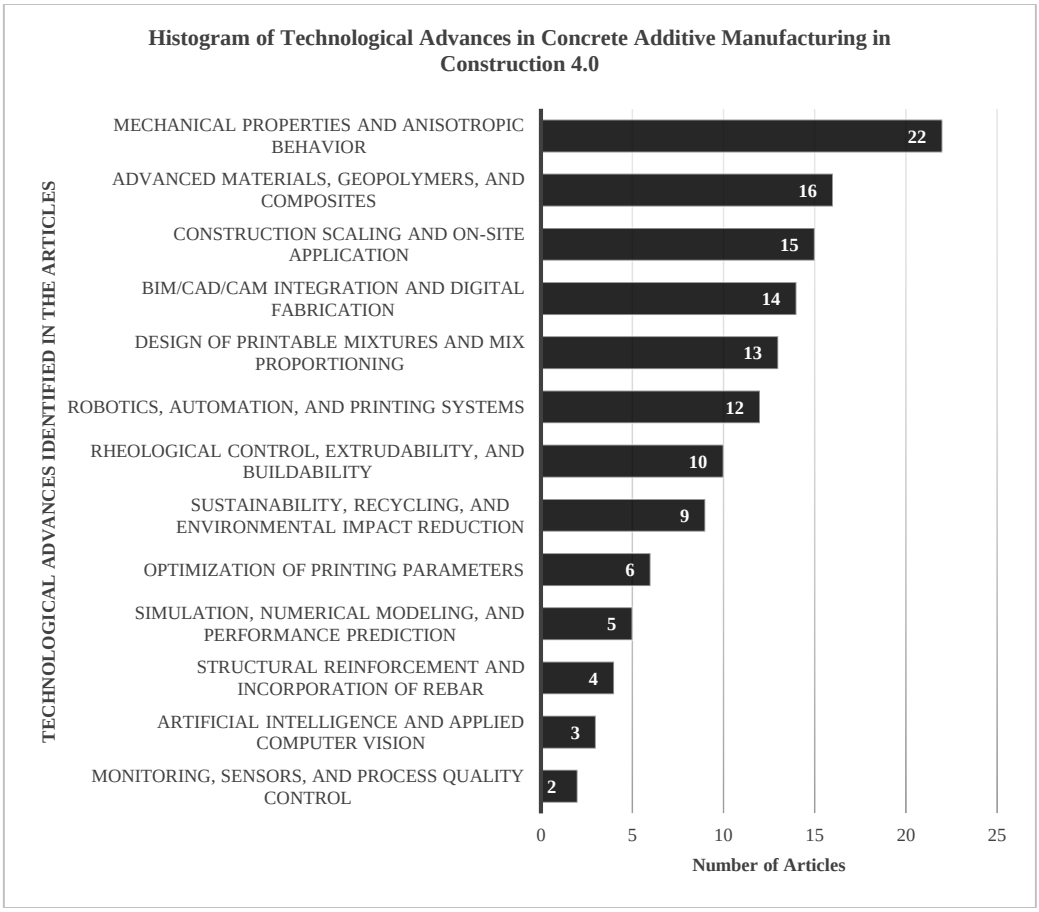

Fig. 7 Histogram of technological advances in concrete additive manufacturing in construction 4.0

In traditional building, pipes, ducts and fluid networks are installed taking advantage of the voids of lightweight partitions or through the subsequent chipping and drilling of hardened structural elements; however, applying this manual and destructive approach to a 3D printed wall contradicts its initial guidelines of prefabrication with reduced material waste, material optimization and speed promoted by Construction 4.0 [1].

