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Review Article

Scientometric Knowledge Mapping of 3D Concrete Printing Research and Perceptions from South Africa: Trends and Sustainable Prospects

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Abstract

This research focuses on scientometric knowledge mapping and trend analysis of three-dimensional concrete printing (3DCP). It is a study based on South African perspectives, and the extracted bibliographic data are from the Scopus and Web of Science databases for the periods of 2015 and 2025. Fifty (50) articles were analysed using performance indicators and science mapping methods to investigate publication trends, key sources, affiliations, funding agencies, and research themes related to 3D concrete printing construction materials. The results reveal a marked increase in publication output related to digital construction and additive manufacturing technologies, particularly from 2020 onwards, reflecting increased scholarly attention at both the national and global levels. There is a strong alignment with sustainable development goals 9, 11, and 12 with the bibliographic data through keyword co-occurrence, revealing varying research emphasis. Approximately 10% of the studies focused on printable concrete sustainability, 20% on rheology, 30% on numerical modelling, 40% on sustainability, 50% on performance, 60% on interlayer bond strength, and up to 70–80% on material innovations, including supplementary cementitious material and alternative binders. The research output of South Africa is driven primarily by research-intensive universities and national science institutions, such as Stellenbosch University, the University of Johannesburg, the University of the Witwatersrand, and the Council for Scientific and Industrial Research. These efforts are supported by funding from the Department of Science and Innovation, National Research Foundation, South African Research Chairs Initiative, and European Commission-funded collaborations. These findings provide evidence to inform future research and policy on sustainable digitally enabled construction materials; however, significant knowledge gaps still remain in areas such as durability, standardization, and large-scale implementation.

Keywords: 3D Concrete Printing, Sustainable, Bibliographic, Construction Materials, Scientometric

Introduction

The construction sector is currently experiencing a paradigm shift because of the influence of digitalization, automation, and sustainability challenges [1-3]. Among the new technologies, three-dimensional concrete printing (3DCP), also known as additive manufacturing, has attracted considerable attention because of its potential to revolutionize traditional construction methods through formwork-free construction, geometric freedom, material conservation, and fast-track construction [4-6]. Unlike traditional cast-in-place concrete construction, 3DCP involves accurate layer-wise extrusion of cementitious materials, necessitating unprecedented convergence of material science, rheology, robotics, and structural engineering [2,7,8]. Over the past decade, the rate of research on 3DCP has risen exponentially, and worldwide research efforts have focused on three interconnected areas: printing system development, control of the 3DCP process, and the development of printable materials [8,9]. Among these, the most important challenge in the development and commercialization of 3DCP is related to the development of cement-based composites that must meet various requirements, including pumpability, extrudability, buildability, bondability, and early-age stability, in addition to long-term mechanical and durability properties [10-12].

In addition, sustainability aspects have contributed to an increased research focus on 3DCP materials, as the material efficiency of the technology has the potential to reduce construction waste, but this can be countered by cement-based mix designs [13,14]. Additionally, recent research has started to investigate the potential of using industrial waste materials and region-specific supplementary cementitious materials (SCMs) to reduce the carbon footprint of printable concretes [6,15]. Within this framework, regional material availability and properties play crucial roles in defining the feasibility of 3DCP.

Furthermore, aggregate morphology, fine material content, mineralogy, and cement chemistry can differ greatly from one region to another, especially between the Global North and the Global South. Thus, the generalization of 3DCP research, especially that developed in Europe or Asia, to the Global South, especially Africa, has received limited attention [16-18]. South Africa, especially in the region of Africa, has a strategic position in the field of research on 3DCP [19,20].

South Africa is confronted with issues such as housing shortages, infrastructure backlogs, high construction costs, and the environmental impact of building practices, as well as the abundance of fly ash, slag, and other industrial byproducts available for the substitution of cement in the mixture [20-22]. However, despite this potential, the current state of scientific literature indicates that the level of South African contribution to 3DCP, especially in the development of construction materials, is still dispersed and relatively small compared to that of international leaders in this field [16,23]. Current

studies focus mostly on rheological characterization, local SCM adaptation, and initial mechanical performance, without much integration of research trends, collaboration, or development in the field [16,19,24].

Additionally, scientometric analyses that can systematically identify the current state of South Africa's contribution to global 3DCP research are limited. scientometric analysis is a strong tool for evaluating research productivity, intellectual structure, and collaboration within a scientific domain [25-27]. Although various scientometric reviews have been conducted on additive manufacturing globally [12,28,29], at the regional level, they are surprisingly limited, thus making invisible the research efforts in the country and hindering the formulation of research agendas that can be aligned with the national agenda for sustainable development.

Thus, this study aims to provide a scientometric analysis of 3DCP, with a particular focus on the research contributions of scholars in the context of South Africa from 2015 to 2025, to investigate the evolution and development of scientific research on 3DCP in South Africa. The application of knowledge mapping and scientometric analysis will reveal (a) trends in South Africa's scientific research on 3DCP over the past two decades and (b) publication patterns, such as annual growth, types of documents, highly influential sources, important keywords used in 3DCP research, affiliations, and significant funding sources, and alignment with sustainable development goals. This study aims to provide strategic guidelines for researchers, industry practitioners, and policy makers as a systematic reference framework for future research, technology, and the development of sustainable, locally adapted 3D printing practices in South Africa.

Methodology

Data Retrieval Strategy

A detailed bibliometric study was carried out using the Scopus database and the Web of Science Core Collection (WoS) to provide comprehensive coverage of scientific literature on the construction materials of 3DCP in the context of construction, with special emphasis on South Africa. The integration of the two databases was found to provide robustness in the dataset, as the databases contain high-quality, peer-reviewed literature in the field of engineering, materials science, and construction management [30-32].

