Sustainability of Additive Manufacturing: A Bibliometric Review of LCA-Oriented Research

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Abstract

This study examines the environmental sustainability of additive manufacturing through a bibliometric analysis of publications indexed in the Web of Science Core Collection. A dataset of 20,000 articles, reviews, and conference papers published between 2019 and 2024 was analyzed using the Biblioshiny interface of the bibliometrix package. The analysis focuses on sustainability-related research in polymer-based additive manufacturing, with particular attention to FDM and SLA technologies, which dominate current industrial applications and exhibit distinct environmental trade-offs. Publication trends, citation patterns, collaboration networks, and keyword co-occurrence structures were evaluated to characterize the evolution and thematic orientation of the field. The results indicate a strongly interdisciplinary research landscape, high levels of international collaboration, and an increasing emphasis on life cycle assessment and energy-related impacts. At the same time, the findings suggest that sustainability considerations remain unevenly integrated across additive manufacturing research, highlighting the need for more systematic and application-specific environmental assessments.

Keywords: bibliometric, 3D printing, sustainability, additive manufacturing

1. Introduction

3D printing has developed rapidly from a prototyping tool into a core industrial technology for producing functional parts. Its increasing use in sectors such as aerospace, automotive, biomedical, or construction highlights its benefits: the ability to obtain complex geometries at low costs and with short production times, product customization, and the elimination of the need for molds or dedicated tools. At a global level, the adoption of 3D printing has become almost widespread, with more and more companies integrating it into their production workflows, and the 3D printing industry is also experiencing an accelerated pace of economic growth. This expansion of additive technologies, however, raises questions regarding the sustainability of these processes and products. It is often stated that 3D printing is "intrinsically" more environmentally friendly than conventional manufacturing, because it uses materials more efficiently and generates less waste, unlike subtractive technologies (such as milling or turning) where a significant portion of the raw material is removed and wasted. In addition, additive manufacturing allows for topology optimization of parts, reducing their weight without compromising functionality, which can decrease fuel consumption during the use of components, for example in transportation and aerospace. At the same time, 3D printing facilitates distributed production, as parts can be manufactured on demand, locally, close to the point of use, reducing the need for transportation and warehouse storage. This flexibility in the supply chain also enables the extension of product life cycles: faulty equipment can be repaired by printing spare parts, even when the original components are no longer manufactured, thus contributing to the circular economy through reuse. Integrating the concept of the circular economy with 3D printing processes can have a synergistic impact; for example, polymer waste can be recycled or reconditioned into printable filament, giving a new life to used plastic materials. Such initiatives to transform industrial composite thermoplastic waste into printable filament demonstrate the potential of additive manufacturing to reduce resource waste and support circularity strategies in industry.

Despite all these theoretical benefits, it is essential that the environmental advantages of additive technologies be validated quantitatively and not merely assumed intuitively. There are numerous factors that can counterbalance material advantages: the energy consumption of 3D printers, process-specific emissions or waste, as well as the environmental impact of the materials used throughout their entire life cycle. For example, FDM (Fused Deposition Modeling), the most widespread plastic 3D printing method, involves continuous heating of the thermoplastic filament above its melting point, operation of motors for extrusion and print-head movement, maintaining the build platform at elevated temperatures, etc., all of which imply substantial electrical energy consumption. Similarly, printers emit ultrafine nanoparticles and volatile organic compounds that can affect air quality and operator health. Another example is SLA (Stereolithography), which uses liquid photopolymer resins. Although SLA can produce parts with superior dimensional accuracy and surface finish, this technology raises different environmental issues: unused resins and resulting residues are hazardous waste, requiring special treatment and being neither biodegradable nor easily recyclable. The comparison between FDM and SLA from an ecological perspective thus highlights important trade-offs. Recent experimental studies show that FDM consumes less energy and has lower production costs per part, while SLA, although providing superior quality, involves higher energy consumption and generates chemical waste that is difficult to manage. Furthermore, while FDM can use biodegradable or at least recyclable filaments that provide an environmental advantage, in the case of SLA the photopolymer resins used have a negative impact precisely because of their toxicity and non-recyclability. These differences underline the importance of a rigorous life cycle assessment (LCA) for 3D-printed products, since only through LCA evaluations can the real impacts be quantified, from raw material extraction, through manufacturing and use, to end-of-life, in order to determine whether an additively manufactured product is truly more sustainable than its conventionally produced equivalent. LCA is a standardized methodology (ISO 14040/44) that provides a holistic perspective on resource-use efficiency and waste generation, enabling the calculation of potential environmental impacts across the entire life cycle of a product or process, and the application of LCA in the context of 3D printing has begun to yield interesting results. This example confirms that only through detailed LCA analysis can differences in sustainability between technologies and materials be correctly identified, avoiding conclusions based on assumptions. Considering the environmental implications and circular economy opportunities, the need for systematic life cycle assessment of 3D-printed products becomes evident, especially for FDM and SLA technologies, which currently dominate the polymer printing market.

Considering the aspects discussed, the main objective of this report is to evaluate to what extent the technologies and materials used in 3D printing are environmentally sustainable, by conducting a detailed bibliometric analysis of the specialized literature. In other words, the study aims to synthesize existing knowledge on the environmental impact of 3D printing, particularly for FDM and SLA processes, and to identify current trends and challenges, using bibliometric tools to ensure an objective and comprehensive view of the field. To achieve this purpose, the report is clearly structured into chapters. The research methodology is described, including the strategy for collecting bibliographic data from Web of Science (WoS) and processing them using the Biblioshiny platform (from the R bibliometrix package) to obtain relevant bibliometric indicators. The criteria for selecting publications, the stages of data cleaning, and the analysis techniques used (analysis of annual scientific production, keywords, and citation networks) are detailed here. The results and their analysis are then presented, including the evolution of research over time, the most frequent themes and concepts (including emerging terms), the geographic and disciplinary distribution of contributions, as well as visual mappings of the field, such as term co-occurrence maps or citation graphs. These bibliometric results are critically discussed to highlight the current state of knowledge regarding the sustainability of 3D printing and the predominant directions of investigation. The report concludes with the main conclusions of the study and future development directions, where the key findings related to the sustainability of FDM and SLA technologies are synthesized, the contribution of the bibliometric assessment to understanding the field is assessed, and possible future research directions are proposed, both for deepening LCA studies and for extending the bibliometric approach or integrating other aspects, such as economic or social analysis of additive manufacturing. Overall, this introduction outlines the general framework of the problem and emphasizes why life cycle assessment of 3D-printed products is a topical issue of strategic importance in modern industrial engineering, justifying the detailed scientific approach presented in the following chapters.

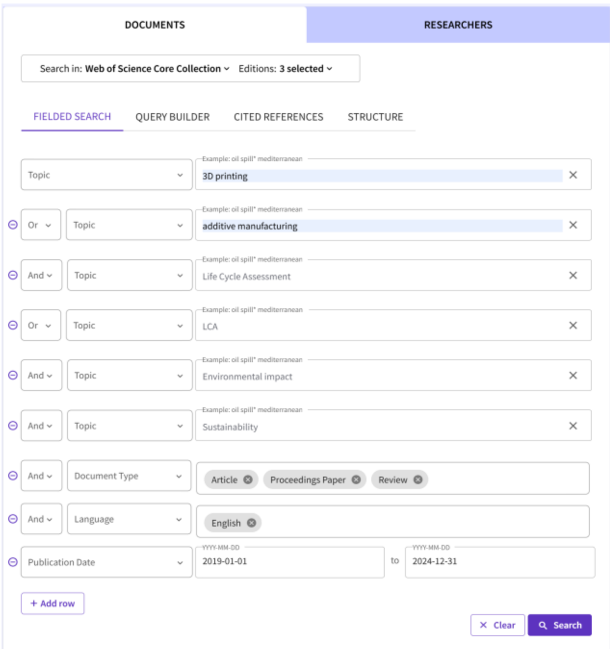
2. Methods

2.1. Search and data collection strategy

In order to be able to begin with an analysis of the latest emerging technologies, it was necessary to choose a solid source of information on which to focus and on which to base this work. I therefore selected the Web of Science (WoS) platform as the main source of bibliographic information, due to its reputation as a solid and trustworthy academic database. WoS is administered by Clarivate Analytics and is considered the oldest and most authoritative database of scientific publications, being widely used in bibliometric analyses [1]. Unlike open-access sources (such as Google Scholar, etc.), WoS includes only journals and conferences of international prestige, selected through a rigorous editorial process. This independent selection process and consistent indexing for over 60 years make WoS "the most trusted citation database" [2], ensuring a high-quality research environment. Consequently, data extracted from WoS are considered representative and valid for obtaining an overall picture of the literature in a given field.

To identify the relevant literature, I used the advanced search module within the WoS Core Collection. I formulated a Boolean query that combines key terms covering the field of 3D printing and environmental sustainability, arranged according to figure 2.1.1.

Figure 2.1.1. Web of Science advanced search interface, illustrating the configuration of Boolean criteria and filters (keywords, document type, language, time period)



Source: Own contribution

I used the main search terms "3D printing" OR "additive manufacturing" (to include both commonly used terms for additive manufacturing) AND "life cycle assessment" OR "LCA" (to capture works addressing life cycle assessment) AND “environmental impact” AND “sustainability.” In addition to these topic field terms, which cover the title, abstract, and author keywords, I also applied additional filters in order to consider only certain types of documents. I applied the Document Type filter limited to Articles, Conference Papers (Proceedings Paper), and Review Articles, in order to exclude other, less relevant document types such as notes, abstracts, etc. I also restricted the documents to those published in the English language, ensuring coverage of the majority of international literature, and limited the publication years to 2019–2024 in order to obtain recent and up-to-date works.

The search thus designed was carried out in the WoS Core Collection, including relevant indexes such as the Science Citation Index Expanded (SCI-EXPANDED), the Social Sciences Citation Index (SSCI), and the Emerging Sources Citation Index (ESCI). The results indicated a significant number of works at the intersection of the mentioned fields, with an initial total of 64,678 bibliographic records obtained. Subsequently, using the bibliometric and filtering functions of WoS, I removed duplicates (the same work indexed, for example, in multiple WoS collections) and organized the records in descending order according to the number of citations. I then selected the top 20,000 unique references for analysis; a substantial volume that suggests a high level of academic interest in the topic of 3D printing and sustainability/LCA in recent years.

2.2. Search and data collection strategy

The bibliographic data obtained from WoS were exported in plain text format, containing all relevant fields (authors, title, abstract, keywords, cited references, year of publication, journal, etc.), as can be observed in figures 2.2.1 and 2.2.2:

Figure 2.2.1. Extraction of metadata from Web of Science for the article “3D printing of ceramics: A review” (Chen et al., 2019)

```
FN Clarivate Analytics Web of Science
VR 1.0
PT J
AU Chen, ZW
   Li, ZY
   Li, JJ
   Liu, CB
   Lao, CS
   Fu, YL
   Liu, CY
   Li, Y
   Wang, P
   He, Y
AF Chen, Zhangwei
   Li, Ziyong
   Li, Junjie
   Liu, Chengbo
   Lao, Changshi
   Fu, Yuelong
   Liu, Changyong
   Li, Yang
   Wang, Pei
   He, Yi
TI 3D printing of ceramics: A review
SO JOURNAL OF THE EUROPEAN CERAMIC SOCIETY
LA English
DT Review
DE 3D Printing; Ceramics; Feedstock; Sintering; Applications
ID PERIODIC HYDROXYAPATITE SCAFFOLDS; 3-DIMENSIONAL PHOTONIC CRYSTALS;
   TRICALCIUM PHOSPHATE SCAFFOLDS; FREE-FORM FABRICATION; OXIDE FUEL-CELLS;
   FUSED DEPOSITION; MECHANICAL-PROPERTIES; CALCIUM-PHOSPHATE; FREEFORM
   FABRICATION; PROCESSING PARAMETERS
AB Along with extensive research on the three-dimensional (3D) printing of polymers and metals, 3D printing of ceramics is now the latest trend to come
under the spotlight. The ability to fabricate ceramic components of arbitrarily complex shapes has been extremely challenging without 3D printing. This
review focuses on the latest advances in the 3D printing of ceramics and presents the historical origins and evolution of each related technique. The main
technical aspects, including feedstock properties, process control, post-treatments and energy source material interactions, are also discussed. The
technical challenges and advice about how to address these are presented. Comparisons are made between the techniques to facilitate the selection of the
best ones in practical use. In addition, representative applications of the 3D printing of various types of ceramics are surveyed. Future directions are
pointed out on the advancement on materials and forming mechanism for the fabrication of high-performance ceramic components.
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EM chen@szu.edu.cn; cslao@szu.edu.cn
RI ; li, junjie/Y-7018-2018; Chen, Zhangwei/N-3199-2014; Liu,
   Changyong/AAN-8402-2021; Wang, Pei/GNW-6506-2022; Chen,
   Zhangwei/W-6793-2019
OI LI, Ziyong/0009-0001-3181-5136; Chen, Zhangwei/0000-0002-5301-3740; Liu,
   Changyong/0000-0003-3919-0713; Wang, Pei/0000-0002-4141-0511
FU Guangdong Provincial Department of Education Youth Innovative Talent
   Project [2017KQNCX179]; Key Project Fund for Science and Technology
   Development of Guangdong Province [2017B090911014]; Shenzhen Peacock
   Plan Technology Innovation Project [KQJSCX20170727101223535,
   KQJSCX20170327150948772]; Shenzhen University Startup Fund [2017035];
   Shenzhen Fundamental Research Project [JCYJ20150626090430369]
FX This work is supported by the Guangdong Provincial Department of
   Education Youth Innovative Talent Project (2017KQNCX179), Key Project
   Fund for Science and Technology Development of Guangdong Province
   (2017B090911014), Shenzhen Peacock Plan Technology Innovation Project
   (KQJSCX20170727101223535, KQJSCX20170327150948772), Shenzhen University
   Startup Fund (2017035) and Shenzhen Fundamental Research Project
   (JCYJ20150626090430369).
CR Agarwala MK, 1996, RAPID PROTOTYPING J, V2, P4, DOI 10.1108/13552549610732034
   Aggarangsi P., 2006, Solid Freeform Fabrication Proceedings, P709, DOI [10.26153/tsw/7174, DOI 10.26153/TSW/7174]
   Ahn D, 2009, J MATER PROCESS TECH, V209, P664, DOI 10.1016/j.jmatprotec.2008.02.050
   Ahn SH, 2002, RAPID PROTOTYPING J, V8, P248, DOI 10.1108/13552540210441166
```