4.1.3. Integration of Concrete Additive Manufacturing with Construction 4.0 Technologies

The detailed analysis of the integration of concrete additive manufacturing with Construction 4.0 technologies is represented in Figure 8, where it is demonstrated how the concepts are closely intertwined. In first place, Construction 4.0 and digital industrialization is mentioned, which leads the record with 23 appearances (25.6%), complemented and closely followed by the fourth place, the operational solutions of BIM, CAD/CAM and digital planning with 14 mentions (15.6%) and the fifth place of automated Robotics and printing systems with 12 records (13.3%). The convergence of these empirical metrics evidences that the scientific community does not evaluate 3D printing as an isolated technique, but as a unified ecosystem that directly links algorithmic design, prior simulation and robotic execution in real time [19]. Likewise, in third place, the robust interest in the development of Smart materials and advanced printable concrete, with 16 appearances (17.8%), is directly related to the second place, Structural integration, reinforcement and automated performance (17 appearances; 18.9%).In sixth place, subtopics such as Sustainability, life cycle and digital circular economy (9 appearances; 10.0%) stand out. In the same way, the seventh place, Computational design and geometric optimization (7 appearances; 7.8%) and the eighth place, Simulation or numerical modeling (5 appearances; 5.6%) exhibit a rather discreet presence. The gap is critically accentuated in deep connectivity technologies: the use of IoT, sensors and real-time monitoring records barely 4 mentions

(4.4%), Artificial intelligence, machine learning and computer vision is limited to 3 contributions (3.3%), and Interoperability, data, cloud and collaborative flows closes the spectrum with a single appearance (1.1%) [19]. This asymmetry in the data indicates uneven thematic coverage within the reviewed literature, giving rise to bibliographic interstices that limit attempts to clarify a definitive integration between both concepts. Although Concrete Additive Manufacturing is already a representative tool of Construction 4.0, and considering that Digital Interoperability is another representative milestone whose integration received limited attention in the reviewed articles, the need becomes present to address topics that enable the fusion of the two topics.