A literature search was conducted for the period from 2015 to 2025, which corresponds to the formative period and the growth period of the research on additive manufacturing in the construction field. A structured query was formulated using a set of keywords related to the field of 3D concrete printing, cement-based materials, and geographical locations. The query was executed in the title, abstract, and keyword fields of the databases. The main keywords used were "3D concrete printing", "3DCP" OR "additive manufacturing in construction" OR "cementitious additive manufacturing" AND "materials" OR "rheology" OR "cement-based composites" AND "South Africa". The search was limited to English-language sources. The types of documents included

in the search were journal articles, conference papers, and review articles (Table 1). This helped ensure that the search results were relevant to scientific communication and that the methodology was rigorous.

Table 1. Data screening criteria for inclusion and exclusion

Criteria	Inclusion	Exclusion
Country	South Africa	Countries other than South Africa
Publication year	2015-2025	Before 2015
Language	English	Non-English
Subject area	Engineering, materials science, and construction management	Studies not related to engineering, materials science, and construction management
Article type	Journal, conference paper, books, review	Concept paper, editorial, and retracted paper
Publication stage	Published	Article in press

Screening and Data Consolidation

The data extracted from the Scopus and Web of Science databases were exported in CSV and RIS formats and merged into a single file. A multi-step screening process was used to ensure the quality and relevance of the data. This involves the following: the removal of duplicate records from merged sources; the removal of records that are not directly related to construction materials (such as the publication of robotics, architectural design, and non-cement-based additive manufacturing); and the verification of the relevance of the records to South Africa, as suggested by the affiliation of the author, the context of publication, and application examples [25-27, 32]. The final dataset is a curated and verified body of information that is ready to be analysed with bibliometric and scientometric techniques. Prior to analysis, the dataset underwent systematic pre-processing to eliminate inconsistencies and fragmentation in the network. This includes normalization of the names and initials of the authors, standardization of institutional affiliations, aggregation of synonymous and related keywords (such as “3DCP” and “3D concrete printing”), and elimination of records with incomplete or inaccurate metadata. This is crucial for ensuring the accuracy of co-occurrence mapping and collaboration analysis. This set of screening criteria was used to ensure that the publications considered in the present review are the most relevant to 3DCP research in South Africa.

Bibliometric Analysis

Scientometric analysis was carried out using the VOSviewer tool with the support of spreadsheet-based statistical tools to investigate the descriptive performance-based indicators and relational knowledge structures of the obtained dataset [27, 31]. The analysis involved examining annual publication trends to assess the progression, research activity, and level of scholarly consolidation within the domain; publication sources and document types to identify the top publications, conferences, and publication types; and keyword co-occurrence analysis to identify the fundamental research themes, new research areas, and the evolution of research themes in the domain of rheology, supplementary

cementitious material utilization, sustainability, and mechanical properties of 3DCP materials.

In addition, an analysis of the authors and institutions was carried out to identify the top authors and collaboration networks of national and international research teams, while a citation impact analysis was carried out to identify the top publications and knowledge clusters that have significantly influenced the research domain. In addition, a funding sponsor analysis was carried out to identify major funding organizations and patterns of support for 3DCP research.

Network visualizations were created using the association strength normalization method, which allowed for easy understanding of the intensity of relations and proximity of themes. While both Scopus and Web of Science offer comprehensive and reliable coverage of peer-reviewed literature, there might be a possibility of missing some regional or non-indexed literature. However, with the use of both databases, the reliability of the data will be ensured along with international comparability and reproducibility, which are critical in carrying out bibliometric research. The methodology adopted will be sufficient for establishing the intellectual structure and evolution of 3D concrete printing construction materials in South Africa.

Results and Discussion

Annual Publication

The annual research publication distribution trend is shown in Figure 1. The analysis of the publication dynamics over time reveals a strong and organized process of maturation of the research field in 3DCP, from dispersed exploratory research to a well-organized and strategically pursued research area. The phase between 2015 and 2017 is marked by scattered publication activity, with one to four publications per year, indicating the infancy of 3DCP research and the lack of standardized methodologies for material design and testing. A definite point of transition can be noted between the years 2018 and 2020, where the number of publications gradually increased, in line with the global advancements in additive manufacturing technology and the understanding of cement rheology and printable concrete as a construction material.

From 2021 onwards, the field of research is marked by a phase of rapid consolidation, where the number of annual research publications gradually increases from seven in 2021 to eleven in 2023 because of the formation of research groups, the availability of national research funding, and the development of research topics such as buildability, interlayer bonding, durability, and sustainability-focused material development. The substantial increase in the number of research publications from 2024 and 2025, amounting to twelve and fifteen publications, respectively, can be attributed to the confluence of institutional capacity, long-term research funding, and alignment with global research priorities, particularly the incorporation of 3DCP into the sustainable construction paradigm and the circular economy approach. Individually and collectively, this upwards publication trend aligns with international research patterns and demonstrates the increasing contribution of South African scholars

to high-impact 3DCP research. This progression indicates a shift from early-stage exploration toward a more established and scientifically consolidated research domain.