Source: Own contribution

Figure 2.2.2. Continuation of the bibliographic record for the previous article, illustrating additional metadata regarding the journal source (publisher, ISSN, location), year of publication, volume, pages, impact factors, and thematic classifications: WoS category and indexing domain

```
   Zocca A, 2015, BIOFABRICATION, V7, DOI 10.1088/1758-5090/7/2/025008
   Zocca A, 2016, J AM CERAM SOC, V99, P1960, DOI 10.1111/jace.14213
   Zocca A, 2015, J AM CERAM SOC, V98, P1983, DOI 10.1111/jace.13700
   [No title captured]
NR 295
TC 1486
Z9 1601
U1 94
U2 1537
PU ELSEVIER SCI LTD
PI OXFORD
PA THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, OXON, ENGLAND
SN 0955-2219
EI 1873-619X
J9 J EUR CERAM SOC
JI J. Eur. Ceram. Soc.
PD APR
PY 2019
VL 39
IS 4
BP 661
EP 687
DI 10.1016/j.jeurceramsoc.2018.11.013
PG 27
WC Materials Science, Ceramics
WE Science Citation Index Expanded (SCI-EXPANDED)
SC Materials Science
GA HK3MC
UT WOS:000457819600001
OA hybrid
DA 2025-07-26
ER
```

Source: Own contribution

The WoS platform does not allow the export of this type of information for more than 500 records at a time. Therefore, I exported the 20,000 bibliographic records into text documents of 500 records each, which were then bundled together, and the resulting file was imported into Biblioshiny, the interactive web interface of the bibliometrix package in R. I chose this tool due to its ease of use and analytical power, providing a user-friendly browser-based platform for performing detailed bibliometric analyses without requiring advanced programming knowledge [3]. The bibliometrix package is a recognized open-source tool for comprehensive science mapping analysis, specifically designed to process data from databases such as WoS or Scopus. Thus, the compatibility between WoS data and Biblioshiny is excellent, allowing the desired analyses to be carried out smoothly. I also preferred Biblioshiny because of its ability to generate detailed visualizations and reports (citation networks, co-authorship maps, temporal trend graphs, keyword co-occurrence analysis, etc.), facilitating the interpretation of results in an interactive and intuitive manner. During the data cleaning stage, I verified the completeness of the fields and any problematic records were automatically removed (figure 2.2.3).

Figure 2.2.3. Biblioshiny data upload report, highlighting the quality of the metadata

Completeness of metadata -- **20000** docs from **Isi**

Metadata	Description	Missing Counts	Missing %	Status
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
WC	Science Categories	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
CR	Cited References	8	0.04	Good
C1	Affiliation	11	0.06	Good
RP	Corresponding Author	13	0.06	Good
DI	DOI	33	0.16	Good
AB	Abstract	48	0.24	Good
ID	Keywords Plus	1537	7.69	Good
DE	Keywords	2422	12.11	Acceptable

Advice Report Save Close

Source: Own contribution

It can be observed that the majority of bibliographic fields (authors – AU, title – TI, year – PY, etc.) are fully present in all 20,000 records (Status: Excellent), indicating a very complete dataset. Only a small percentage of works lacked information in certain fields, for example: approximately 0.2% without an abstract (AB), about 0.16% without a DOI (DI), around 7.7% without Keywords Plus (ID), and about 12% without author keywords (DE). These low proportions of missing data are acceptable and do not significantly affect subsequent analyses. Therefore, the final dataset is clean and ready for in-depth bibliometric analyses.

Before proceeding to complex bibliometric analyses, it is useful to perform a descriptive analysis of the corpus of approximately 64,000 publications in order to understand their distribution across fields, sustainability-related topics, and the main concepts addressed. WoS provided such descriptive indicators, presented in figures 2.2.4, 2.2.5, and 2.2.6.

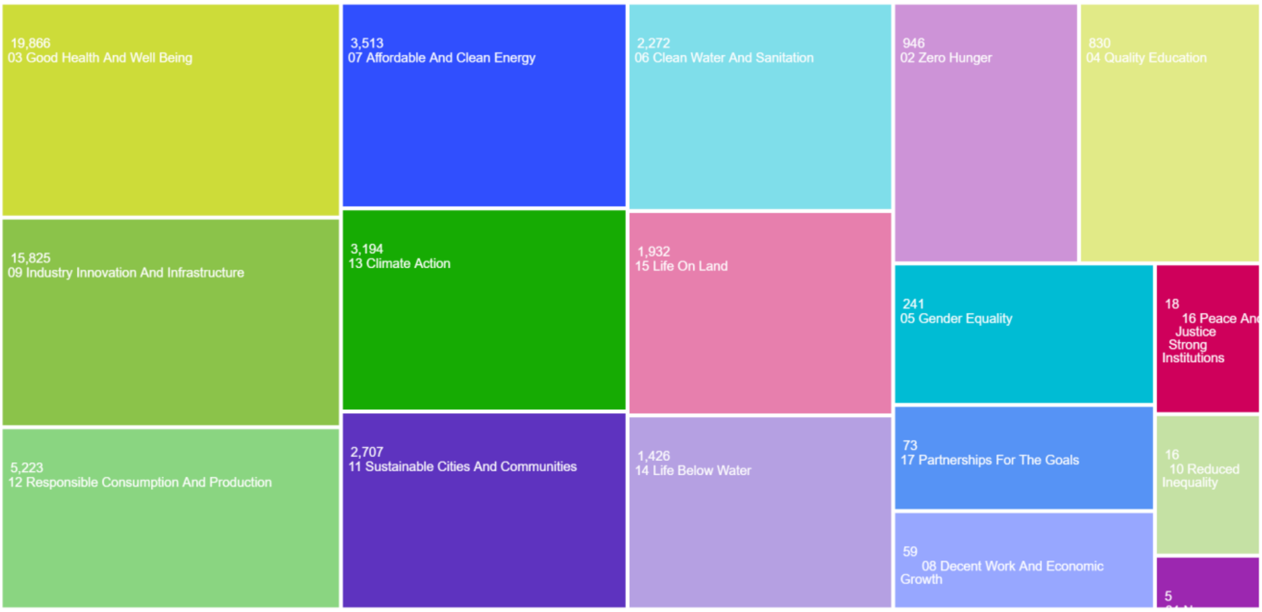
Figure 2.2.4. Distribution of publications by Web of Science categories (treemap visualization)

Source: Own contribution

Each rectangle represents a WoS disciplinary category, with its size being proportional to the number of articles in the dataset associated with that category. It can be observed that the predominant field is Materials Science Multidisciplinary with 16,187 articles in the sample, followed by categories in Applied Physics (5,902), Nanotechnology (4,968), and Multidisciplinary Chemistry (4,887), highlighting a strong orientation toward materials science and an interest in the design and process aspects of additive manufacturing. The presence of categories such as Green & Sustainable

Science & Technology (2,114) and Environmental Sciences (2,587) also indicates that a significant portion of these works directly address sustainability and environmental impact topics. The interdisciplinary nature of the subject is also reflected by the appearance of other related fields: Biomedical Engineering (4,386) and Biomaterials (4,221), related to biomedical applications of 3D printing; Dentistry and Oral Medicine (2,014), suggesting the use of 3D printing in dentistry; or Construction & Building Technology (1,776), indicating applications in construction. This broad distribution underscores the multidisciplinary character of research on 3D printing with sustainability concerns, combining materials science, engineering, environmental sciences, and even medicine.

Figure 2.2.5. Distribution of publications according to the Sustainable Development Goals (SDGs), based on Clarivate (WoS) classification



Source: Own contribution

In Figure 2.2.5, each rectangle represents a UN 2030 objective, with its size proportional to the number of associated works. The dominance of SDG 3: Good Health and Well-Being, with 19,866 publications, and SDG 9: Industry, Innovation and Infrastructure, with 15,825 publications, is evident. This reflects the fact that a large portion of the works have applications in the medical field (tissue bioprinting, personalized implants, medical devices) and in industrial technological development (innovations in additive manufacturing processes and production infrastructure). The next most represented objectives are SDG 12: Responsible Consumption and Production (5,223 works) and SDG 7: Affordable and Clean Energy (3,513 works), suggesting researchers' interest in sustainable materials, the circular economy, and energy efficiency in 3D printing. SDG 13: Climate

Action (3,194 works) and SDG 11: Sustainable Cities and Communities (2,707 works) are also represented, indicating links to carbon footprint reduction and applications in sustainable urban development (such as 3D-printed construction). In contrast, objectives with a pronounced social component, such as SDG 2: Zero Hunger (946 works) or SDG 10: Reduced Inequalities (16 works), have very few associated publications. This imbalance suggests that the analyzed literature addresses sustainability mainly from a technological and environmental perspective, contributing indirectly to health and industrial innovation, but having minimal connections with the broader socio-economic aspects of sustainable development. The mapping to the SDGs confirms the relevance of the dataset to sustainability topics, with most studies focusing on objectives related to the environment, technology, and well-being.

Figure 2.2.6. Frequently used terms in the titles and abstracts of the works (treemap visualization of the most commonly occurring words)

Source: Own contribution

In figure 2.2.6 it can be observed that the most prominent terms are precisely the core of the researched subject: “3D printing,” which appears 6,637 times, and “additive manufacturing,” with 2,715 occurrences, which validates the relevance of the dataset with respect to additive manufacturing technologies. Beyond these central terms, many technical keywords appear frequently, reflecting the dominant concerns of the research: “mechanical properties,” “fabrication,” “design,” “performance,” “microstructure,” or “optimization,” indicating that numerous studies focus on the characterization and optimization of the mechanical properties of 3D-printed parts, on manufacturing processes, and on the design of printed structures. The biomedical field is well represented through terms such as “tissue engineering,” “bone,” “hydrogel,” “in vitro,” or “stem cells,” highlighting the use of 3D printing for tissue regeneration, biomedical engineering, and the development of biomaterials. Terms specific to 3D printing methods appear: “stereolithography” (a photopolymerization technology), “extrusion” (extrusion, specific to FDM technology), “FDM (fused deposition modeling),” as well as material-related concepts such as “polymers,” “nanoparticles,” “nanocomposites,” and “PLA” (polylactic acid, a biodegradable polymer widely used in printing). With regard to the sustainability elements introduced through the search strategy, terms such as “sustainability,” “life cycle assessment,” and the acronym “LCA” also appear in the visualization, but with a lower frequency, each at around a few hundred occurrences. This suggests that, although all selected works refer to environmental impact or life cycle aspects (according to the search criteria), their discourse is often dominated by the technical and scientific aspects of 3D printing, with the in-depth integration of sustainability concepts in many cases being subordinated to engineering objectives such as the development of new materials and performance improvement. Nevertheless, the consistent presence of these environment-related terms confirms that the issue of environmental impact and life cycle assessment is recognized and addressed to a considerable extent in the analyzed specialized literature.

The data collection and processing methodology described above ensured a robust set of publications relevant for bibliometric analysis. The choice of WoS guarantees the quality and international recognition of the sources, and the use of Biblioshiny will allow a detailed and reliable analysis of these data. The initial characterization of the corpus highlights the multidisciplinary nature of the field (engineering, materials science, environment, health) and confirms the connection with the sustainability aspects (SDGs and LCA-related terms) proposed in the objective. Based on this dataset, I will proceed to carry out and present in-depth bibliometric analyses, ranging from collaboration and citation networks to the identification of the most influential works and conceptual trends, using Biblioshiny, aiming to obtain a comprehensive picture of the evolution and structure of knowledge in the field of sustainable 3D printing.

3. Results

3.1. Analysis of general bibliometric indicators

To understand the research landscape on 3D printing and sustainability in the recent period, I conducted a bibliometric assessment using the Bibliometrix package, by importing a set of 20,000 scientific works from Web of Science published between 2019 and 2024 inclusive, applying rigorous filtering in accordance with the methodology described earlier. I included only articles, reviews, and conference papers (proceedings papers) written in English, which address 3D printing in relation to life cycle assessment, environmental impact, and sustainability. Below, I present the interpretation of the general bibliometric indicators (“Main Information”) generated, as can be observed in figure 3.1.1.