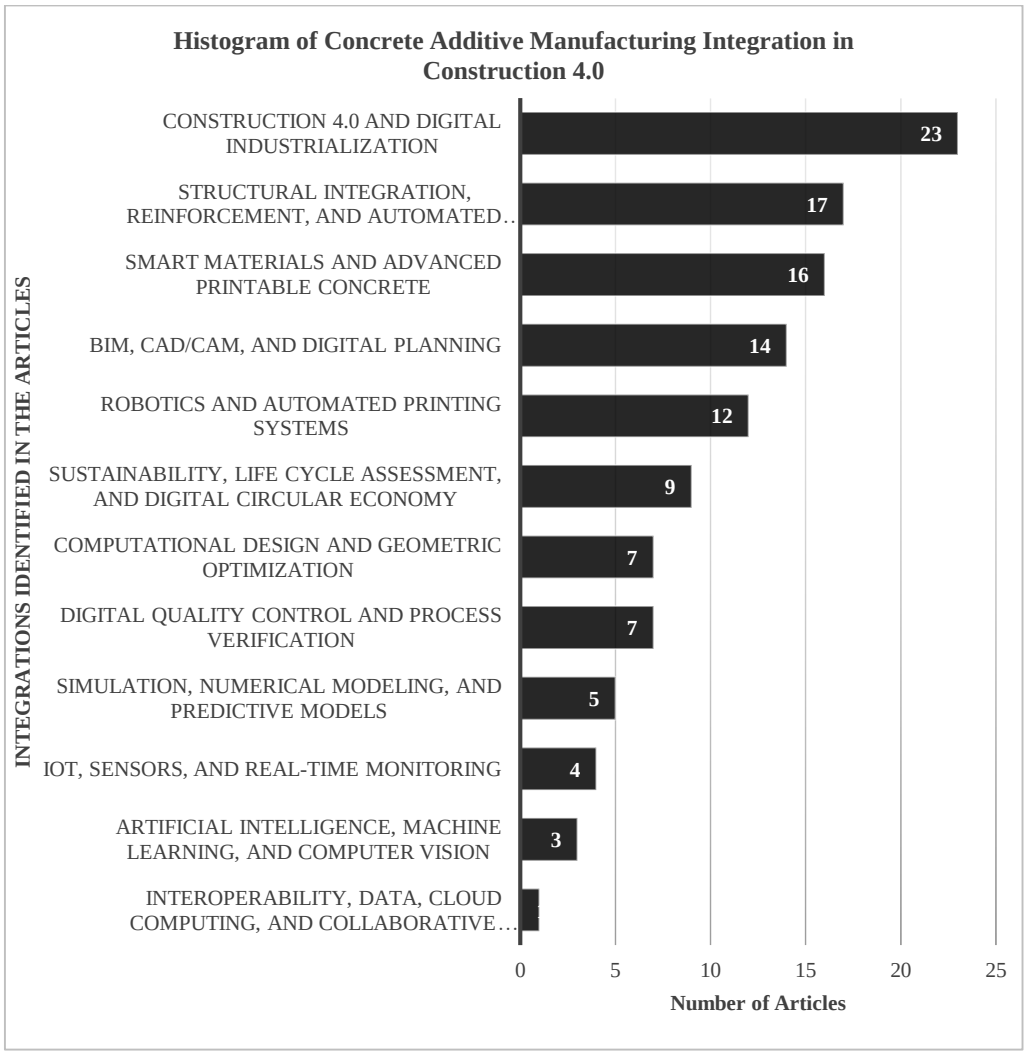

Fig. 8 Histogram of concrete additive manufacturing integration in construction 4.0

4.1.4. Gaps of Concrete Additive Manufacturing Versus Construction 4.0

The mentioned gaps of concrete manufacturing versus Construction 4.0 in the 90 articles were analyzed in the histogram of Figure 9 reveals a critical but necessary limitation for the sector: 3D concrete printing is trapped in a complex transition. Although the global scientific community has amply demonstrated that it is capable of extruding amazing figures and small-scale structures in impeccable laboratories, the true leap toward massive and industrialized production is slowed down by a series of deeply interconnected "bottlenecks", one of these problems are the production of horizontal structural elements such as lightweight slabs that are still represented with innovative proposals, but it is still a research topic regarding electrical and sanitary networks in their production, thus generating new additional fields of research [8, 11].

The research gaps identified in the reviewed articles were organized into the following three groups:

Group 1: Experimental validation and methodological reproducibility. This category was identified in 28 articles (31.1%), making it the most frequently reported research gap in the reviewed sample.