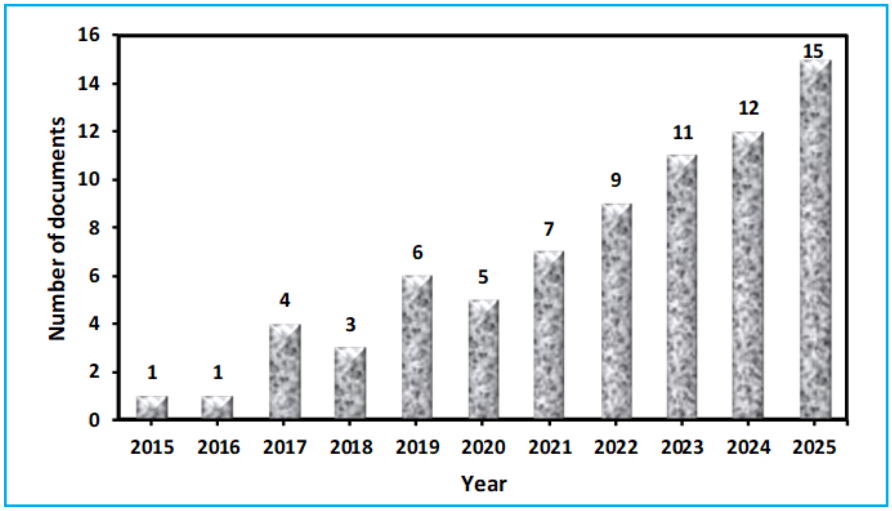

Figure 1. Annual research publication distribution trend

Type of Document

The document type distribution related to 3DCP research in South Africa is shown in Figure 2. The distribution of the document types also reveals the maturity and dissemination of the research on 3DCP in South Africa. Journal articles constitute approximately 54% of the total published papers, indicating the strong emphasis given to experimental validation and analysis of the materials being developed for 3DCP. Journal articles are the best place to present experimental work and analysis since they provide a comprehensive platform for the dissemination of research on the materials being developed for 3DCP.

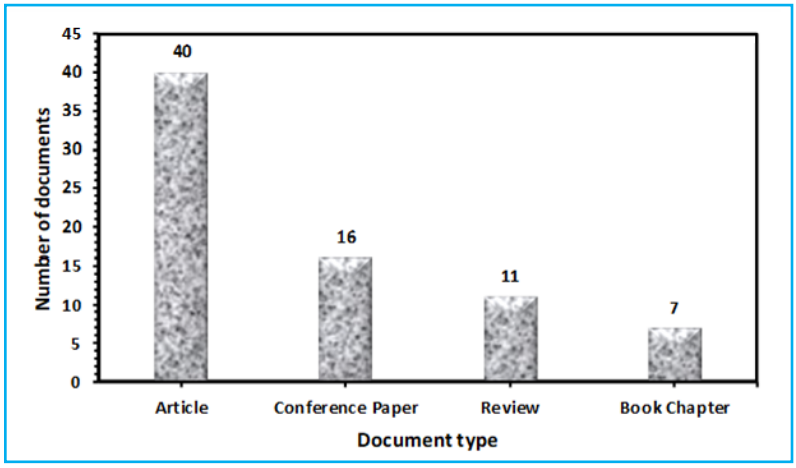

Figure 2. Distribution types for published documents

Conference papers constitute approximately 22% of the total published papers. This is because the research on 3DCP is more engineering and technology-based, where innovations are presented at conferences before they are published as journal articles. The review articles account for approximately 15% of the overall

dataset, suggesting a level of knowledge consolidation and intellectual maturity, given the increasing body of research that has necessitated the systematic synthesis, critical evaluation, and agenda-setting review contributions. The book chapters account for approximately 9% of the overall dataset, suggesting a supplementary role to the overall research landscape, providing conceptual frameworks, educational content, and contextual discussion pieces within edited works on construction innovation and additive manufacturing. The proportional distribution of the overall dataset is suggestive of a maturing interdisciplinary research field, closely mirroring the dissemination trends for additive manufacturing and advanced construction materials within Scopus and Web of Science, thereby supporting the overall credibility of the bibliometric dataset informing this top-tier review.

Keyword Co-Occurrence and Thematic Interpretation

Analysis of keyword co-occurrence reveals that the intellectual foundation of research on 3DCP is clearly an established and well-developed research domain, with emphasis on methodology, materials, and performance. Table 2 illustrates the keyword co-occurrences for 3DCP research in South Africa, and Figure 3(a) illustrates the network visualization of keyword co-occurrence. The descriptions of the core technology are well represented in the network, and keywords such as “3D printers”, “3D printing”, and “3-D concrete printing” are the dominant hubs of the network. These findings indicate that keywords are being used consistently in the literature and that the area of 3DCP research has developed well from being a peripheral area of additive manufacturing to being a mainstream area of research.

Material composition and mix design constitute a second dominant thematic cluster, with a group of keywords that are strongly interlinked, including “concrete mixtures”, “cements”, “calcined clay”, “limestone”, “lime”, and “supplementary cementitious material”. The dominance and interconnectivity of these keywords strongly indicate that material optimization, including other cementing materials, is a prominent area of research, and this is also very closely tied to the sustainability and optimization of performance that 3DCP aims for. The set of keywords that are associated with mechanical and structural performance is a highly interconnective set of keywords, which points to the engineering complexity of the field of study. Keywords such as “compressive strength”, “bond strength (materials)”, “interlayer bond strength”, “mechanical performance”, and “reinforced concrete” highlight the importance of structural strength and anisotropic properties that are typical of layered materials.

The high values of TLS indicate a strong coupling between experimental research, material science, and structural analysis. Another cluster of methodological and modelling approaches emerges with keywords such as “finite element analysis”, “finite element method”, “numerical models”, and “numerical methods”. Although fewer in number than experimental approaches, these studies indicate an emerging shift toward the use of numerical techniques to simulate material responses, predict performance, optimize geometries, and

reduce costs. This reflects the increasing adoption of performance-based design approaches in 3DCP research.