Figure 3.1.1. General main information resulting from loading the dataset into Biblioshiny

Source: Own contribution

The analysis covers a six-year interval (2019–2024), during which a total of 20,000 documents relevant to sustainable 3D printing were identified. These publications appeared in 2,124 distinct sources, such as scientific journals and conference proceedings, indicating an extremely wide dissemination of research on this topic. The high number of sources suggests that the topic of 3D printing and sustainability is strongly interdisciplinary, with works published across a variety of fields, from engineering and materials science to environmental sciences and sustainable management. This observation is consistent with general trends in the literature on 3D printing, which show that this technology is present in multiple research areas, the most prominent being engineering and materials science. The fact that the 20,000 works are distributed across more than two thousand journals and conferences also indicates that there is no single dominant publication channel; the scientific community presents its results across a systemic echo of scientific forums, which may reflect both the diversity of subtopics addressed and the widespread interest in sustainability in 3D printing. This dispersion of sources implies, on the one hand, that innovations and knowledge related to sustainable 3D printing reach diverse audiences, but on the other hand it can make unified synthesis of progress more difficult, requiring efforts of interdisciplinary integration of information.

A notable aspect of these data is the annual growth rate of publications, calculated at -55.7%. In other words, in the 2019–2024 interval, a pronounced decrease in the number of works published annually on this topic was observed. This result is surprising, as many emerging techno-scientific fields usually show positive growth in publication volume. A possible explanation for the negative growth rate may be related to the gradual maturation of the field: after an initial peak of interest and a wave of publications in earlier years, the pace of output may be declining, signaling that research in sustainable 3D printing has entered a consolidation phase. For example, a global bibliometric analysis of the literature on 3D printing showed that after 2015 the strong growth began to slow as the technology became increasingly mature [4]. Thus, it is possible that the initial explosive interest in the combination of 3D printing and life cycle assessment reached its peak, and after 2020–2021 the scientific community shifted toward more specific directions or already established approaches, which reduced the volume of new works in exactly this niche. It should be noted that the negative growth rate could also be partially influenced by methodological or contextual factors. For instance, the year 2024 included in the analysis may be incompletely covered, which would underestimate the actual number of publications appearing in 2024. Additionally, the very specific search criteria, which required the simultaneous presence of terms related to LCA, environmental impact, and sustainability, might exclude some newer works that address the sustainability of 3D printing under other concepts, such as the circular economy or energy analysis, thus leading to the impression of a decline. Regardless of the cause, the value of -55.7% highlights a potential warning signal: if the decline is real, it could indicate a saturation of the subject or a decrease in interest and funding in this niche, which would require a reassessment of future research directions.

The analyzed dataset includes an impressive number of 72,461 unique authors who contributed to works on 3D printing and sustainability, a figure that reflects a very large and diverse research community involved in the field, likely spread across multiple specializations and geographic regions. The average number of authors per paper is 5.98, which shows that publications were mostly the result of relatively large research teams. In fact, I identified only 235 single authors, meaning authors who published individually (without co-authors), corresponding to a total of 268 works produced by a single person. Therefore, the overwhelming proportion of documents (over 98%) are collective works, produced in co-authorship, an authorship profile that indicates a high level of scientific collaboration in the field of sustainable 3D printing. The tendency toward collaboration is consistent with general developments in science and engineering, where in recent decades the average number of authors per article has steadily increased. For example, the literature shows a shift from about 2 authors per article in the 1980s to approximately 7 authors per article in 2019 [5]. In this context, the average of ~6 authors in the analyzed field is natural, reflecting the fact that research on sustainability in 3D printing often requires multidisciplinary expertise, which is more easily found within a team. The involvement of multiple authors also suggests the existence of large-scale projects (possibly academic consortia or collaborations between universities and industry) aimed at addressing complex issues related to the sustainability of additive manufacturing technologies.

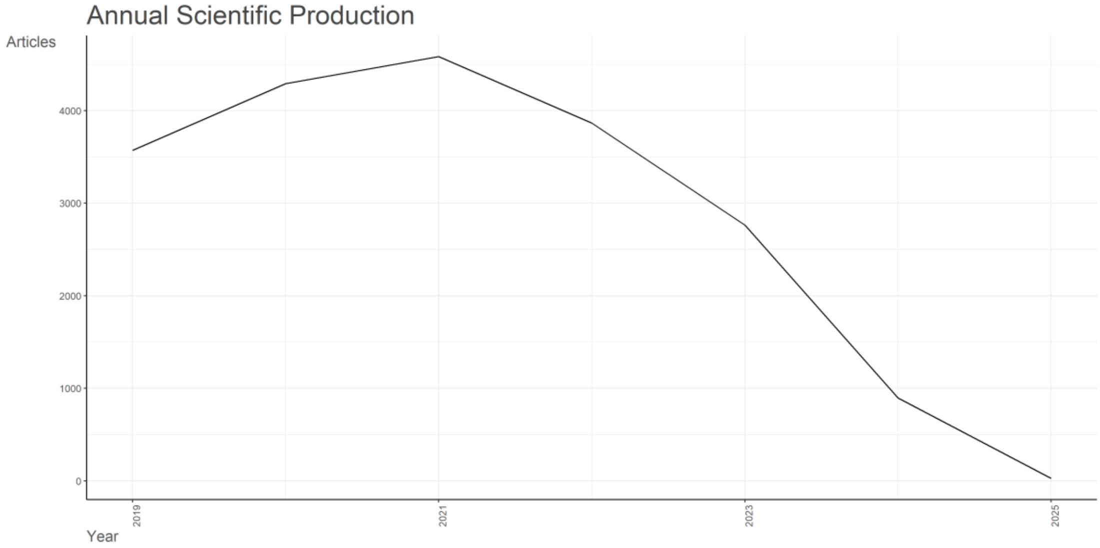
Extensive collaboration can have beneficial effects on the quality and visibility of research: studies show that articles with multiple authors tend to be more influential and more cited than those written by a single author [6], as they bring together diverse perspectives and broader citation social networks. A key indicator of international collaboration in the dataset is the percentage of international co-authors, which reaches 32.91%. This means that approximately one third of all publications involve authors affiliated with institutions from at least two different countries. This level of internationalization of collaborations is quite high and highlights the global nature of concerns related to sustainable 3D printing. By comparison, at the level of science and engineering as a whole, the average proportion of articles with co-authors from different countries was about 23% in 2020 [6]. The fact that in our field this percentage is significantly higher suggests that sustainability and environmental impact issues in additive manufacturing have a pronounced international relevance, prompting researchers to collaborate across borders to share infrastructure, data, and specialized knowledge. For example, research initiatives may involve European consortia or partnerships between laboratories in different countries, given that sustainability often has both local components (regulations, resources) and universal applicability. This international collaboration not only broadens the scope of application of the results, but can also increase the scientific impact of the works: there is clear evidence that works with authors from multiple countries receive, on average, more citations, benefiting from visibility in diverse scientific networks.

The analyzed works cover a wide range of topics, a fact reflected by the total number of author keywords identified: 36,404, a number that represents the totality of key expressions chosen by authors to characterize their studies. This very high value suggests considerable thematic diversity within the corpus. Practically, researchers used more than thirty-six thousand distinct terms, indicating that the field of sustainable 3D printing does not yet have a narrow set of standardized concepts, but rather encompasses numerous directions and niches of investigation. For example, under the general umbrella of sustainability in 3D printing, there may be works focused on biodegradable printing materials, on the energy efficiency of the additive manufacturing process, on recycling powders and waste, on life cycle assessment for various applications such as medical, construction, and many others. Each such sub-domain has its own set of specialized keywords, which cumulatively leads to a very rich vocabulary. From a critical perspective, this may signal that the discipline is still in a phase of broad exploration, where different authors experiment with varied approaches and invent new terms or use terms specific to their base field. As the field matures, one might expect some convergence of terminology; for example, a consensus on the use of certain sustainability indicators or the establishment of preferred phrases for ecological printing technologies. For the moment, however, the large number of keywords denotes the richness and thematic fragmentation of the literature in the analyzed interval. From the perspective of anchoring the works in the existing literature, the dataset includes a total of 671,281 bibliographic references. This means that, on average, each of the 20,000 documents cited approximately 33–34 previous bibliographic sources. This average number of references per work is consistent with academic practices in the field; scientific articles in engineering and environmental sciences usually include several dozen references to substantiate the methodology and compare results with previous studies. Observing this indicator, I inferred that authors in the field of 3D printing and sustainability pay significant attention to the theoretical framework and the research context already published. The approximately 671 thousand bibliographic citations likely come both from the additive manufacturing literature (for technical aspects related to 3D printing) and from environmental science and LCA evaluation literature (for impact and sustainability aspects). Thus, the analyzed works draw their knowledge from two major directions and combine them, once again demonstrating the interdisciplinary nature of the field. The large number of total references may also indicate the presence of substantial review-type articles in the dataset (which, by their nature, cite hundreds of sources). In fact, with over 3,300 reviews included in the dataset (according to Document Types, where review appears frequently), it is expected that these bibliographic syntheses significantly increased the total number of references. I interpreted the high number of references as a sign of scientific rigor and extensive integration of pre-existing knowledge into new publications, which is an essential aspect of research, where each study must clearly relate to the prior literature.

One of the most relevant indicators of academic influence in this dataset is the average number of citations per article, which is 52.23. This significant value shows that, on average, each work on 3D printing and sustainability has been cited more than 52 times by other works. Considering that the analyzed time period (2019–2024) is relatively short and that the average age of the documents in the corpus is only 3.96 years, I consider such a level of citation to be remarkable. Practically, even relatively recent articles (published approximately 4 years ago on average) have managed to generate a notable impact within the scientific community. This fact may indicate that the topic of sustainable 3D printing is one of high interest and relevance, attracting the attention of many researchers who, in turn, cite these works in their own studies. As a doctoral student, I was impressed by this metric, as it suggests that the literature I am examining is highly relevant and visible: frequent citations indicate either that the respective works have made important contributions through reference studies, novel LCA methodologies applied to 3D technologies, or comprehensive evaluations of the sustainability of additive manufacturing processes, or that the subject itself is a fashionable one that appears in the bibliographies of many other related studies. There is, of course, the possibility that the average of 52 citations is influenced by the uneven distribution of citations, with a relatively small number of highly cited articles (for example, an influential review article or a pioneering study on the environmental impact of 3D printing) raising the average, while many ordinary articles have much more modest citation counts. To fully understand the impact, it would also be useful to analyze the citation median or to identify “highly cited papers”; however, even so, the high average conveys a clear message: the field of 3D printing and sustainability has produced works with substantial resonance. Contributing to this impact, as discussed, is the high degree of collaboration (especially international), which tends to amplify the visibility and relevance of results [6]. The fact that the publications are relatively recent yet heavily cited may reflect the global urgency of technological sustainability issues and the fact that the academic community pays immediate attention to any data and conclusions regarding the reduction of the environmental impact of new technologies such as 3D printing, rapidly integrating this knowledge into subsequent works. Last but not least, the average age of the documents of approximately 3.96 years confirms that the dataset is composed predominantly of recent literature from the past few years. Older articles in the set (2019–2020) have had the opportunity to accumulate citations over a period of 5–6 years, which partially explains the high average citation level. At the same time, the presence of very recent works (2023–2024) slightly lowers the average age, showing that the analysis also covers the current frontier of research. As a doctoral student examining these works, I benefit from analyzing a rapidly evolving field, with works that are intensely discussed within the community. I must also be aware that the rapid pace of publication and citation implies the need to constantly update the bibliographic base and monitor emerging directions, since such a dynamic field can undergo notable changes from one year to the next.

3.2. The dynamics of scientific production vs. the impact of citations

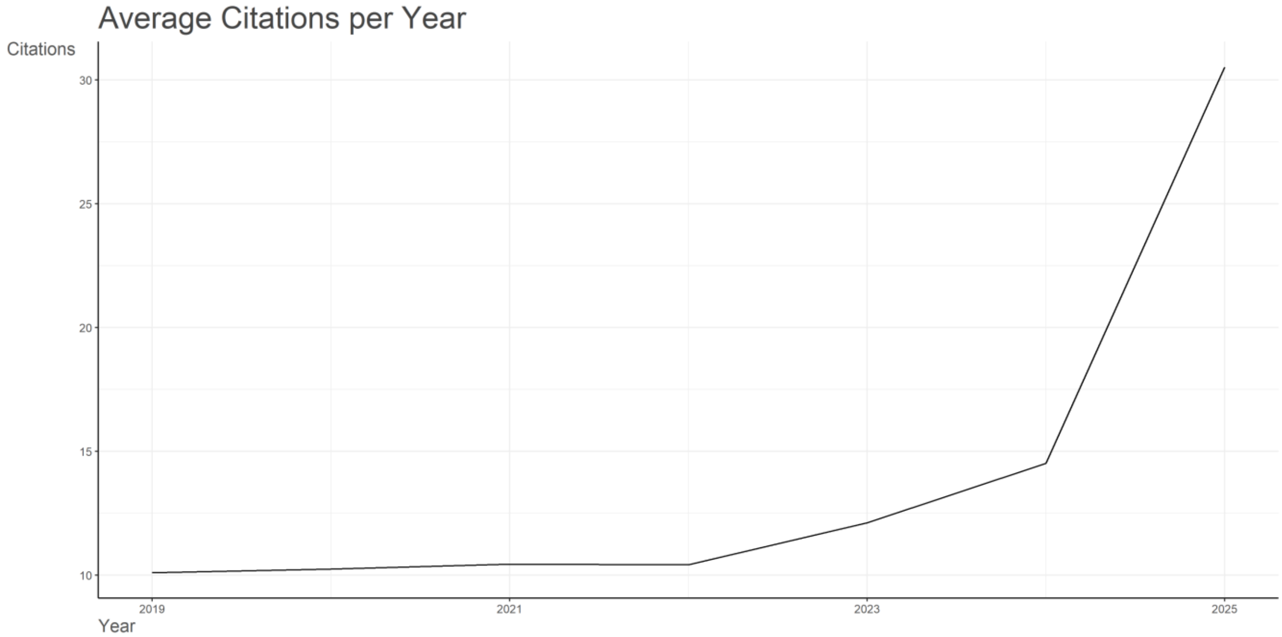
Figure 3.2.1. Scientific article production chart for the period 2019–2025



Source: Own contribution

Analyzing the graph of the evolution of annual scientific production for the period 2019–2025 in figure 3.2.1, I observed an initial increase in the number of articles, followed by a significant decrease in recent years. The number of publications increases steadily from 2019 to 2021, reaching a peak in 2021, after which a downward trend is observed: in 2022 production decreases moderately, and in 2023 and 2024 the decline becomes pronounced. This pattern of sharp growth followed by decline can be placed in the context of recent events and trends. For example, I correlated the 2021 peak with the intensified scientific effort during the COVID-19 pandemic, a period during which the specialized literature records a surge in the number of articles in 2020–2021 due to COVID-related research, followed by a return to usual levels after 2022 [7]. Thus, the obtained data confirm a similar pattern (maximum in 2021 and subsequent decrease), suggesting that after a period of academic effervescence the field entered a phase of relative contraction. This contraction may indicate a maturation of the field, a saturation of leading research topics, or contextual factors (for example, the end of post-pandemic emergency funding or the reorientation of researchers toward other subjects). I also note that the very low values for 2024–2025 may be influenced by incomplete coverage of these years in the analyzed database; however, the general downward trend remains evident.

