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(Review Article)

Life cycle assessment of additive manufacturing process: A systematic literature

Sairul Alam * and Riri Ramadhani Putri

Department of Management and Industrial Engineering, Faculty of Engineering, Diponegoro University, Semarang, Indonesia.

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Abstract

Additive Manufacturing (AM) or 3D printing is a breakthrough in the industrial world, providing freedom to create designs that have never existed before and achieve high material efficiency. Nevertheless, it turns out that additive manufacturing still faces significant challenges, particularly in terms of energy consumption and emissions during production. This study conducted a systematic literature review to assess the environmental impact of AM technology using the Life Cycle Assessment (LCA) method. This study analyzes 80 articles from the Scopus database using VOSviewer software to identify research trends over the past ten years, knowledge gaps, and the challenges faced in implementing sustainable AM. The study results indicate that although the AM method has proven more efficient in material utilization than conventional methods, environmental challenges such as material waste and greenhouse gas emissions produced require further investigation. This study emphasizes the importance of ISO 14044:2006 standards in LCA to evaluate environmental impacts more comprehensively and to support more sustainable decision-making in implementing this technology. This study provides important insights for future studies to focus on reducing the negative environmental effects of the AM process to enhance sustainability in manufacturing processes.

Keywords: Additive Manufacturing; 3D-Printing; Systematic Literature Review; VOSViewer

1 Introduction

The technology known as additive manufacturing (AM), or 3D printing, has enormous potential in a number of different industries [1], such as aerospace, automotive, and biomedical [2]. In simple terms, the AM process is carried out by directly creating parts from its digital model by combining materials [3], the emergence of AM marks an essential milestone in product development [4]. AM has experienced rapid growth in recent years due to its ability to create 3D objects layer by layer [5] and transform models with complex structures into products directly [6]. Additive manufacturing (AM) technology offers high geometric freedom and flexibility in producing components with many highly complex features [7], raw material savings, excellent production efficiency, and customizable manufacturing. AM has increasingly expanded into commercial applications [8]. AM has revolutionized the manufacturing industry by offering unprecedented design freedom previously impossible with traditional manufacturing methods [9].

AM still faces challenges, such as higher error and failure rates [10]. Although additive manufacturing (AM) can reduce material waste, it does not automatically make it a “more environmentally friendly” process. The production of raw materials for AM often requires additional steps, such as powder automation or wire drawing, depending on the type of process and materials used. In addition, the quality of components from AM cannot be overlooked [11]; this can lead to consumer dissatisfaction, loss of company reputation, economic losses, and environmental impacts from wasted resources due to a lack of product quality [12]. Other losses include limitations on size, longer production times, and high costs for machines and materials. The AM process is slower than traditional methods, with a longer total production time despite no waiting time between production stages [13].

* Corresponding author: Sairul Alam.

A variety of resources, including raw materials, energy, and consumables, are utilized in the AM process. This leads to emissions and waste at each stage of the process, and to assess this impact, the Life Cycle Assessment (LCA) method is used. LCA is a quantitative analytical tool that can measure the environmental impact related to the life cycle of a product from start to finish, according to ISO definitions [14]. LCA encompasses various stages such as raw material production, manufacturing, distribution, use, and end-of-life. This method considers a holistic assessment of the entire life cycle steps: raw material extraction, manufacturing, distribution, use, and disposal/recycling/reuse of waste[15]. LCA in AM aims to identify critical stages with the most significant environmental impact, evaluate various strategies to reduce that impact, and support more sustainable decision-making. Using LCA according to the ISO 14044:2006 standard makes it possible to measure and understand the environmental impact of additively manufactured products, which supports better resource management, lower emissions, and enhanced sustainability of the overall manufacturing process.

The LCA method in AM involves several steps, including defining the goals and scope of the study, collecting life cycle inventory data, assessing life cycle impacts, and interpreting the results. Defining the goals and scope includes identifying the product or process to be analyzed and the boundaries of the analysis. All inputs and outputs of the system under analysis, including raw materials, energy, emissions, and trash, are included in the data collection process [16]. Several LCA case studies have been conducted to assess the environmental impact of various AM technologies. For example, research [17] shows that the Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) processes have higher energy consumption compared to conventional manufacturing processes but produce less material waste. Further research by [18] Although AM technologies like SLS and FDM are more energy-intensive, their material efficiency is higher because they only use the necessary materials to build the structure without generating excessive waste.