Table 2. Keywords co-occurrences

S/N	Keyword	Occ.	TLS	S/N	Keyword	Occ.	TLS
1	3d Printers	49	78	19	Finite Element Analysis	21	29
2	3-D Printing	41	51	20	Finite Element Method	19	18
3	3d Concrete Printing	38	29	21	Interlayer Bond Strength	19	19
4	3d Printed Concrete	36	70	22	Life Cycle	18	18
5	3d Printing	33	58	23	Lime	18	42
6	3d-Printing	32	42	24	Limestone	17	47
7	Additive Manufacturing	32	11	25	Mechanical Performance	17	36
8	Bond Strength			26			
	(Materials)	30	34		Numerical Methods	17	21
9	Buildability	29	30	27	Numerical Models	16	20
10	Calcined Clay	28	47	28	Performance	13	20
11	Cement-Based Material	28	33	29	Reinforced Concrete	11	57
12	Cements	27	54	30	Rheology	9	21
13	Concrete Aggregates	27	31	31	Scanning Electron Microscopy	9	35
14	Concrete Construction	27	25	32	Structural Design	8	32
15				33	Supplementary Cementitious		
	Concrete Mixtures	26	74		Material	7	32
16	Concretes	24	32	34	Sustainability	7	23
17	Construction Industry	23	64	35	Sustainable Development	5	44
18	Cost Effectiveness	23	33				

Occu. = Occurrences and TLS=Total link strength

Sustainability and system-related issues represent another cluster of terms that is rising but still strategically relevant. The occurrence of terms such as “sustainability,” “sustainable development,” “life cycle,” and “cost effectiveness” reflects the increasing integration of sustainability-related considerations within the research domain. The terms have a moderate frequency but strong linkages to other terms, implying that sustainability studies have been incorporated as part of material studies. The keyword network indicates a cohesive and dynamic research landscape focused on 3D printing technologies, material science, and mechanical performance evaluation, along with increased emphasis on numerical modelling and sustainability-focused research approaches. The high total link strength of key words indicates significant interconnectivity in the research landscape, supporting the claim that 3DCP research has moved beyond exploratory experimentation and into a technologically established and multidisciplinary research area with established research agendas, in keeping with the intent and scope of this level of review.

The overlay visualization of recent studies on 3DCP in South Africa is shown in Figure 3(b). The visualization clearly shows the trends and themes of recent studies. The co-occurrence of keywords reveals that 3D printing, supplementary

cementitious materials, sustainability, life cycle, calcined clay, limestone, lime, bond strength, and numerical methods are the most prominent themes in current studies. This is a clear indication of the shift in the field from isolated studies to a holistic approach that encompasses material optimization, structural performance, and sustainability. In particular, the emphasis on alternative