Figure 3.2.2. Chart of average citation values per year for the analyzed works during the period 2019–2025



Source: Own contribution

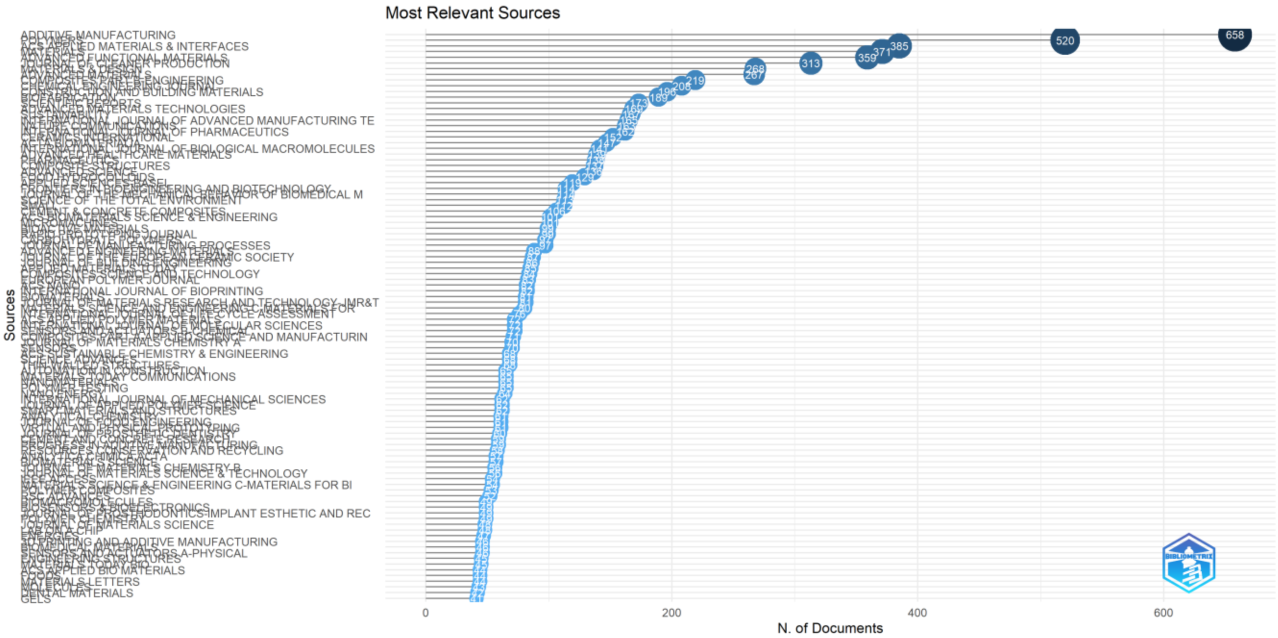
On the other hand, the graph in figure 3.2.2 regarding average annual citations per article reveals that the impact of the works has remained high or has even increased despite the reduction in article production. I observed that for works published in 2019–2022, each article accumulated on average around 10 citations per year (a relatively constant value), while for the recent years 2023–2025 the average citations per article are even higher (around 12 in 2023, 14 in 2024, exceptionally reaching approximately 30 in 2025, according to the available data). I interpreted this increase in average impact as an effect of delayed visibility and changes in citation behavior. First of all, citations of an article usually appear with a time lag and reach a maximum 2–4 years after publication. Therefore, the numerous articles published during the peak period (2019–2021) fully manifested their influence only in the following years, contributing to maintaining a high total number of citations even after the pace of new publications decreased. Secondly, I considered the importance of document age: older works tend to accumulate progressively more citations over time. Thus, even if fewer articles were published after 2021, the existing body of literature, especially influential articles from previous years, continued to be cited intensively. The decrease in production may mean that the community's attention focused on a smaller number of works, but with higher impact. I noted the possibility that, in recent years, researchers predominantly published review studies or high-quality works that quickly attract significant citations, a phenomenon similar to that of "hot papers" [8], which are immediately recognized in the literature. For example, the unusually high value of average citations for 2025 (after only one year since publication) suggests that some articles published in that year had an immediate impact, rapidly accumulating a large number of references from other authors. This is possible either due to the particular relevance of the topics addressed or due to intense collaborations and increased online visibility in the current academic environment.

I found that the dynamics of the number of publications are not mechanically reflected in the dynamics of citations per article. The increase in the average impact of works alongside a decrease in publication volume indicates a delayed effect of scientific visibility and an orientation toward quality: the existing literature exerts its influence over time, and the community can capitalize more intensively on a limited set of essential works. This critical analysis highlights the importance of considering the temporal and structural context of the field, from global events such as the pandemic to the life cycle of scientific ideas, when evaluating research performance. I realized that interpreting trends must go beyond raw numbers; by correlating the evolution of production with impact and identifying possible causes, a more nuanced understanding of the development of the field is achieved.

3.3. Relevance, citation, and temporal dynamics in literature

In figure 3.3.1 I illustrated the most prolific sources based on the number of articles published in the analyzed dataset. I observed that a limited number of journals dominate scientific production in the field of sustainable 3D printing. The most active source was the journal Additive Manufacturing, with 658 articles published during the interval, which underscores its central role in this research community. The next in terms of volume is Polymers, with 520 articles, followed by ACS Applied Materials & Interfaces with 385 articles. Among the top five sources are also the journals Materials with 371 articles and Advanced Functional Materials with 359 articles. The presence of the journal Journal of Cleaner Production with 313 articles among the top sources highlights the close connection between sustainability concerns and research in 3D printing, indicating the interdisciplinary character of the field.

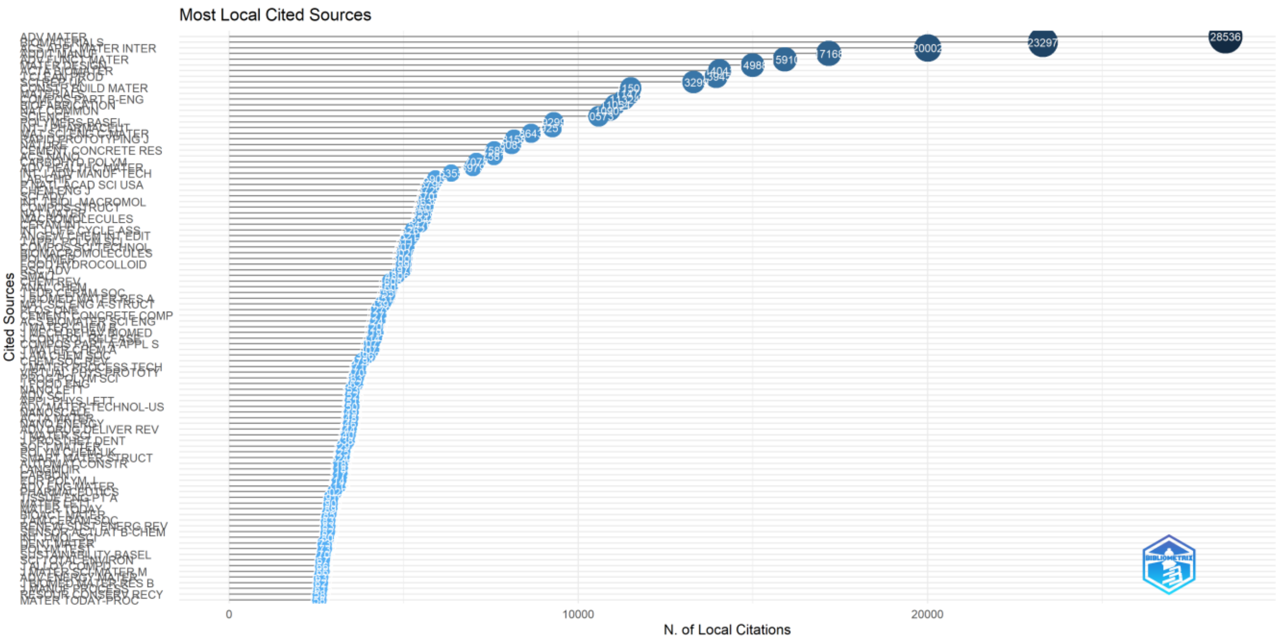
Figure 3.3.1. Most relevant sources by number of documents published between 2019–2025



Source: Own contribution

In the analysis of local citations (figure 3.3.2), I found that the influence of sources follows a different hierarchy compared to publication volume. High–overall-impact journals, which contributed fewer articles to the dataset, nevertheless accumulated a very large number of citations. For example, Advanced Materials recorded the highest number of local citations (28,536), even though it provided only 267 articles in the dataset, highlighting the influence of its flagship works. Similarly, Biomaterials, with 23,297 citations, is heavily referenced by articles in the field, despite not being among the most prolific sources in terms of article count. On the other hand, some specialized journals appear in both rankings, indicating that their publications are not only numerous but also highly cited. Additive Manufacturing, for instance, accumulated 17,168 local citations, and ACS Applied Materials & Interfaces around 20,002 citations, confirming their status as both prolific and influential sources.

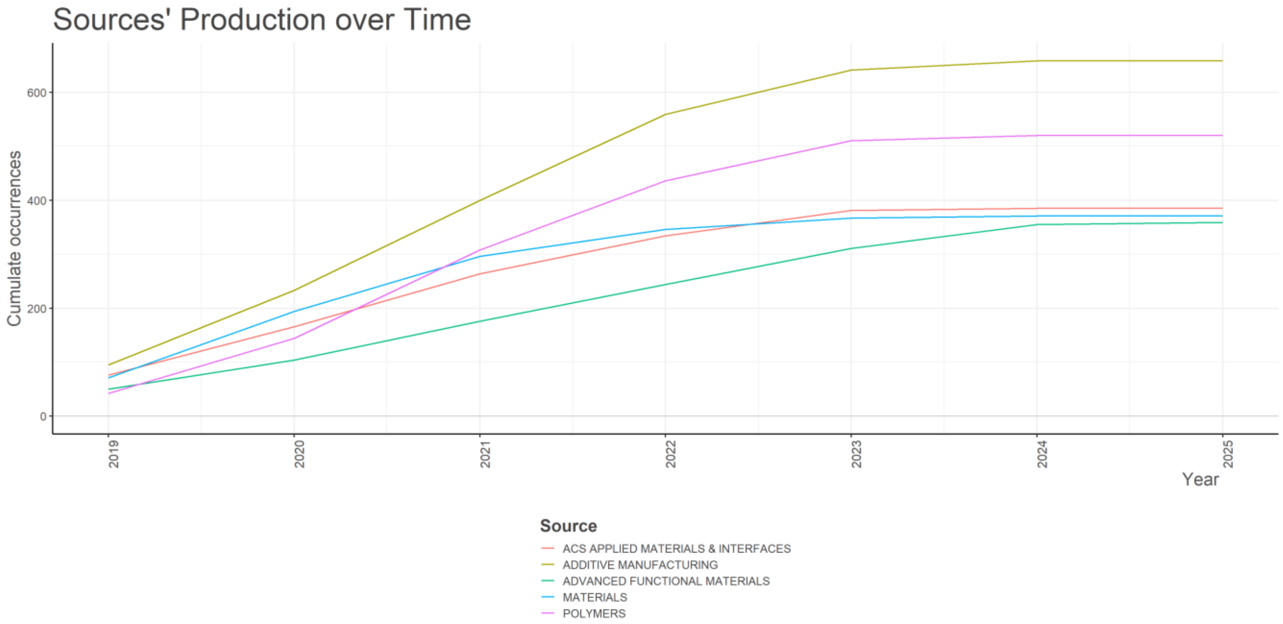
Figure 3.3.2. Most frequently cited sources by number of local citations between 2019–2025



Source: Own contribution

Advanced Functional Materials, with 15,910 local citations, is also among the most frequently cited sources, alongside Materials & Design (14,988) and Journal of Cleaner Production (13,945). By contrast, some journals with a very high volume of publications do not rank highly in terms of citations, a notable example being Polymers, which, although it was the second most productive source, accumulated only 9,299 local citations. This gap suggests a lower average impact per article for such sources or the fact that many of the works published there are relatively recent and have not yet benefited from sufficient citations. I also noted the appearance among the top cited sources of prestigious generalist journals such as Science, Nature Communications, or Scientific Reports, indicating that authors in the field rely on essential contributions published in top-tier journals, even if these do not rank among the most productive sources of sustainable 3D printing during the studied interval. Regarding the evolution over time of the production of these sources (figure 3.3.3), I observed a pronounced upward trend in the period 2019–2023. All five top journals steadily increased their cumulative number of articles from year to year, reflecting the rapid expansion of research in the field. For instance, Additive Manufacturing grew from 95 cumulative articles in 2019 to 641 in 2023, consolidating its leading position. Similarly, Polymers increased from 42 articles in 2019 to 510 in 2023, highlighting the growing interest in polymeric materials in sustainable 3D printing. Consistent growth was also recorded by ACS Applied Materials & Interfaces, from 76 articles in 2019 to 381 in 2023, and by Advanced Functional Materials, from 50 to 311 articles over the same period. These developments demonstrate that, as sustainable 3D printing has become an increasingly important topic, both specialized journals and materials science journals have published ever larger volumes of relevant works.