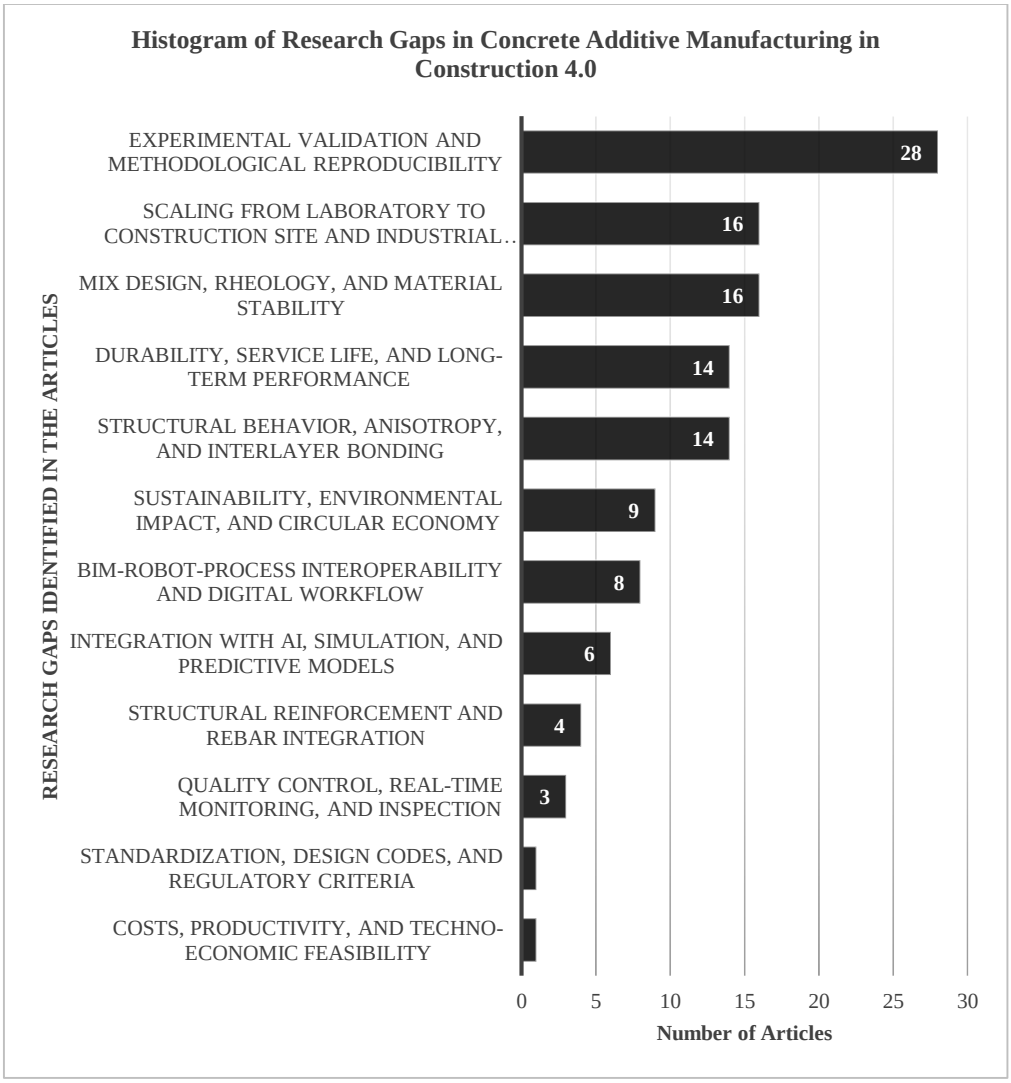

Fig. 9 Histogram of research gaps in concrete additive manufacturing in construction 4.0

Group 2: Scaling and material stability. Scaling from the laboratory to construction sites and industrial adoption, and mix design, rheology and material stability, were each identified in 16 articles (17.8%). These findings highlight the combined challenges of implementation at construction scale and control of printable mixtures [10]. In traditional construction, concrete is poured and stiffens with the formwork, but in additive manufacturing, the formwork disappears, and the fresh material must be fluid enough to be pumped without clogging the hoses [7, 9].

Group 3. Durability and structural performance, the decreasing part of the histogram in Figure 9 makes evident the challenges inherent to the physics of the process. In fourth place, the topic of Durability, service life and long-term performance is mentioned, in the same way, fifth place, structural behavior, anisotropy and interlayer bonding register a presence of 14 publications (15.6% each). By eliminating monolithic pouring, layer-by-layer printing generates interlayer interfaces where cold joints may form [9]. If one layer takes longer to receive the next one, surface drying may create a plane of physical weakness.

These contact points not only act as vulnerable zones to tension or shear failures during earthquakes, but they become microscopic highways for the infiltration of aggressive agents (such as chlorides or sulfates), sowing serious doubts about the real long-term durability of these infrastructures [12, 20].

4.1.5. Future Perspectives

The projection of the future study branches of Concrete Additive Manufacturing (3DCP) no longer resides only in the discovery of isolated laboratory techniques, but in the comprehensive optimization and systemic validation of existing technologies. When examining the data of the future perspectives of additive manufacturing versus construction 4.0 from the 90 scientific articles, it translates into the histogram of Figure 10.