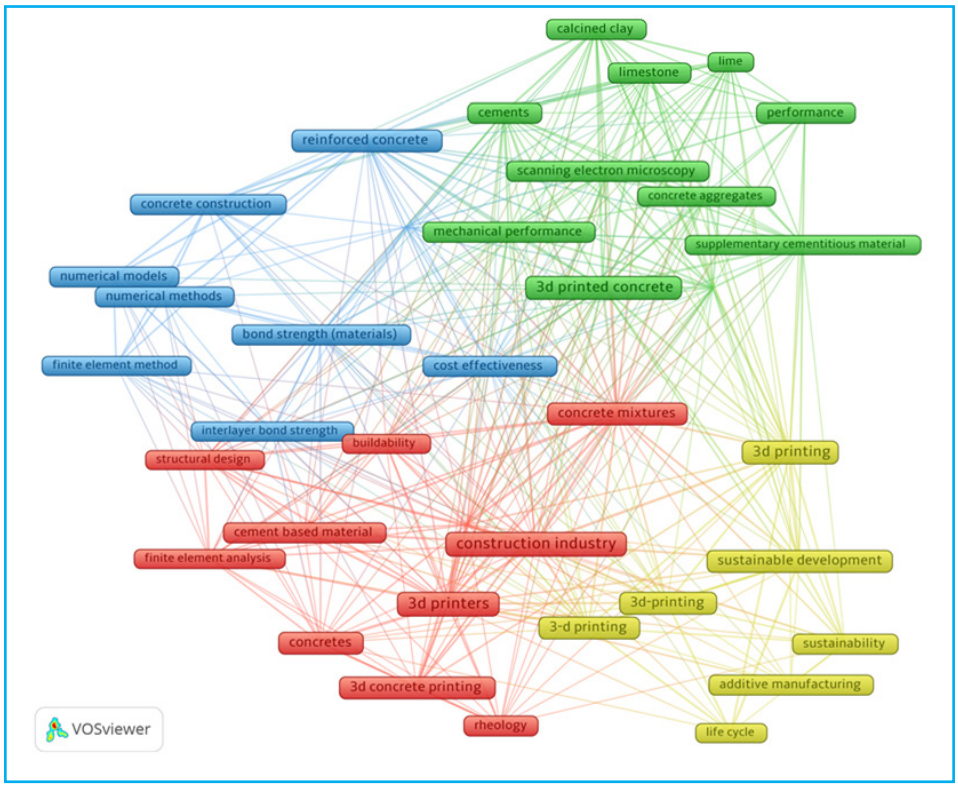

Figure 3 (a). Network visualization for keyword co-occurrence

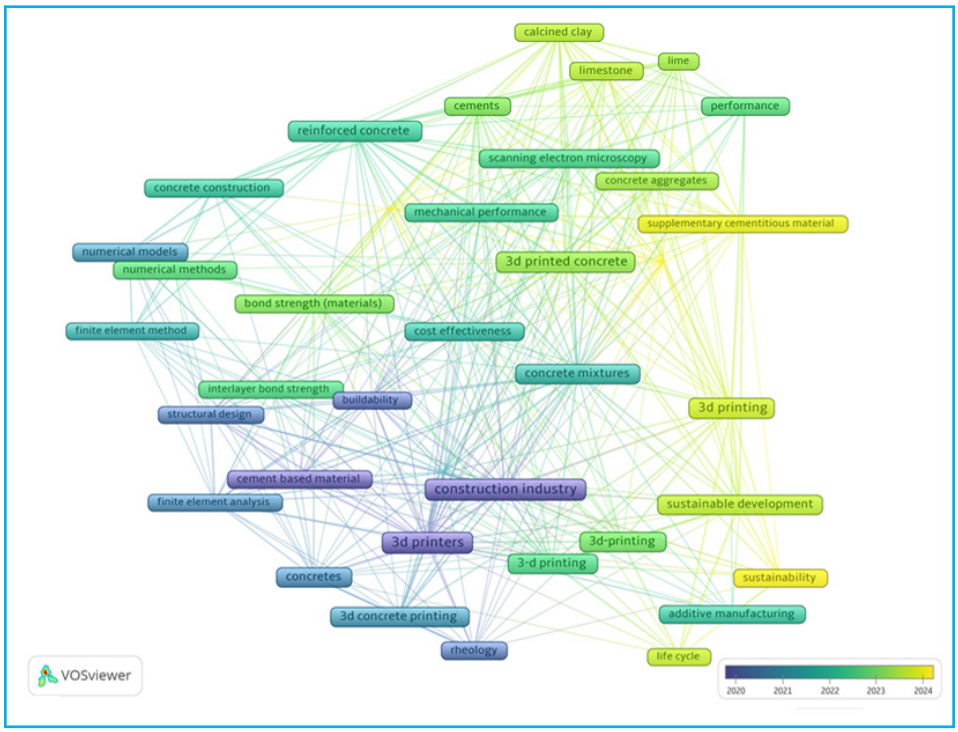

Figure 3 (b). Overlay visualization for keyword co-occurrence

binders and life cycle approaches serves to reinforce the importance of resource-efficient and low-carbon construction solutions, and the frequency of the use of keywords related to computation serves to reinforce the importance of numerical prediction in construction. Collectively, these trends indicate that 3DCP research in South Africa is moving beyond the exploratory phase of experimentation and embracing a more systematic, performance-based, and sustainability-focused framework, laying the groundwork for academic and practical applications in digitally enabled construction.

Publication Sources

Table 3 shows the publication sources, and Figure 4(a) shows the network visualization for publication sources related to 3DCP research in South Africa. The analysis of publication sources for 3DCP research indicates that there is stratification in sources, particularly between international journals and others. Engineering Structures and Journal of Composites Science, despite containing only two publications each, have 160 and 148 citations, respectively, suggesting that these are highly influential and widely recognized publications in the field of engineering structures and materials science.

Construction and Building Materials, which has four publications and 128 citations, is an important publication channel for rigorous experimental and applied research, suggesting both methodological maturity and readership. Moderate citation performance is also noted for specialized and regional-focused outlets such as the FIB Symposium and the Journal of the South African Institution of Civil Engineering, which each contain two documents with 67 citations. These outlets are significant knowledge dissemination channels within professional and regional networks, facilitating early research, collaborative projects, and industry-based applications. Although the overall document coverage of the outlets is low, the high level of citations suggests the applicability of the content presented within the outlets, specifically for the structural performance and innovation of concrete materials.

On the other hand, publications such as the Journal of Building Engineering, RILEM Book series, Case Studies in Construction Materials, and Lecture Notes in Civil Engineering display relatively low citation impact but contribute almost equally to the total number of publications. These findings indicate that these publications are likely to contain emerging research, initial studies, or conference papers that are still being recognized by the wider scientific community. Nevertheless, these publications are important, especially when novel methodologies, experimental procedures, and applications are presented, particularly in regional contexts such as South Africa. Overall, the above analysis of publication sources supports the proposition of a two-pronged dissemination strategy for 3DCP research: international high-impact journals as the dominant channel for influential studies focusing on methodological sophistication and theoretical contribution and regional journals as a key channel for knowledge transfer at an early stage of development, as well as for building networks of collaboration. The stratified publication landscape of 3DCP research may thus

be a function of the level of maturity of the science as well as the need to balance globalization with regionalization.

Table 3. Publication sources

S/N	Source	Documents	Citations
1	RILEM Book series	5	16
2	Construction and Building Materials	4	128
3	Journal of Building Engineering	3	39
4	Engineering Structures	2	160
5	Journal of Composites Science	2	148
6	FIB Symposium	2	67
7	Journal of the South African Institution of Civil Engineering	2	67
8	Case Studies in Construction Materials	2	11
9	Lecture Notes in Civil Engineering	2	7