The still limited research examining the negative impacts of AM requires further studies in this field. AM offers various advantages, such as material efficiency and design flexibility. The environmental impact, primarily related to energy use, greenhouse gas emissions, and the waste produced, has not been extensively studied. Research generally focuses more on technical and economic benefits than a comprehensive evaluation of the environmental impacts produced. With the increasing popularity of AM technology, it is crucial to develop more research related to environmental effects, guided by ISO 14044:2006 standards, to measure and understand the environmental impacts of AM processes comprehensively. This research aims to systematically review the literature to identify knowledge gaps and areas that require further investigation. A systematic literature review allows for a thorough analysis of existing research. It helps to identify unexplored topics, such as the environmental impact and sustainability of the AM process.

2 Methods

The Scopus database is considered the most reliable and well-known bibliographic information source, with comprehensive coverage across various disciplines. Therefore, the researcher chose the Scopus database to conduct bibliometric analysis subsequently. Three hundred thirty-nine journals on additive manufacturing were taken from the Scopus database on July 1, 2024. The keywords (“life cycle assessment”) AND (“additive manufacturing”) OR ("3d printing”) were used to conduct the analysis. This keyword is searched in the article's title, abstract, and keywords. Next, VOS Viewer [19] has been used to create, visualize, build relationships in literature, and analyze bibliometrics. Using a VOS viewer to build networks of co-occurrences of keywords and citation networks [20].

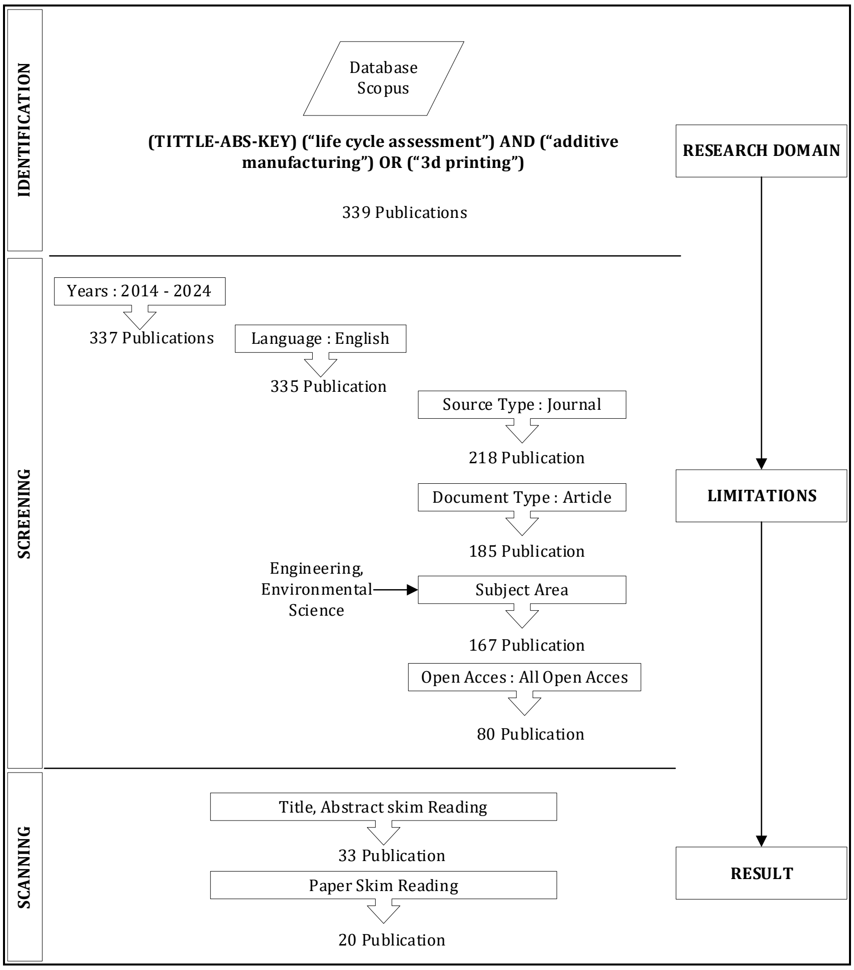

Figure 1 Filtering Process

Bibliometrics plays an essential role in conducting systematic literature reviews by providing tools to analyze and visualize large and complex research data. This is particularly beneficial in helping researchers gain a deeper understanding of the developments in the fields of Life Cycle Assessment and Additive Manufacturing and addressing unmet research gaps. In the context of systematic literature reviews, bibliometrics is crucial in organizing a comprehensive and structured literature framework. Using this software, researchers can categorize studies based on specific themes or topics, evaluate the quantity and distribution of publications over time, and identify the most influential research in their research domain. Bibliometric analysis also helps in measuring the engagement and impact of research, such as the number of citations received by a scientific work, which provides valuable insights in assessing the relevance and contribution of a study to the existing literature. Thus, bibliometric software enhances the quality of systematic literature reviews and broadens our understanding of the direction and evolution of knowledge in the researched field.