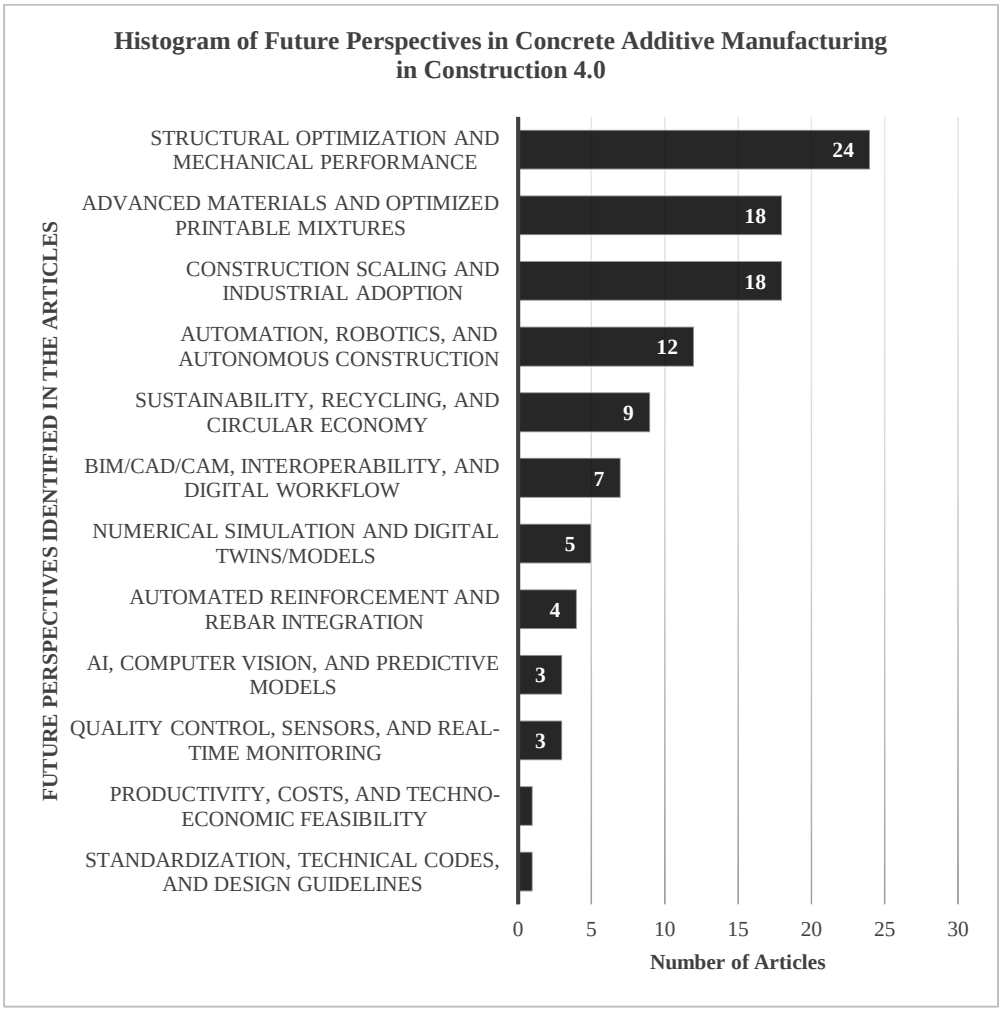

Fig. 10 Histogram of future perspectives in concrete additive manufacturing in construction 4.0

In first place, there is Structural optimization and mechanical performance, with 24 mentions (26.7%), in second place, the development of Advanced materials and optimized printable mixtures together with Construction scaling and industrial adoption, with 18 appearances (20.0% each). In third place, Automation, robotics and autonomous construction is positioned records 12 publications (13.3%), in fourth place, Sustainability, recycling and circular economy with 9 mentions (10.0%).

In sixth place, the topic of BIM/CAD/CAM, interoperability and digital flow has 7 contributions (7.8%), followed by Numerical simulation and digital twins/models with 5 records (5.6%) and Automated reinforcement and integration of reinforcements with 4 publications (4.4%). The convergence of these fields seeks to provide the process with rigorous mathematical predictability, coupling finite element computational models with the digital twin of the structure to anticipate buildability failures before activating the physical extrusion of the cementitious mixture.

4.2. Discussions

4.2.1. Advances of Concrete Additive Manufacturing (3DCP) in Construction4.0

Concrete additive manufacturing is part of the broader development of digital fabrication in construction. In extrusion-based 3D concrete printing, cementitious material is deposited in successive layers under digital control, creating challenges related to material rheology, interlayer bonding and reinforcement [10]. The thematic trends and technological advances summarized in Figures 6 and 7 are discussed below in relation to previous studies, with particular attention to material behavior, construction-scale implementation and digital integration.