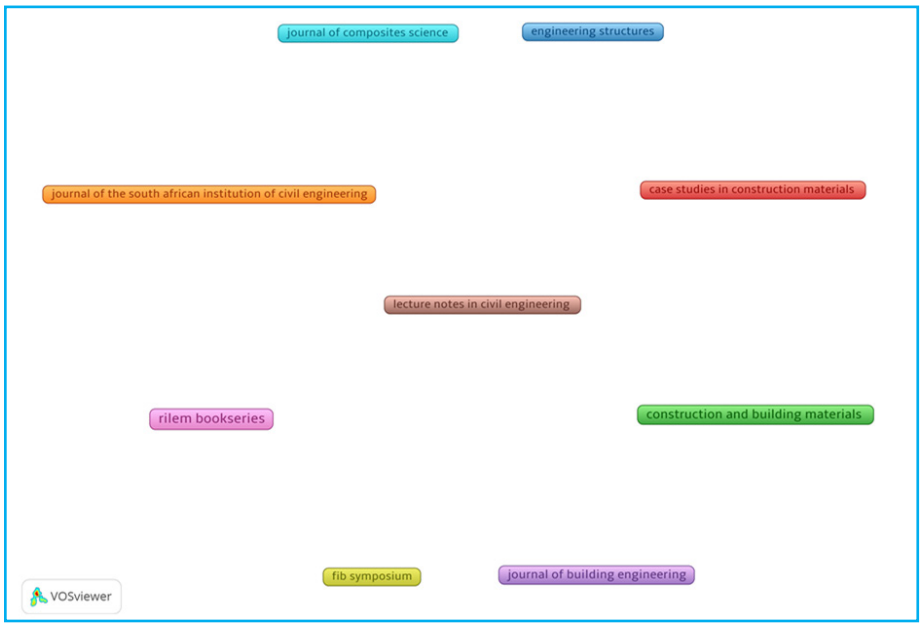

Figure 4 (a). Network visualization for publication sources

Moreover, Figure 4(b) shows a density map produced by VOSviewer, where the zones of concentrated research activity are represented for 3DCP research in South Africa, covering the time period from 2015 to 2025. The visualization of the research activity, collaboration, and productivity of researchers is represented by zones of high-density activity, where the darker shades of color are used to represent the zones of high research activity, collaboration, and productivity, whereas the brighter shades of color, represented by bright yellow, are used to represent the zones of higher research activity, collaboration, and productivity. The zones of low research activity, collaboration, and productivity are represented by the dimmer shades of color, indicating zones of low research

activity, collaboration, and productivity. This kind of visualization of the research activity, collaboration, and productivity of researchers provides a clear overview of where the research activity is more prolific, where the researchers are working, and where the opportunities exist to conduct further research in the field of sustainable construction materials.

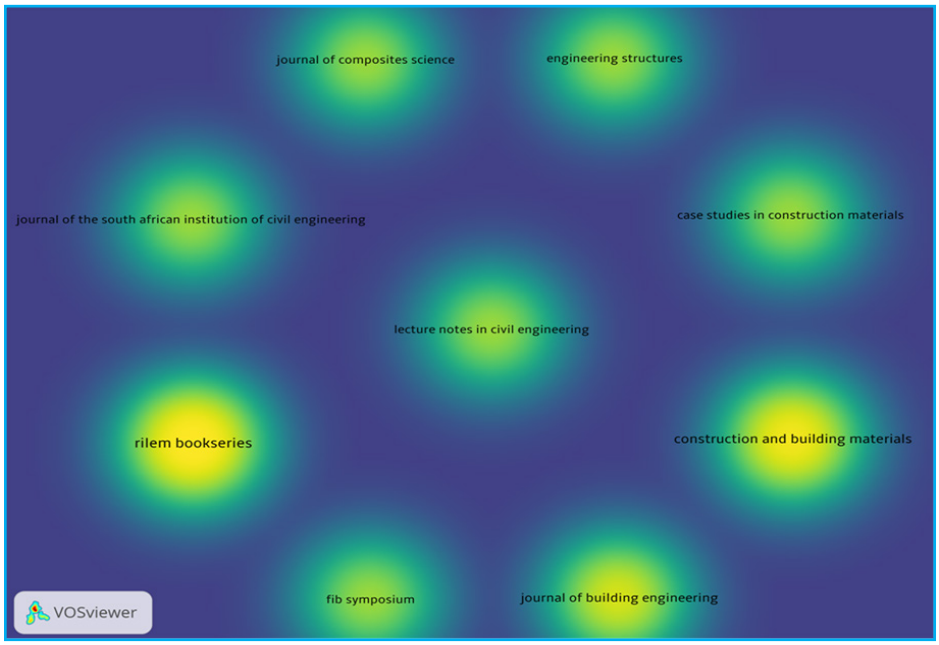

Figure 4 (b). Density mapping for publication sources

Bibliometric Affiliation Analysis

The key affiliation related to 3DCP in South Africa is shown in Figure 5. Research related to 3DCP in South Africa is clearly highly centralized, with only a handful of research centers dominating the majority of scholarly output. The literature on 3DCP is dominated by a few institutions, which have the highest volume of publications on 3DCP. Stellenbosch University is the leading institution, contributing 35 publications to the field, which is justified by the university's long-standing expertise in the design of cement-based mixtures, rheology, green materials, and durability. It is not only the institution that produces the greatest number of publications but also the one that has the greatest citation impact, which is an indication of the visibility of the publications. The University of Johannesburg (16 publications) and the University of Witwatersrand (14 publications) are the next institutions involved in the implementation of 3DCP, its structural integration, and industry collaboration. Their research outputs also tend to integrate laboratory innovations with practical applications, such as 3D-printed housing and infrastructure, and they also have strong co-authorship links with SUs and CSIRs, thus contributing to the national collaboration network.

The Council for Scientific and Industrial Research (CSIR) and the University of Cape Town (UCT), both with nine publications, play complementary roles. The CSIR is involved in research and development and technology transfer on an industrial scale, while the UCT is involved in actual performance, durability, and sustainability, and its research is highly cited and contributes to both national and

international knowledge bases. However, new entrants such as the University of the Western Cape (8 publications), University of Pretoria (7), Nelson Mandela University (6), Central University of Technology (5), and University of South Africa (4) are also contributing to the research environment in the country, with a focus on sustainable materials, composite development, and pilot-scale research. Overall, it is estimated that 65–70% of the 3DCP material research in South Africa is carried out by SU, UJ, and Wits, which indicates the dominance of expertise in the country, although the inclusion of new entrants suggests the beginning of diversity in the region. These trends reflect the leadership role of the dominant institutions in knowledge creation and their pivotal position in building a collective and powerful 3DCP research community in South Africa.