Figure 3.3.3. Evolution of the cumulative article production for the top five sources between 2019–2025

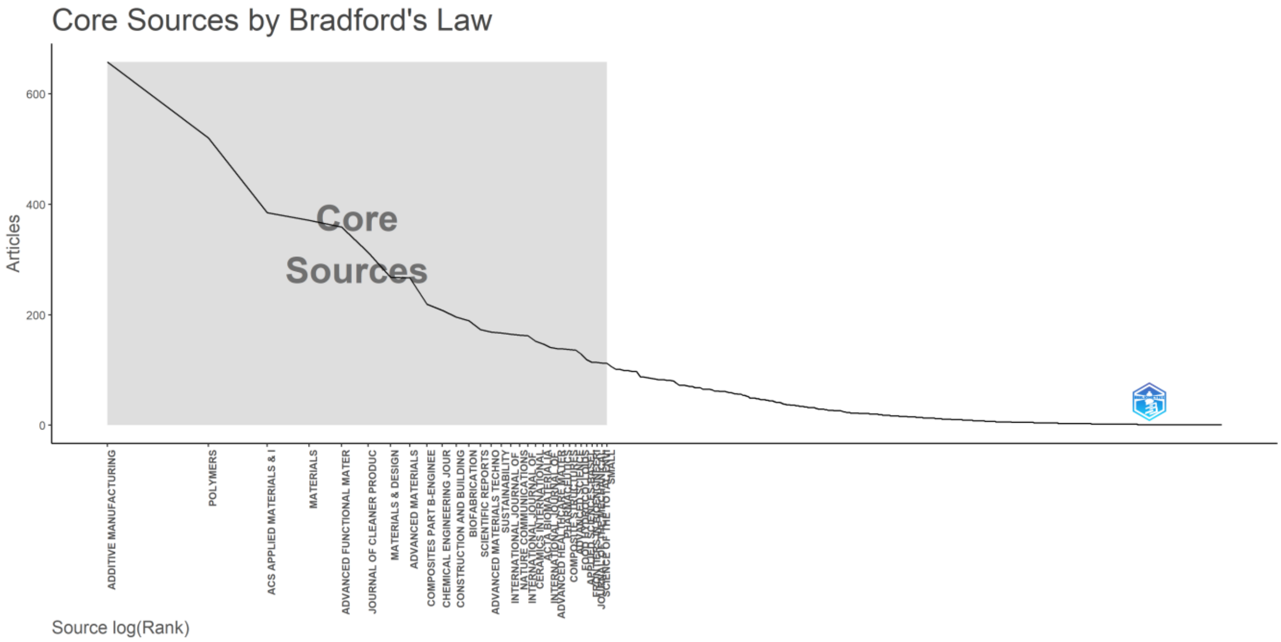


Source: Own contribution

Starting in 2024, however, I observed a moderation in the growth rate for these major sources, indicating a possible stabilization. Additive Manufacturing reached approximately 658 cumulative articles in 2024 and did not show a significant increase up to 2025, partly because the analyzed dataset ends at that point. Polymers shows a similar trend, stagnating at around 520 articles after 2023. This slowdown suggests that, after the initial boom, the field has entered a maturation phase in which the annual volume of publications remains more constant. It is worth noting that none of these curves indicate a decline in production—the interest in sustainable 3D printing remains high; even if the growth rate has slowed, top journals continue to publish new research in the field consistently.

To better understand the structure of the literature in the field of sustainable 3D printing, I applied Bradford's Law. This bibliometric law states that the majority of relevant articles in a scientific field are concentrated in a relatively small number of key journals, referred to as "core sources," while a large number of secondary sources publish fewer articles. Thus, researchers can efficiently identify the essential journals on which they should focus their publishing and consultation efforts.

Figure 3.3.4. Distribution of publication sources according to Bradford's law in the literature on sustainable 3D printing during the period 2019–2025



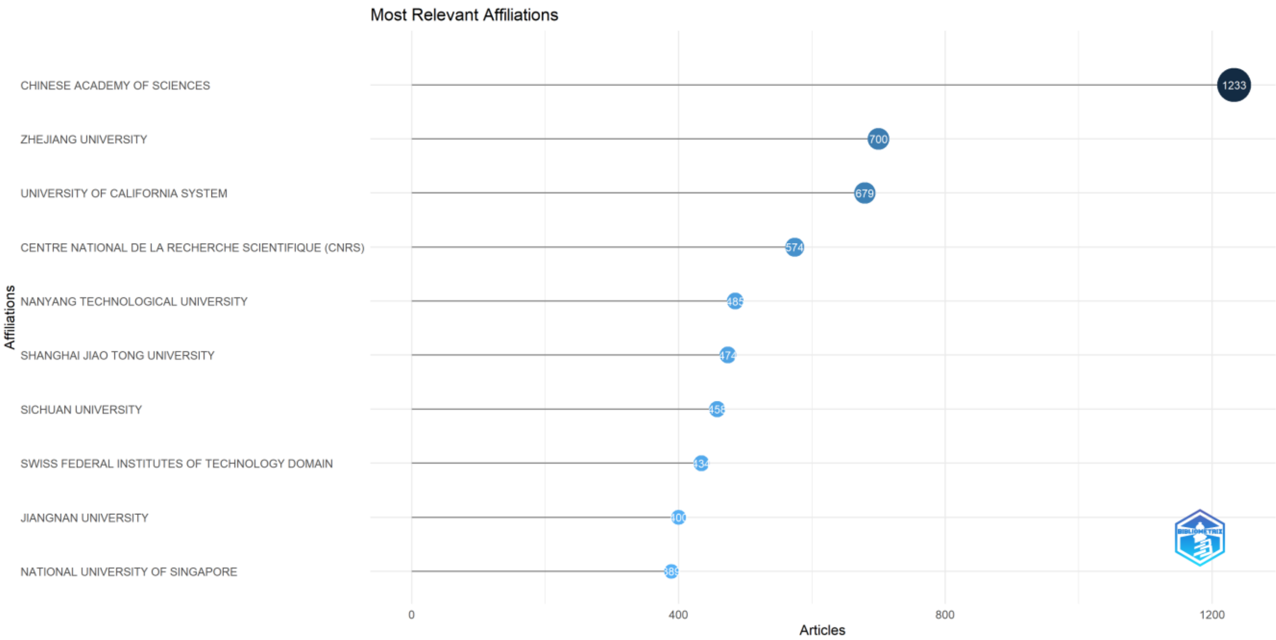
Source: Own contribution

Analyzing the distribution of publications according to this law (figure 3.3.4), I observed that a limited number of journals form the central core of the analyzed literature. In the core zone, visually identified by the gray area of the graph, key journals appear such as Additive Manufacturing, Polymers, ACS Applied Materials & Interfaces, Materials, Advanced Functional Materials, and Journal of Cleaner Production. These core sources concentrate the majority of relevant articles on sustainable 3D printing published between 2019 and 2025, confirming their central importance in this research field. The figure clearly highlights that after this central core there is a sharp decrease in the number of articles published per journal, indicating a large dispersion across secondary and tertiary sources. This distribution supports the idea that only a few key journals clearly dominate scientific production, while the remaining publications are spread across a wide variety of journals with much lower and more occasional contributions. From a practical perspective, identifying these core sources is extremely valuable for me as a doctoral researcher, as it allows me to focus on consulting and publishing in the journals with the highest impact and relevance in the field. Moreover, this concentration of the literature suggests that future research efforts, in order to be well disseminated and to reach a broad and relevant target audience, should primarily target these key journals.

4. Discussion

4.1. Analysis of affiliations and countries in scientific production

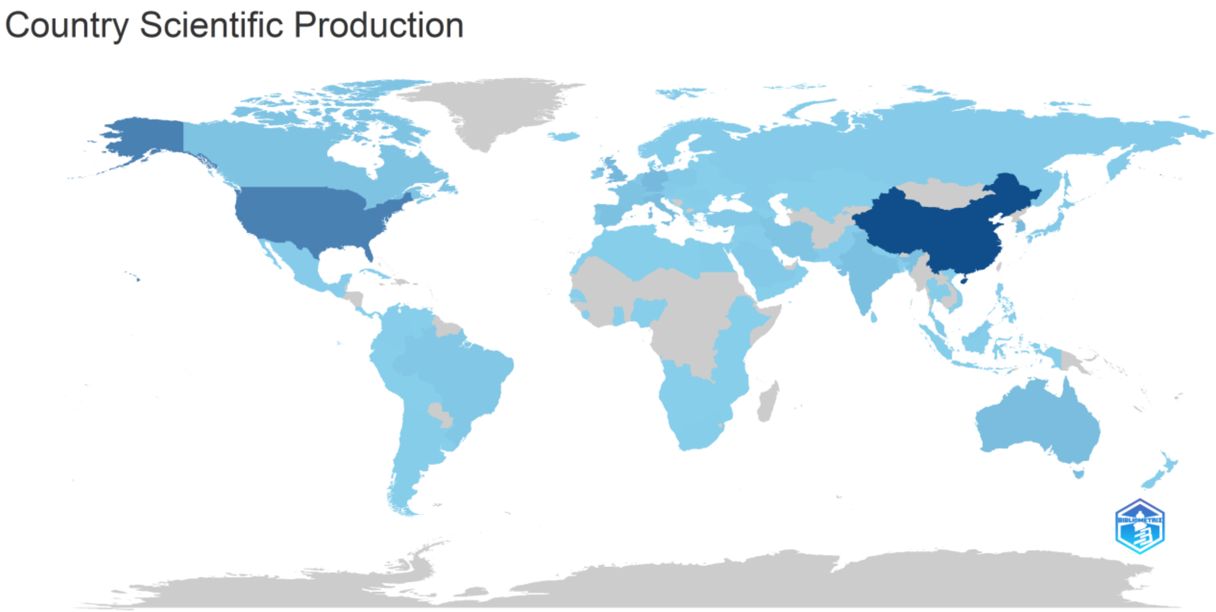
Figure 4.1.1. Most relevant affiliations by volume of scientific production



Source: Own contribution

As can also be observed in figure 4.1.1, scientific production is strongly concentrated at the level of the top few institutions. I examined the chart of the most relevant affiliations and found that the most prolific institution was the Chinese Academy of Sciences, with 1,233 published articles. This number is almost double that of the next-ranked institution, Zhejiang University, which contributed 700 articles. The following positions are occupied by the University of California system with 679 articles and the French National Centre for Scientific Research (CNRS) with 574 articles. The top 10 also includes other notable organizations, such as Nanyang Technological University with 485 articles and the National University of Singapore with 389 articles, alongside prestigious Chinese universities such as Shanghai Jiao Tong, Sichuan, Jiangnan, and the ETH Domain consortium in Switzerland with 434 articles. I thus observed a pronounced concentration of scientific production within these few leading institutions. Many of them are large-scale organizations or extensive academic networks, such as the Chinese Academy of Sciences with its numerous research institutes, the University of California system with multiple campuses, or CNRS as a national network of laboratories. This hierarchy suggests that research resources and capacity are concentrated in the hands of a few major centers. The implication is a possible polarization of scientific production: top institutions, benefiting from superior funding and infrastructure, attract talent and collaborations and consolidate their leadership positions, while smaller or peripheral institutions remain with relatively modest contributions. This unequal distribution may influence research directions at a global level, as dominant centers can shape the scientific agenda and exert a disproportionate influence on innovation and science policy.