Lim et al. [8], in “Developments in construction-scale additive manufacturing processes”, examined large-scale additive manufacturing, with particular attention to Concrete Printing as an automated extrusion process. Their discussion emphasized the importance of fresh material properties and the opportunities for greater geometric design freedom. These

contributions provide context for the attention given to printable mixtures, rheological control and construction-scale implementation in Figure 7. The present review connects these material and process considerations with the broader technological development of concrete additive manufacturing within Construction 4.0.

From another perspective, Bos et al. analyze the potential of Concrete Additive Manufacturing, emphasizing the topic of Construction scaling and application on site, likewise the rheology of the mixtures, mechanical anisotropy and the lack of industrial standardization, coinciding with the findings of the present research [9].

Another article is "Rheological requirements for printable concretes." by Roussel, analyzes the behavior of the material in the fresh state with the integrity of the printed component. It concludes, and coincides with the present systematic review, that the success of Concrete Additive Manufacturing (3DCP) depends on the strict compliance with specific rheological requirements, such as extrudability, immediate dimensional stability and the optimal time window to guarantee adhesion between the layers [7].

The results of these articles coincide with several points of the Histograms of Figures 6 and 7, they demonstrate how the scientific community has responded to these mechanical challenges. The fact that the topic of Mechanical properties and anisotropic behavior is positioned in first place with 22 mentions (24.4%) suggests research interest in the assessment of structural safety and durability of the elements.

These observations are discussed in relation to the findings of Ngo et al. (2018), who highlight that the mechanical behavior of printed materials is a broad and complex topic, since the stratified nature of this process can lead to anisotropic mechanical behavior [12, 20].

4.2.2. Research Gaps of Concrete Additive Manufacturing (3DCP) in Construction 4.0

This review examined the integration of concrete additive manufacturing with Construction 4.0 technologies and the associated research gaps, summarized in Figures 8 and 9, respectively. The most frequently identified gap was experimental validation and methodological reproducibility, reported in 28 articles (31.1%). Scaling from the laboratory to construction sites and industrial adoption, and mix design, rheology and material stability, were each identified in 16 articles (17.8%). These findings are discussed below in relation to previous studies.

For his part, Paolini et al. [11] mentions the gap of Experimental validation and methodological reproducibility through the dilemmas of the rheological contradictions of the material, the weakness of structural anisotropy and digital disconnection, complementarily, Ngo et al. highlighted the virtues of customization and sustainability of additive manufacturing, but conditioned its deployment on the maturation of new materials and the strict standardization of processes [12].

Likewise, the conceptual framework evolves toward the paradigm of Construction 4.0., In the article "Digital Concrete: Opportunities and Challenges" by Wangler et al. coined the concept of digital concrete, stating that 3D concrete printing should not be understood as an isolated problem, but as the coordinated interaction between computational design, robotics and automated process control [10]. Zhang et al. [13] discuss fuzzy modeling and reasoning within construction engineering and management, providing methodological context for the use of artificial intelligence in the sector.

Garcés et al. [19] proposed a framework connecting additive construction and Construction 4.0 through horizontal and vertical integration. The present review complements this perspective by documenting the uneven representation of integration topics in the selected literature: structural integration, reinforcement and automated performance appeared in 17 articles (18.9%), whereas interoperability, data, cloud and collaborative flows appeared in one article (1.1%). This contrast suggests a research direction focused on connecting structural performance with information exchange and coordination across the construction process. These frequencies describe the reviewed sample and should not be interpreted as measures of industrial adoption.

4.2.3. Future Perspectives Of Concrete Additive Manufacturing (3DCP) in Construction 4.0

The processing and analysis the future perspectives of Concrete Additive Manufacturing (3DCP) in relation to the concept of Construction 4.0, evidenced in the Histogram of Figure 10, elaborated according to the frequency of data from the 90 articles, shows the distribution of future research topics in the reviewed sample. The research horizon is dominated by Structural optimization and mechanical performance with 24 publications (26.7%), followed by Advanced materials and optimized printable mixtures and Construction scaling and industrial adoption, with 18 records (20.0%) each. This distribution highlights research priorities for broader construction applications of 3D concrete printing, particularly in relation to digital technologies and sustainability. Garcés et al. In their article Additive construction 4.0: a systematic review of 3D concrete printing for Construction 4.0" argue that 3D printing is the digitalized solution that has been rethought, allowing intelligent and sustainable construction practices aligned with Industry 4.0 [19]. For their part, Placzek et al. In their article "How productive is 3d concrete printing? A systematic review." quantify this impact, reporting time savings of up to 88% and cost savings of up to 79%. However, they warn that these results are highly dependent on the context and that, in some cases, the lack of technological maturity can increase costs by 50 % [21].