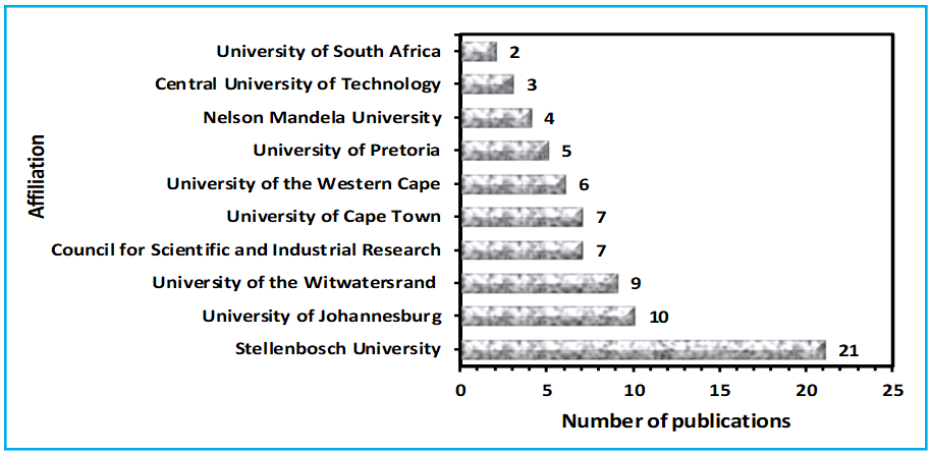

Figure 5. Key affiliation related to 3DCP in South Africa

Funding Analysis

The key funding sponsors related to 3DCP in South Africa are shown in Figure 6. The literature data clearly indicate that 3DCP research in South Africa is significantly influenced by the country's strategic funding initiatives, whereas international collaborations contribute to the research efforts in a supporting role. The Council for Scientific and Industrial Research (CSIR) is the leading organization in terms of visibility and impact, given that the organization offers not only funding but also access to experimental facilities for testing materials and pilot-scale additive manufacturing facilities, which are critical in the advancement of 3DCP research. This is supported by the Department of Science and Innovation (DSI) and the National Research Foundation (NRF), which cover basic research, postgraduate studies, and project grants, which is also supported by the high volume of publications and citations that have been analysed. These funding agencies allow for the systematic study of the material behavior of 3DCP under local environmental conditions, sustainability, and optimization, which is in line with the scope of this review.

The South African Research Chairs Initiative (SARChI) also contributes to the quality and sustainability of research by supporting long-term research chair programs in specific materials and additive manufacturing, yielding high-impact research that is well represented in the Scopus and Web of Science databases, thereby influencing the bibliometric results presented in this study.

Finally, funding from the European Commission supports collaborative research efforts that can enable the adoption of new methodologies, the validation of material performance, and the integration of research from South Africa into the international knowledge space. Overall, the funding environment contributes to the publication trends, research collaboration efforts, and knowledge gaps identified in this review, providing a context and rationale for the focus on high-performance materials for 3D printing that are sustainable and can be adapted to the needs of the country.

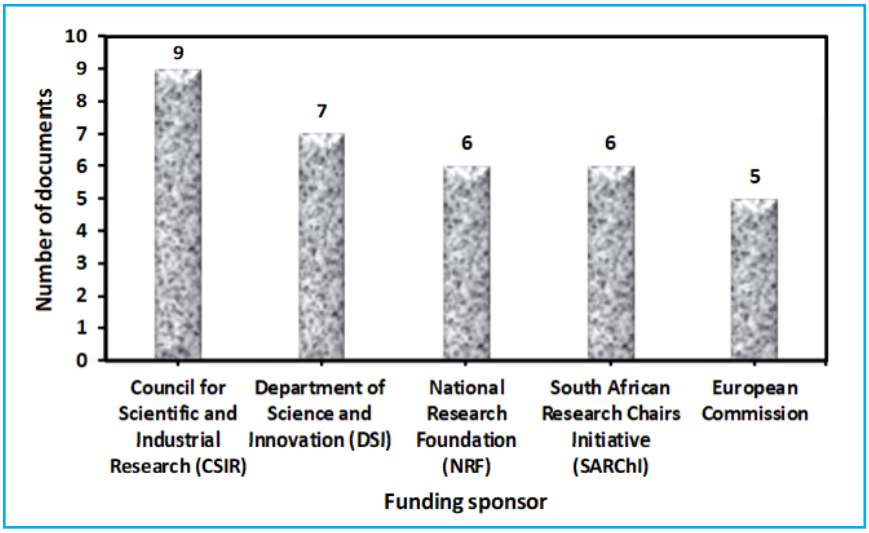

Figure 6. Key funding sponsors related to 3DCP in South Africa

Alignment with Sustainable Development Goals

As made evident through this review, research on 3DCP is inherently linked to a number of the United Nations' Sustainable Development Goals, as digital construction technologies such as 3D concrete printing are increasingly being used as a means of addressing global sustainability issues. The study aligned with SDG 9: Industry, Innovation, and Infrastructure, which is due to the predominance of keywords related to additive manufacturing, concrete printing technologies, material optimization, and structural performance and reflects the field's contribution to innovation in industry and infrastructure development. Additionally, it supports SDG 11: Sustainable Cities and Communities is directly addressed through research studies on printable concrete for housing, structural members, and efficient construction. The growing need for buildability, interlayer bonding, and printable concrete reinforced with materials indicates the need to develop safe and sustainable construction solutions that can meet the challenges of urbanization, housing shortages, and infrastructure needs, especially in developing countries.