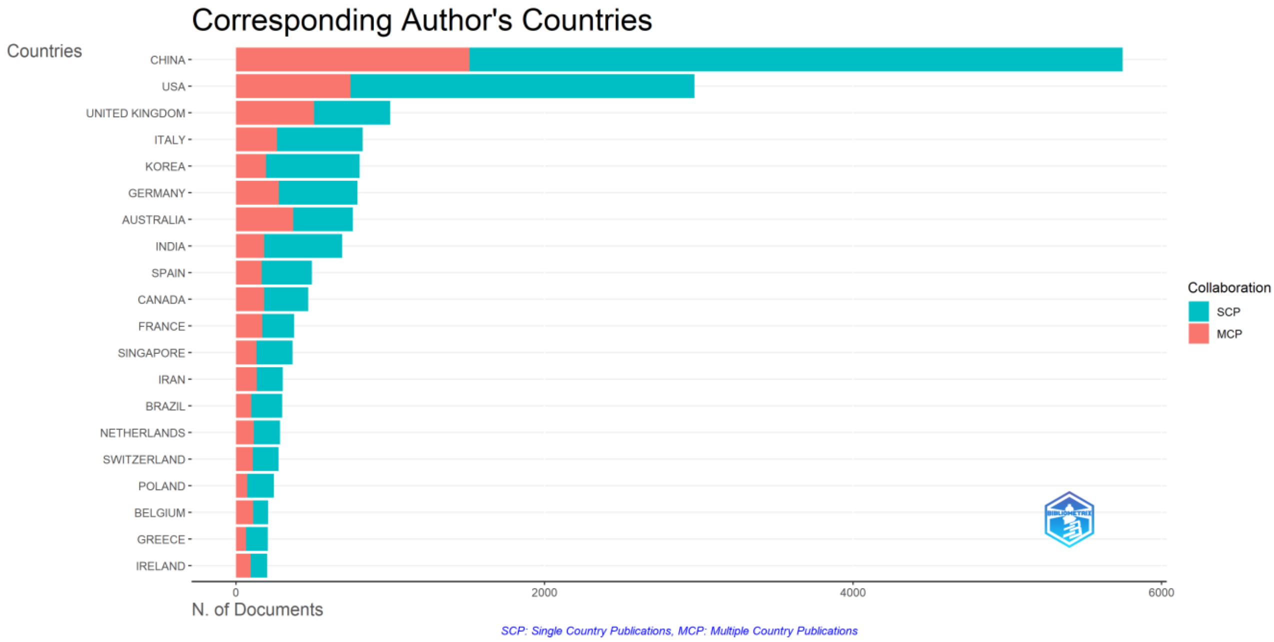
Figure 4.1.2. Global scientific production map based on the number of publications per country



Source: Own contribution

At the geographic level, an uneven distribution of scientific production among countries can be observed (figure 4.1.2). I found that the largest contributions come from China and the United States, which stand out clearly on the global map as the main hubs of scientific publications. According to the data, China generated the highest number of articles, surpassing even the United States; together, the two scientific superpowers represent a majority share of global academic literature production. A second tier of countries, such as the United Kingdom, Germany, South Korea, Italy, or Australia, also contributes significantly, but their publication volumes are far below the level of the top two countries. By contrast, many developing nations have a very limited contribution; entire regions in Africa and other areas appear with minor production on the map, highlighting pronounced geographic imbalances in research capacity and access to scientific resources at the global level. These disparities are clearly visible in the distribution illustrated in figure 4.1.2 and underscore the fact that global scientific production is dominated by a relatively small group of highly developed countries.

Figure 4.1.3. Publications by corresponding author's country: publications produced entirely within the same country (SCP) versus publications produced through international collaborations (MCP)



Source: Own contribution

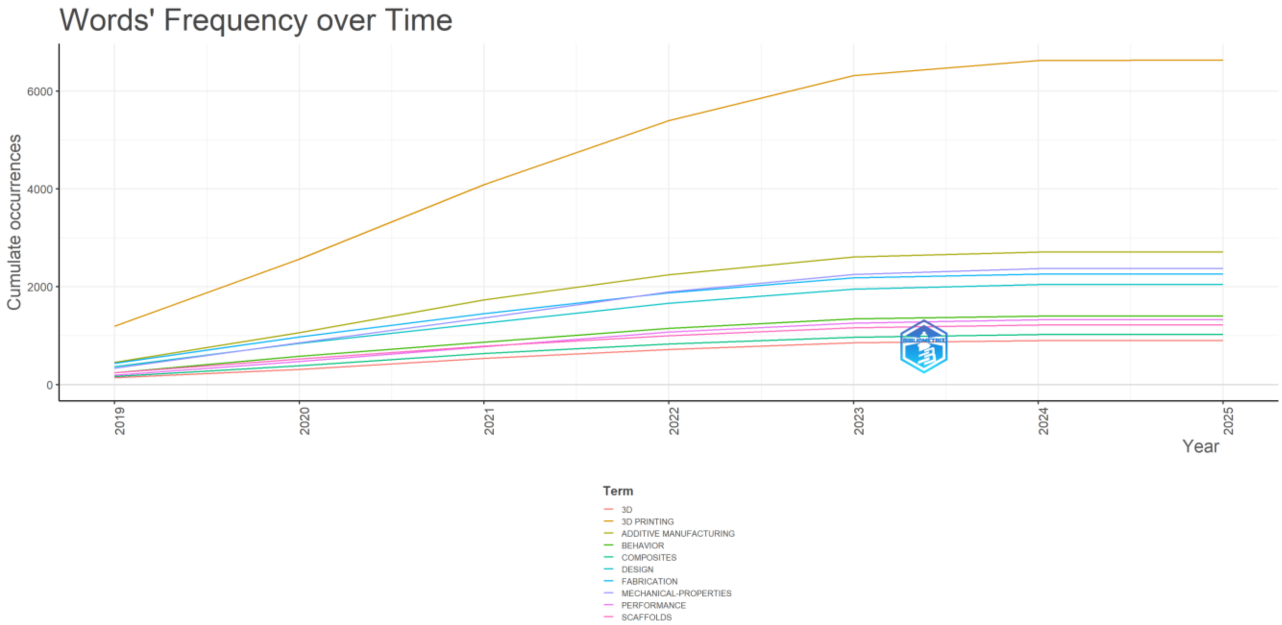
Analyzing the degree of internationalization of research, the diagram in figure 4.1.3 shows significant differences between countries with regard to international collaboration. I observed that major scientific powers, such as China and the United States, tend to publish predominantly within national collaborations. In the case of these countries, most publications are produced exclusively with authors from the same country, with publications involving international partners representing only about one quarter of the total (MCP ~25 - 26%). In contrast, countries with relatively lower scientific output but strong international integration, such as the United Kingdom, Australia, or Canada, show much higher percentages of international collaboration, with around 40–50% of their publications involving co-authors from other countries. This indicates that second-tier countries rely more heavily on international partnerships to amplify their scientific presence and impact. As shown in figure 4.1.2 and figure 4.1.3, although global academic production is quantitatively dominated by a few leading nations, international collaboration plays an essential role in the scientific landscape. In particular for smaller countries, cross-border cooperation contributes to partially balancing disparities and to the circulation of knowledge, mitigating to some extent global research gaps.

4.2. Recent bibliometric trends in industrial engineering: 3D printing and other key topics

The literature of recent years highlights an explosive growth of interest in 3D printing and additive manufacturing. These terms appear with very high frequency in post-2018 industrial engineering publications, ranking among the most common bibliometrically identified keywords. For example, bibliometric analysis indicates an annual publication growth rate of approximately 20% in the field of 3D printing, with a peak in the number of works during the years 2020–2022 [9]. This trend reflects the fact that 3D printing has become a central technology in the era of Industry 4.0, being considered a disruptive innovation that transforms the traditional manufacturing paradigm [10]. The specialized literature states that, recently, the emergence of new printable materials has led to an exponential increase in the applications of 3D technology [11]. Indeed, three-dimensional printing technology has experienced unprecedented development, revolutionizing the manufacturing industry through flexibility, customization, and the ability to create complex geometries. The terms "3D printing" and "additive manufacturing" are often used interchangeably (both describing layered manufacturing processes) and dominate keyword co-occurrence in recent literature. In parallel, industrial adoption confirms this academic popularity: for instance, industrial reports show significant growth in the additive manufacturing market, with global revenues of ~13.8 billion USD in 2020, compared to ~6 billion in 2016 and estimated annual growth of ~21% until 2028 [12], indicating increasing practical interest in these technologies.

The growth in the number of works on 3D printing has been accompanied by a strong emphasis on material characterization and the performance of manufactured parts. Terms such as "mechanical properties," "performance," and "behavior" appear frequently in titles and abstracts, highlighting researchers' concern with ensuring that parts obtained through additive methods meet strength and functionality requirements, as can be observed in figure 4.2.1. The literature shows that the additive manufacturing process involves numerous technical parameters that must be optimized in order to obtain parts with optimal mechanical properties, with over 50 process parameters influencing the outcome in terms of mechanical quality. Consequently, many studies investigate the behavior of 3D-printed parts under different loads and ways to improve their performance (for example, fatigue resistance, thermal behavior, or vibrational behavior). A notable advantage of additive manufacturing is the possibility of reducing component weight through optimized design, while maintaining performance or even improving it.

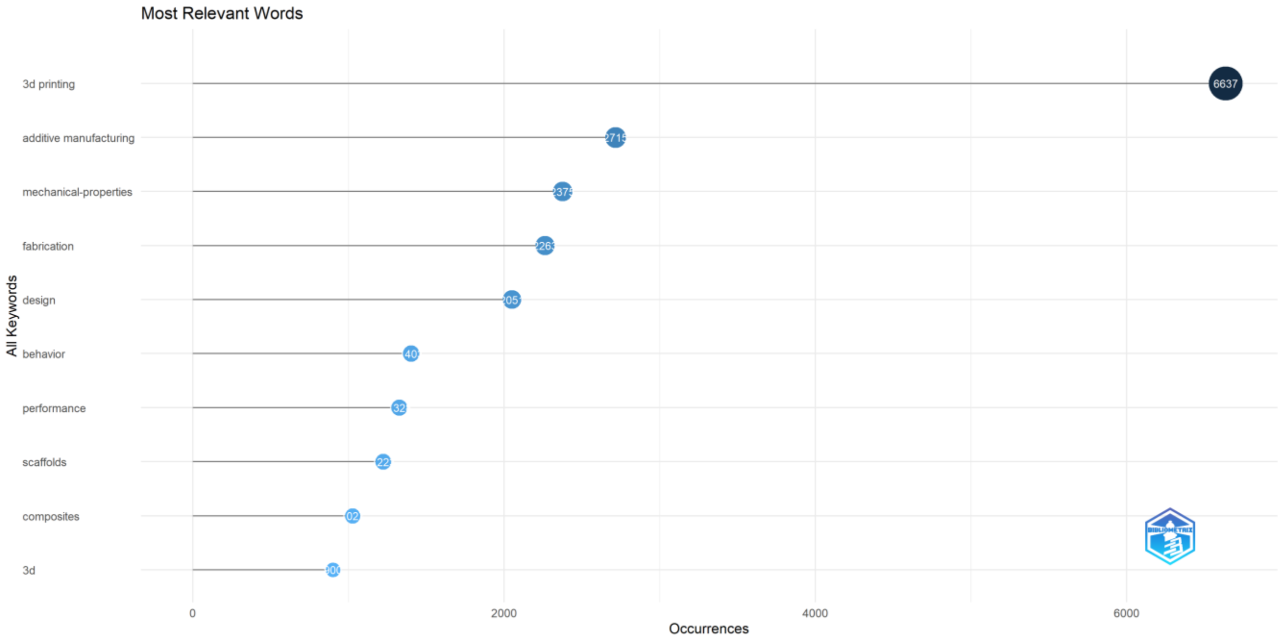
Figure 4.2.1. Evolution of the use of specific terms in publications during the period 2019–2025



Source: Own contribution

Such improvements have a direct impact on industrial applications: for example, lighter parts can increase energy efficiency and the performance of mechanical assemblies. A distinct theme in recent literature is represented by composite materials and advanced structures produced through 3D printing. The integration of reinforcing fibers or nanoparticles into printed polymer matrices allows the production of composites with improved mechanical properties and innovative functionalities (e.g., electrical conductivity or self-healing) [13]. Additive manufacturing has proven to be a transformative method for producing composite parts, offering unprecedented freedom in material selection and geometric complexity of components. Over the past decade, the field of 3D-printed composites has advanced rapidly, expanding the range of printable materials and introducing new processes, which enables the customization of material properties beyond the limits of conventional methods. As the technology matures, design objectives for printed composites are evolving; the focus is no longer solely on maximizing stiffness or strength, but also on achieving multifunctional properties (thermal, electrical, shape-related, etc.), highlighting the maturation of the field. Within the broader scope of industrial engineering, the term “scaffolds” (support structures, templates) has appeared frequently, indicating the application of 3D printing in fields such as biomedical engineering and porous materials, as observable in figure 4.2.2. 3D printing is used to create complex scaffold-type structures, for example customized supports for tissues or medical implants, which were previously difficult to obtain. The presence of the word “scaffolds” in recent literature underscores the importance of these biomedical applications within industrial engineering, highlighting the convergence between additive manufacturing and the medical field.