While the first studies celebrated 3D concrete printing (3DCP) simply for material savings and the elimination of formworks [22], recent authors such as Gümrük et al. In their article "3DCP-CI: Development of a circularity indicator to evaluate 3D concrete printed architectural designs" [23] and Rabayah et al. in their article "The 3D Eye: From Blueprint to Build – Unveiling the Lifecycle and Future of 3D Printing in Sustainable Construction." [24] elevate the discussion toward the integral circular economy. The future trend is not only to print with low-carbon cements such as LC3, but to design structures under principles of disassembly and reuse. The development of specific circularity indicators can help incorporate end-of-life considerations into the design of 3D concrete printed buildings [23].

Finally, a promising perspective is the scalability of the technology for construction in space. Wang et al. [25] review additive manufacturing for lunar and Martian habitats using local resources, such as regolith.

4.2.4. Complementary Comparative Synthesis

To complement the frequency analysis, Table 1 compares selected published examples of material behaviour and application scale.

This supplementary comparison draws on the cited sources and does not constitute an article-by-article extraction of the 90-study corpus. The digital-integration column presents the authors' interpretation of each example.

Table 1. Selected published evidence and implications for digital integration

Material or application	Scale	Published quantitative evidence	Implication for digital integration
CEM I with fly ash [20]	Laboratory material and extrusion tests	Yield stress: 0.59 ± 0.08 kPa. Plastic viscosity: 38.7 ± 4.5 Pa·s. Printing example: 30 mm/s with a 40 × 10 mm nozzle.	Coordinate material delivery, nozzle geometry and toolpath speed.
CEM I with limestone filler [20]	Laboratory material tests	Yield stress: 0.27 ± 0.03 kPa. Plastic viscosity: 21.1 ± 2.4 Pa·s.	Calibrate process settings for the formulation rather than transferring a single rheological threshold.
High-performance printing concrete [26]	Laboratory specimens	Interlayer tensile bond strength: 0.7–2.3 MPa; lower values with longer printing time gaps.	Coordinate layer intervals and verify interface performance.
Bathroom unit; Weng et al. (2020) [27]	Component	Experimental comparison with precast construction: productivity +48.1%; overall cost −25.4%.	Record production boundaries when assessing the benefits of automated fabrication.
Building geometries; Han et al. (2021) [28]	Building	Theoretical comparison for the silo, construction phase only: RMB 2,451.61 for 3D printing versus RMB 11,894.52 for cast-in-situ construction. Material acquisition costs were assessed separately.	Include geometry and the basis of comparison in assessments of digital fabrication.

These examples distinguish material/process compatibility from performance at component and building scales. Rheology and speed must be considered alongside geometry and layer intervals [10, 20], while productivity comparisons require explicit boundaries and a distinction between experimental and theoretical evidence [21]. A single speed or strength value is therefore insufficient to establish integrated Construction 4.0 performance.

Weng et al. [27] reported that a printed bathroom unit had lower costs and CO_2 emissions than its precast counterpart. In contrast, Han et al. [28] found that printed building models had higher environmental impacts than cast-in-situ construction, mainly due to their higher cement content. Since each study compared printing against a different conventional method, these outcomes cannot be generalized.

Economic and environmental benefits should therefore be assessed separately, within clearly defined comparison boundaries. For electrical and sanitary integration, Table 2 proposes categories for future assessment. These categories are analytical priorities, rather than coded findings or frequency estimates from the 90 articles.