Moreover, it also satisfied SDG 12: "Responsible Consumption and Production" through material research studies on supplementary cementitious materials, calcined clay, limestone, lime, and other binders. Keywords and source analysis highlight the key interest in research on how to reduce cement, improve material efficiency, and utilize local materials to decrease embodied energy and material waste in the construction industry. The integration of life-cycle thinking

and material and performance optimization reflects the shift toward low-carbon construction methods, where additive manufacturing reduces formwork waste, maximizes material efficiency, and supports climate-resilient infrastructure. The relevance of the research topic of 3D printing to multiple SDGs highlights the importance of this research topic. By addressing the interrelated themes of materials science, fabrication, structural performance, and sustainability, the literature on this topic places 3DCP as a key enabler of resilient infrastructure, sustainable development, and resource management, which further highlights the relevance and global significance of this research topic.

Research Gaps and Future Research

Analysis of scientometric data on the topic of 3DCP research in South Africa from 2015 to 2025 reveals that the topic is developing at a rapid pace in terms of intensity and complexity. First, more studies should be conducted on the spheres of alternative binders, supplementary cementitious materials, and mixed designs with low carbon footprints to increase the sustainability and compatibility with SDGs 9, 11, and 12.

Second, studies on the long-term behavior of 3D-printed cement-based structures, the interlayer bond strength, and the mechanical performance under different loading and environmental conditions are needed. Standardization of tests for such parameters can help facilitate the approval process for the technology. Moreover, the use of computational methods, including the simulation of finite elements and optimization through the application of artificial intelligence, can expedite the processes of mix design and the evaluation of structural performance.

Finally, pilot and field studies, especially in relation to housing and infrastructure development, are needed to ensure the applicability of innovations developed in laboratory settings. The formation of interdisciplinary and interinstitutional collaborations, including in the fields of materials science, structural engineering, and sustainability studies, is an important step toward increasing scientific impact and visibility and the creation of strategies for the development of cost-efficient and sustainable 3DCP solutions.

Implementation pathways for sustainable 3D concrete printing in South Africa

The application of 3DCP in South Africa needs to be based on the findings of the existing gaps and emerging themes from the literature review. Despite the fact that the field has moved from understanding the printability properties of materials, numerous aspects, such as sustainability, performance, and material innovation, still need to be explored. There are still no local standards or pilot studies and a lack of industry confidence in the technology.

Previous studies have shown that 3DCP is capable of accelerating the construction process and enhancing the productivity and delivery of housing, but the implementation of this technique faces some obstacles, such as limited technical guidelines, expensive first investment, a shortage of skills and a lack of regulatory approval [10,20,23]. It seems reasonable for future implementation

of 3DCP to concentrate on demonstration projects for affordable housing, public infrastructure and community facilities to determine the constructability, durability, cost-effectiveness and social acceptance of the technology under South African circumstances.

Furthermore, the use of SCMs, recycling and low-carbon binders should be encouraged to increase sustainability and reduce the environmental impact of construction [11,15,17]. Finally, more interactions between universities, industry, government and standardization institutions are needed to speed up technology transfer, training and commercialization. In summary, the implementation of 3DCP in South Africa will require material innovations, structural reliability, policy considerations and sustainable construction goals.

Conclusion

The scientometric analysis in this review provides a comprehensive overview of the research field related to 3DCP in South Africa during the period between 2015 and 2025. Keywords co-occurrence and network analysis provide evidence that the research interest in 3DCP changed progressively from the initial topics related to feasibility and printability to more complex themes such as supplementary cementitious materials, sustainability, life cycle assessment, bond strength, numerical modelling, and structural performance. As far as the publication sources are concerned, Engineering Structures, Construction and Building Materials, and the Journal of Composites Science are recognized as the most innovative publication media in terms of publishing 3DCP research papers of high impact in the international context. The role of regional and applied publication sources such as the Journal of the South African Institution of Civil Engineering and FIB Symposium in the context of knowledge transfer can also be noted.

The results of the institutional mapping exercise highlight the prominent role of Stellenbosch University, University of Johannesburg, University of the Witwatersrand, and Council for Scientific and Industrial Research as the key institutions that lead the process of the advanced research and development of the technology as well as the transfer of innovations from the laboratory scale to the pilot scale. As seen from the analysis of funding trends, various funding bodies, both locally and internationally, have had a significant influence on the research development pathway of 3DCP in South Africa. The continuous support of various funding bodies, such as the Department of Science and Innovation, National Research Foundation, and South African Research Chairs Initiative, was significant for research development and infrastructure development in the country, while international bodies such as the European Commission were significant for global research development. Owing to these sources, interdisciplinary research combining materials science, structural engineering, sustainability studies, and digital fabrication became possible.

In general, the results of the present research reveal an interconnected and interdisciplinary research environment that is gradually integrated into national development goals and international sustainability goals. With the help of

identifying the major research themes, actors, and funders, this review provides a basis for further research that aims at advancing sustainable, scalable, and 3DCP technologies. Moreover, South Africa is well prepared to contribute to the international development of additive manufacturing in the construction industry in relation to the most important challenges of sustainable infrastructure, housing, and climate change.

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Conflicts of Interest

All authors declare that they have no conflict of interests.

Author Contributions

Jacob Adedayo Adedeji: writing-original draft, writing- reviewing and editing, methodology, investigation, formal analysis, visualization. **Nura Shehu Aliyu Yaro:** conceptualization, project administration, writing- reviewing and editing. **Adeyinka Kabir Akanbi:** writing- reviewing and editing. **Xoliswa Evelyn Feikie:** writing- reviewing and editing. **Mohamed Mostafa Hassan Mostafa:** writing- reviewing and editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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