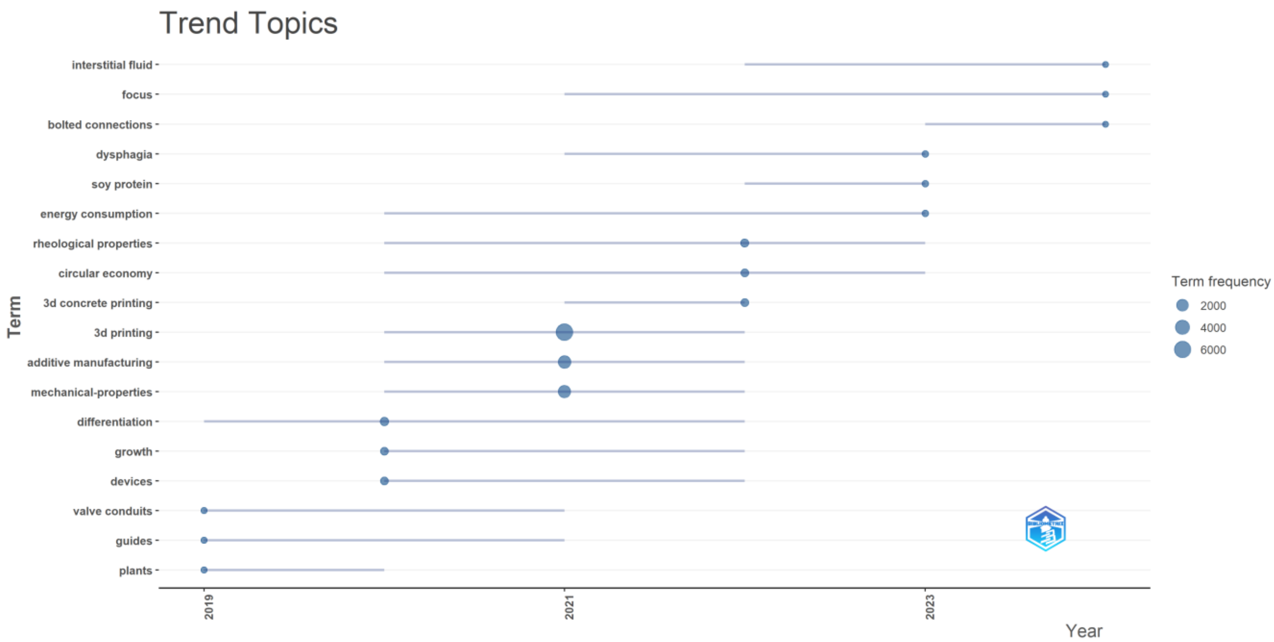
Figure 4.2.2. Chart showing the occurrence of the most relevant keywords from the analyzed publications during the period 2019–2025



Source: Own contribution

The analysis of thematic trends reveals that the vocabulary in industrial engineering has expanded after 2018 to include concepts increasingly oriented toward sustainability and efficiency. A notable example is the expression “circular economy,” which appears with increasing frequency in the literature on 3D printing after 2020. This indicates the scientific community’s concern with integrating circular economy principles into additive manufacturing processes, from design oriented toward recycling to waste reduction and material reuse. Indeed, recent research highlights that additive manufacturing technologies can facilitate the transition to sustainable and circular business models by enabling digital design optimization to minimize waste and extend product life cycles. A systematic study from 2021 dedicated to additive manufacturing in the context of the circular economy notes that this intersectional field is relatively new and rapidly developing, with most scientific contributions dating from the period 2015–2020 [10], confirming the emerging nature of the topic. Another term that has recently gained traction is “rheological properties.” This appears especially in works on the 3D printing of materials with fluid-like behavior (such as concrete, ceramics, or bio-inks), where material rheology is crucial for printability. Studies show that rheological properties, such as static/dynamic yield stress, plastic viscosity, and thixotropy, dictate material flow and behavior during the 3D printing process [14]. Particular attention is given to 3D-printed concrete, a field that has expanded rapidly in recent years, where rheological parameters must be strictly controlled to ensure the stability of the deposited layer and the desired final shape. The growing interest in rheological properties reflects the need to scientifically understand new printable materials and to overcome technical challenges as these processes are scaled up. Additionally, the concept of "energy consumption" has entered the lexicon of recent research related to additive manufacturing. These emergent themes can be easily observed in figure 4.2.3.

Figure 4.2.3. Frequency of the occurrence of thematic trends in the analyzed documents from the period 2019–2024



Source: Own contribution

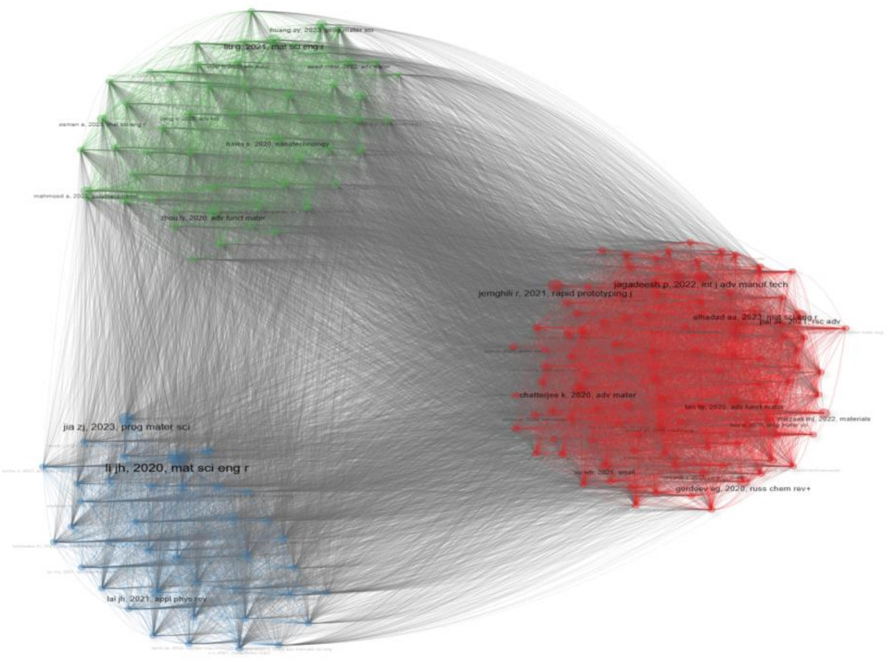
Against the backdrop of sustainability concerns, an increasing number of studies evaluate the energy impact of 3D printing compared to traditional manufacturing methods. Some results suggest that 3D printing can reduce the energy consumption required to produce certain objects, as it uses only the necessary material and eliminates energy-intensive stages specific to conventional manufacturing [15]. In addition, energy and time are saved through the simplification of the logistics chain, as production localized close to the end user reduces the need for global transportation, contributing to efficiency [11]. However, the literature also highlights nuances: in large-scale production, if additive processes are not optimized, they may increase energy and material consumption, having a negative impact compared to classical methods [16]. This balance has generated interest in optimizing AM processes from an energy perspective, emphasizing that efficiency must go hand in hand with innovation. Not least, the recent vocabulary includes terms such as “3D concrete printing,” “3D bioprinting,” and others, indicating increasingly specialized branches of 3D printing. For example, 3D concrete printing rapidly evolved from the conceptual stage into a standalone subfield after 2018–2019, reflecting efforts to apply additive manufacturing in construction and infrastructure. Such compound terms illustrate the maturation and diversification of the field: 3D printing is no longer viewed monolithically, but rather as a family of technologies adapted to different materials and industries.

The surge in research along these directions has been accompanied by the emergence of influential review papers and bibliometric studies aimed at mapping the field and guiding the community. For example, Ponis et al. (2021) conducted a systematic review of the literature on Additive Manufacturing in the context of the circular economy, highlighting the development stage of this emerging field and existing gaps [10]. In turn, a bibliometric assessment published in 2025 on 3D printing applied in surgery confirmed the accelerated growth of publications and identified key terms such as “additive manufacturing” among the thematic core of the field [9]. Moreover, the literature abounds in review articles that synthesize technical progress: a comprehensive review from 2023 highlights recent trends in 3D printing materials and technologies, emphasizing the need to overcome current limitations (costs, printing speeds, dimensions) in order to fully exploit the potential of these technologies [11]. Such sources provide an overview of research directions and confirm the importance of the analyzed terms. From an industrial perspective, it is worth mentioning case studies that have catalyzed interest in 3D printing within industrial engineering. An emblematic example is the case of General Electric (GE), which adopted additive manufacturing to produce fuel nozzles for LEAP aircraft engines. This application demonstrated the concrete advantages of the technology: an assembly traditionally composed of approximately 20 parts was redesigned as a single 3D-printed part, eliminating assembly operations and reducing the nozzle’s weight by about 25% [17]. The printed part proved to be more durable than the conventional version, allowing for improved engine efficiency and increased reliability. The success of this project, with over 30,000 3D nozzles manufactured in serial production by 2018, was widely publicized and served as an industrial benchmark for the potential of 3D printing in large-scale manufacturing. Such practical achievements, reported both in technical literature and in the specialized press, also fueled the volume of academic publications, creating a positive feedback loop between research and industry. Between 2018 and 2025, industrial engineering literature has been marked by strong dynamics in topics related to 3D printing and additive manufacturing. The high frequency of the analyzed terms, from “3D printing” and “additive manufacturing” to “mechanical properties,” “design,” “composites,” or “circular economy,” indicates a scientific community orientation toward innovation in manufacturing processes, material optimization, and the integration of sustainability objectives. Each of these terms is supported in recent literature by concrete studies and evidence: from quantifiable bibliometric growth, to large-scale academic reviews, and up to technological achievements in industry. This corpus of sources underscores the convergence of academic and industrial efforts to leverage the potential of additive manufacturing, making it an important pillar of contemporary industrial engineering.

4.3. Clustering in citation and coupling Map Networks

The following presents a detailed analysis of document clusters obtained from bibliometric networks, in the context of industrial engineering and additive manufacturing. The analysis combines two complementary perspectives: the article citation network map (Network Map), highlighting groupings of works based on direct citations, and the bibliographic coupling map (Coupling Map), which positions thematic clusters along the axes of centrality and impact. These bibliometric clustering methods reveal the intellectual structure of the field by grouping thematically similar documents either on the basis of shared references (bibliographic coupling) or shared citations (co-citation) [18]. By interpreting these maps, we can identify major research subdomains, such as multi-material additive manufacturing and the mechanical properties of printed materials, as well as the level of development and relevance of each cluster within the current scientific landscape.

Figure 4.3.1. Citation network between articles



Source: Own contribution

The citation network in figure 4.3.1 groups the articles into three major clusters, highlighted by different colors (red, green, and blue). The nodes represent scientific works, and the gray links between them indicate direct references. The high density of links within each cluster shows the thematic cohesion of the group, with articles within the same cluster frequently citing one another, indicating that they address a common core of topics.

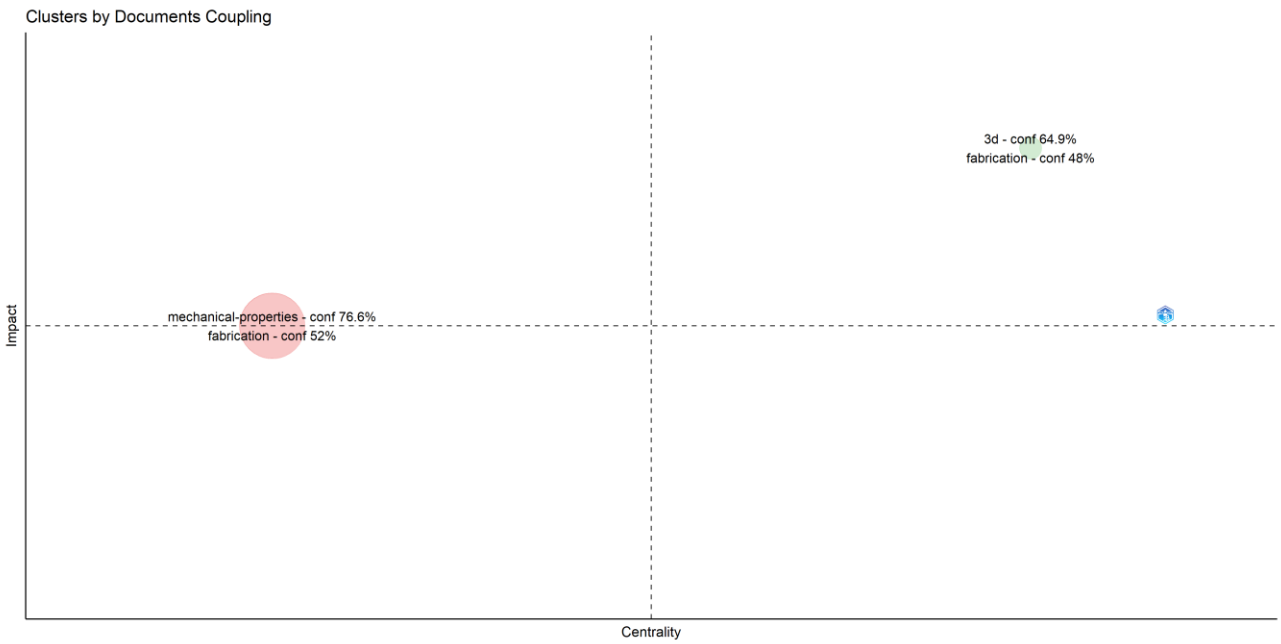
- The red cluster is the largest and densest cluster in the network, indicating a broad and intensively researched subdomain. The theme of this group revolves around the mechanical properties of additively manufactured materials and the optimization of 3D printing processes to improve these properties. Many works in the cluster focus on studies of the structural behavior of printed parts and on post-processing methods aimed at achieving superior performance. For example, a seminal work is the review by Mostafaei et al. (2021) in Progress in Materials Science, which provides a detailed synthesis of the binder jetting printing process and the influence of process parameters on the microstructure and properties of the resulting materials [19]. This review addresses aspects such as powder processing, sintering, and the heat treatments required to achieve optimal mechanical properties in manufactured parts. Other reference works in the red cluster include studies on polymer and composite printing (Rahim et al., 2019), with an extensive review of polymeric materials for 3D printing [20], as well as articles on advanced metal alloys (Penumakala et al., 2020), which present the properties of FDM-printed composites [21]. The presence of these works indicates that a major focus of the cluster is the improvement of mechanical characteristics (strength, toughness, durability) of products made through additive technologies. Central authors in this group come from both materials science and mechanical engineering. The frequent connections among articles within the cluster reflect a well-defined research community concerned with validating the properties of printed materials and standardizing testing methodologies. This is consistent with observations in the specialized literature, which emphasize the need for standard testing protocols to ensure consistency of mechanical properties across different additive manufacturing technologies.
- The green cluster represents the second largest group identified in the network and is centered on themes of emerging additive technologies and advanced functional materials. This cluster, somewhat more compact in size, groups frontier works from the last decade that explore the expansion of 3D printing capabilities toward new materials, smart structures, and innovative applications. A notable example is the article by Kuang et al. (2019) in Advanced Functional Materials, which reviews progress in “4D printing” through the printing of structures capable of changing their shape or function over time under the action of external stimuli