Table 2. Proposed framework for assessing electrical and sanitary integration

Integration aspect	Proposed verification	Potential digital contribution
Electrical routing	Conduit continuity and position; access to boxes; interference with reinforcement.	BIM coordination and robot path planning.
Sanitary routing	Pipe clearance, drainage slope, connections and maintenance access.	Parametric routing and dimensional inspection.
Printed interfaces	Strength around openings and sealing at pipe penetrations.	Local structural modelling and geometric inspection.
Installation and maintenance	Effects of printing pauses; leakage testing; access for repair or replacement.	Coordinated work sequences and digital records of the installed systems.

These proposals require validation in assemblies with installed services. Printed channels or voids alone do not demonstrate functional electrical or sanitary integration. No prevalence estimates for these categories are inferred from the thematic frequencies.

5. Conclusion

From the systematic analysis of the 90 scientific articles selected in this review, the following conclusions are established, structured around the technological advances, the research gaps and the future perspectives of Concrete Additive Manufacturing (3DCP) in relation to the concept of Construction 4.0:

The main technological advances of the articles were analyzed in the histogram of Figure 7, and the most representative were mechanical properties and anisotropic behavior with 22 publications (24.4%) and the development of Advanced materials, geopolymers and composites accumulates 16 appearances (17.8%), it is observed that the first topic focuses on the characteristics of the product, and the second on how to improve the raw materials, it can be deduced that materials engineering is a popular topic, these results go hand in hand with the main thematic trends that come to be classified in the histogram of Figure 6 where it is observed in first place, construction applications, housing and infrastructure, leading topic with 40 mentions (44.4%) and systematic reviews, conceptual frameworks and state of the art with 30 mentions (33.3%), it can be seen that the most discussed topics go hand in hand with the experimental character.

The technology of Concrete Additive Manufacturing (3DCP) shows potential for further digital integration and industrial application. Likewise, digital consolidation (BIM/CAM) may help 3d concrete printing (3DCP) evolve from a simple extrusion technique to an intelligent construction solution aligned with Industry 4.0 [22]. Despite the prominent technological evolution, old problems of Concrete Additive Manufacturing (3DCP) still persist, which has reached an unprecedented boom, although with technical interstices that prevent the definitive transition toward conventional construction, and according to the research gaps summarized in Figure 9, the gap of Experimental validation and methodological reproducibility can be mentioned, with 28 appearances (31.1%), in second place, the two topics with 16 appearances (17.8% each), the analysis identifies scaling from the laboratory to the work and industrial adoption together with Mix design, as central research gaps, intersecting topics such as durability validation where field data on long-term behavior (greater than 5 years) and the monitoring of structures under real environmental conditions are not sufficient nor exact to validate service life predictions, another important topic is the lack of regulations that many authors mention is a pending topic that should be addressed with national authorities [22].

The vision of the future perspectives of Concrete Additive Manufacturing (3DCP) in relation to the next decade is defined by three main research directions led in the Histogram of Figure 10 and they are Structural optimization and mechanical performance with 24 publications (26.7%), followed by Advanced materials and optimized printable mixtures and Construction scaling and industrial adoption, each identified in 18 articles (20.0%), understanding that the main concern for the future is structural optimization, since according to Paolini et al. warn that the true viability of the technology depends on overcoming the limitations of anisotropic behavior and the mechanical weaknesses of the interlayer interface, and emphasize that this advance requires a simultaneous co-design between digital architecture and the rheological behavior of the material in the fresh state (pumpability versus buildability), since long-term structural stability is conditioned by the initial hardening rate and the correct physical adhesion between the extruded filaments [11]. Overall, the review of 90 articles highlights the importance of integrating digital technologies with material development and structural design in concrete additive manufacturing. The identified research gaps and future perspectives suggest that progress toward broader industrial

implementation would benefit from coordinated research on experimental validation, standardization and sustainability. This synthesis provides a basis for prioritizing future research and technological development within the Construction 4.0 framework.

Conflicts of Interest

The authors declare no conflicts of interest. None of the authors has any affiliation with or professional or financial ties to the WasiTek project, and none has received funding from it.

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