(temperature, light, water, etc.). The authors highlight the enormous academic and industrial interest in these smart materials and anticipate a major impact of 4D printing technology on the future of industrial production [22]. Another central node in the green cluster is the review by Saadi et al. (2022) in Advanced Materials on the Direct Ink Writing (DIW) technique, representing a versatile method for the direct printing of functional inks, enabling the fabrication of complex structures from a wide range of materials such as polymers, ceramics, gels, etc. [23]. The green cluster also includes numerous works on metamaterials and additively manufactured multi-material structures; for instance, Surjadi et al. (2019) discuss mechanical metamaterials produced through 3D printing [24]. The presence in this cluster of articles from top-tier journals (Advanced Materials, Advanced Functional Materials, Chemical Society Reviews) suggests that the addressed themes, such as metamaterials, shape-memory materials, bioprinting, and multi-material printing, constitute highly dynamic and high-impact research directions. Influential authors in the green cluster form an interdisciplinary core spanning mechanical engineering, materials science, and robotics, extending the boundaries of additive manufacturing. The density of links within this cluster is high, but the network has a more "chain-like" architecture compared to the red cluster, since many works cite a few common references and are strongly connected to them. Overall, the green cluster reflects the technological frontier of the field, focused on innovations such as printed devices that change behavior during use and advanced materials with functional applications, including smart biomedical devices, integrated sensors, adaptive structures, and others.

- The blue cluster is a visually smaller and less dense grouping, located at the periphery of the citation network. Although it contains relatively few articles, the blue cluster appears to represent a specialized or emerging thematic niche within the context of the analyzed dataset. The works in this group either address a very specific subject or are recent synthesis papers that have not yet become strongly connected to the rest of the network. For example, a notable node corresponds to a comprehensive review published in Progress in Materials Science (2022–2023), focused on biomimetic materials and tissue engineering through additive techniques (Germaini et al., 2022) on the additive manufacturing of biomaterials for bone engineering [25]. This type of review article, covering an interdisciplinary domain of regenerative medicine and additive manufacturing, is often cited by different communities and may appear relatively isolated within the citation network of traditional industrial engineering. Therefore, the blue cluster may indicate an emerging subdomain at the intersection of industrial engineering with other disciplines, such as biomedical applications of 3D printing or the use of machine learning algorithms in the optimization of additive manufacturing processes. The low density of links within this cluster suggests that its articles do not cite each other intensively, likely due to the diversity of subtopics or the still nascent nature of this research segment. Nevertheless, its presence on the map signals new directions that the scientific community is beginning to explore, in line with recent trends of expanding additive technologies toward new sectors such as medical applications, sustainability, and artificial intelligence.

Figure 4.3.1 reveals that the literature in industrial engineering related to additive manufacturing has coalesced into a few main focal areas: one oriented toward material performance and processes (the red cluster), another toward cutting-edge material and technological innovations (the green cluster), alongside emerging niches (the blue cluster). This organization results directly from the bibliometric clustering of documents, a method that groups publications according to their citation links, reflecting the conceptual structure of the field. Practically, documents that share bibliographic references and cite each other tend to belong to the same research theme, a fact confirmed by the thematic coherence observed in the clusters above.

Figure 4.3.2. Thematic clusters based on impact and centrality



Source: Own contribution

Figure 4.3.2 presents the so-called thematic map of clusters, which maps the importance and degree of development of each cluster within the field. In this strategic diagram, each bubble represents a cluster of documents (similar to those discussed previously), with its position determined by two metrics: centrality (horizontal axis) and density/impact (vertical axis). According to standard methodology, centrality indicates the degree of interconnection of a cluster with other clusters; in other words, how "central" or transversal the topic is within the context of the entire literature [26]. A cluster with high centrality has strong links to multiple other themes, being essential to the structure of the field. Thematic impact, often assessed through the internal density of the cluster, aggregated citations, or normalized citation score, reflects the internal strength of development of the respective theme; in short, the extent to which the topic is well developed in itself, with an active and coherent research community. Based on these two criteria, the diagram is divided into four conceptual quadrants:

- Upper-right quadrant: "motor themes", themes that are well developed internally and very important for the field, with high centrality and high density. These topics constitute the core and driving force of research in the field, being both mature and strongly connected to other key themes.
- Lower-right quadrant: "basic themes", fundamental themes that are highly relevant but less developed internally, with high centrality and low density. These are general subjects, broadly connected within the field, but which may not yet have a very rich or in-depth internal literature.
- Lower-left quadrant: "emerging or declining themes", weakly developed and weakly connected themes, with low centrality and low density. These may represent either emerging directions that are still forming, or themes that have reached their peak and are in decline, not being strongly integrated into the main discourse.
- Upper-left quadrant: "niche themes", themes that are well developed internally but isolated, with low centrality and high density. Here we find highly specialized subdomains: research communities that are active internally, but which do not yet have major relevance for the rest of the field.

Interpreting figure 4.3.2 through this framework, we observe that the two main clusters identified (corresponding to the red and green clusters from the citation network) occupy different quadrants, suggesting distinct roles in the landscape of the analyzed bibliometric research. The cluster focused on "mechanical-properties/fabrication" (represented in red on the map) is positioned toward the lower-left area of the diagram. This indicates a theme with moderate to low centrality and relatively reduced impact compared to the other themes in the analysis. In other words, although the red cluster has the largest number of associated publications (105 documents) and constitutes an important pillar of the literature on additive manufacturing, its connections with other clusters are less pronounced, and its internal thematic development is below the average of the other themes. This result may seem counterintuitive, but it can be explained by the nature of the subject: the mechanical properties of printed parts represent a highly applied and fragmented domain. Many studies in this cluster examine a specific material or process, such as the strength of a particular FDM-printed polymer composite or the heat treatment of an SLM metal alloy, generating specialized knowledge that is not always integrated transversally with other directions, such as smart materials or new processes. Thus, the red cluster appears as a possible example of an "emerging or specialized theme," with a multitude of experiments and accumulated data, but with reduced conceptual connectivity compared to other themes. In the scientometric literature, such a cluster could be interpreted as either an emerging topic or a niche topic, marginal to major strategic directions. Given the practical importance of mechanical properties in industrial engineering, I am inclined toward the conclusion that this cluster reflects a basic theme under development, essential for applications, which explains the large number of works, but still requiring conceptual consolidation and standardization. This interpretation is also supported by recent discussions in the literature, which show that a major trend in additive manufacturing is the need to standardize mechanical testing methods and to develop unified certification frameworks, so that disparate results can be compared and used industrially [27]. The red cluster seems to correspond precisely to these efforts of numerous separate studies, which tackle the problem of mechanical performance from different angles, on the path toward a common framework. In contrast, the "3D/fabrication" cluster (represented in green in figure 4.3.2) is positioned in the upper-right quadrant of the diagram. This position corresponds to the category of "motor themes," that is, a theme that is very central and very well developed within the field. The green cluster has high centrality (0.552, above the axis average) and the highest thematic impact (density ~3.7, significantly above average) among the identified clusters. Practically, the subjects grouped here are related to advanced 3D printing, multifunctional materials, and innovative processes, and are both well represented by highly visible works and tightly interconnected with the rest of the research directions. This cluster functions as a driver of scientific progress in additive manufacturing, generating new concepts and technologies that influence the entire field. The fact that it includes many works published in top journals and synthesis reviews suggests the maturity and internal cohesion of the theme. The interdisciplinary character of the subjects, ranging from smart materials to robotics and computational design, makes this cluster connected to multiple other subdomains; for example, advances in 4D printing also influence research in classical mechanical engineering, biomedical fields, and materials science. I can therefore state that the green cluster represents an essential and positively emerging theme: a pivotal domain around which recent innovations are articulated. The literature confirms the importance of these directions: new technologies such as 4D and multi-material printing are frequently mentioned as frontiers that will transform manufacturing practices in the near future. For example, predictions show that the integration of active materials and smart structures created through 3D printing has the potential to revolutionize product design in various industries, such as aerospace, medical, and electronics. The fact that the green cluster is mapped as a "motor theme" confirms that these innovations have moved beyond the stage of academic curiosity, becoming key themes that drive progress in modern industrial engineering. It is noteworthy that, although the green cluster has fewer documents than the red cluster, its centrality and impact scores are superior. This indicates that it is not quantity, but the quality and connectivity of works that give weight to a theme. In the case of the green cluster, the presence of highly cited and interconnected works elevates the profile of the theme, highlighting its character as a "hot topic." On the other hand, the red cluster, although voluminous, has a more focused and local influence, indicating that many works have limited impact outside their sub-niche. This difference is a typical outcome of coupling analyses: revolutionary and interdisciplinary themes tend to appear in the motor quadrant due to broad citations and integration, whereas highly specialized themes appear as emerging or niche until they expand their sphere of influence.

In conclusion, figure 4.3.2 provides a strategic perspective on the identified clusters. The cluster related to advanced printing materials and technologies (3D/4D, multi-material) stands out as a central and well-developed direction, a driving force of research in contemporary additive manufacturing. By contrast, the cluster focused on mechanical properties and process optimization appears as a basic theme undergoing consolidation, important for applications but still relatively conceptually independent. This mapping reflects how the scientific community prioritizes and structures its efforts: cutting-edge innovations gain visibility and become pivotal, while applied studies accumulate necessary knowledge and gradually converge toward common standards and principles. The bibliometric methodology of bibliographic coupling thus made it possible to highlight the thematic impact of each cluster, showing not only which topics exist, but also how influential and mature they are within the overall field. The obtained results are consistent with other recent bibliometric studies in industrial engineering and additive manufacturing, which have identified similar trends: an increasing emphasis on new materials and design, including the integration of artificial intelligence, alongside a deepening of knowledge about the performance and reliability of printed parts. By correlating the observations from these maps with the current literature, I can conclude that cluster analysis provides a structural understanding of the field, highlighting both established pillars and the emerging seeds of new research directions that will define the future of industrial engineering.

5. Conclusions

Bibliometric analysis and recent studies show a growing interest in evaluating the sustainability of 3D printing, particularly FDM technology. This is often perceived as a "green" method due to efficient material usage and the possibility of distributed manufacturing, which reduces transportation requirements. However, the energy consumption of the process remains a critical factor: layer-by-layer printing requires considerable time and energy, which can make FDM environmentally disadvantageous compared to traditional methods, especially in large-scale production. In the absence of renewable energy sources, the high impact of electricity consumption diminishes the benefits of other aspects; therefore, the transition to electricity from renewable sources is essential to increase the sustainability of these processes.

In industrial engineering, 3D printing has demonstrated its usefulness through a range of relevant applications, from the manufacturing of customized tools and fixtures, to the production of functional components in small series, the creation of prototype molds for casting or injection, and rapid prototyping in product development. Life cycle analyses suggest that in such uses, 3D printing can provide indirect environmental benefits: for example, reducing the stage of manufacturing machinery or dedicated molds for prototyping shortens the production chain and avoids material and energy waste associated with traditional tooling. The technology's ability to rapidly transform digital design into a physical prototype accelerates the development cycle and reduces the need for costly iterations, while also offering high design flexibility and reducing potential losses from scrap. These advantages can offset the energy impact of printing in small-series applications or "just-in-time" production. On the other hand, it has been confirmed that for large production volumes, conventional methods remain more efficient per product in terms of resources and emissions, making 3D printing best suited for cases where customization, high complexity, or low quantities justify its adoption.

The general conclusions underline the importance of integrating life cycle assessment into decisions regarding printing technologies and materials. The sustainability of 3D printing is contextual: it depends on the application context, energy sources, materials, and the way the product and its waste are managed at end of life. By applying the LCA methodology, both benefits and trade-offs have been highlighted: for example, additive manufacturing can be more sustainable than conventional manufacturing if it reduces transportation through local production and avoids overproduction, but it can be more burdensome if printers consume electricity from fossil sources or if printed parts become unrecycled waste. The circular economy approach, in which materials are continuously reused and recycled, emerges as a key solution: although in current practice a significant share of materials becomes waste, there are initiatives to recycle this waste into new filament, demonstrating a substantial reduction in environmental footprint by closing the material loop. The literature up to 2024 increasingly indicates that the future of 3D printing must include strategies for eco-design, reuse, and recycling in order for the benefits of the technology to be fully realized without shifting the burden onto the environment.

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