3 Results and discussion

In the results and discussion section, this study analyzes the final findings of 80 documents that were examined from Scopus results using VOSviewer software.

3.1 Scopus Analysis

3.1.1 Title Abs Key

The search results yielded a total of 80 articles in format *TITLE-ABS-KEY ((("life cycle assessment") AND ("additive manufacturing") OR ("3d printing"))) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO(SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA, "ENVI")) AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(SRCTYPE, "j")) AND (LIMIT-TO (OA ,"all")).*

3.1.2 Annual Publication

The pattern of publications on Life Cycle Assessment issues and Additive Manufacturing shows a tendency to increase. The highest number of annual publications was in 2023, with a total of 28 articles, followed by 2022 with 14 articles. It can be seen in full in Figure 2.

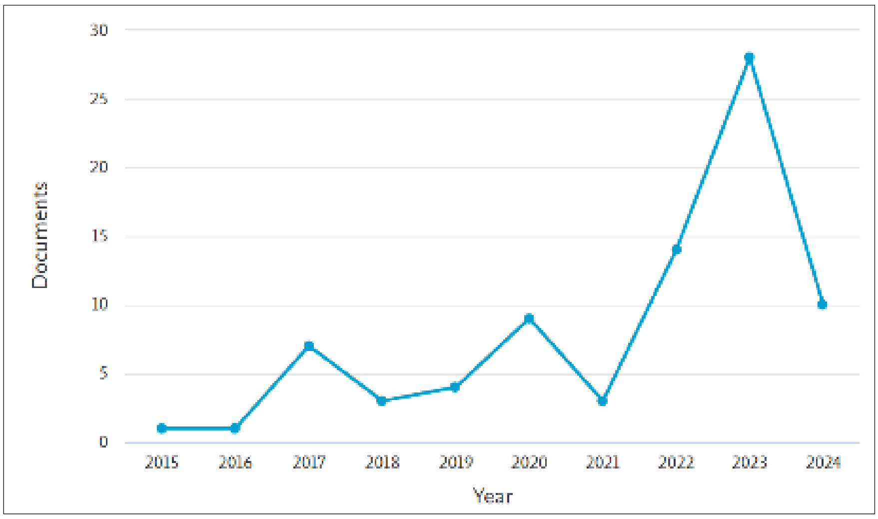

Figure 2 Annual Publication

3.1.3 Publication by Author

The author with the most publications related to Life Cycle Assessment and Additive Manufacturing is Godina, R., with three articles and 58 citations. Other authors have published two articles each from a total of 80 articles analyzed. It can be seen in full in Figure 3.

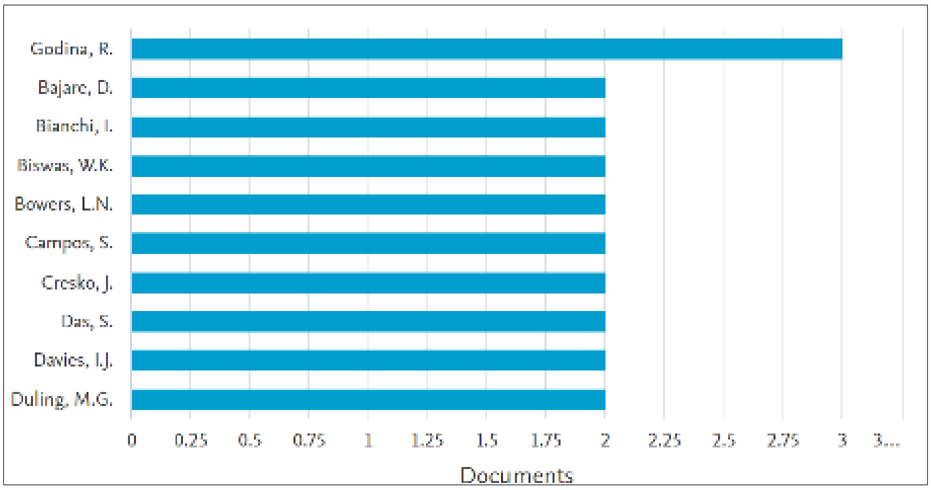

Figure 3 Publication by Author

3.1.4 Publication by Country

The country with the most published articles is the United States with 13 articles, followed by Italy with 12 articles, the United Kingdom with ten articles, Portugal with nine articles, Spain with eight articles, China with seven articles, Australia, Brazil, and France each with four articles, and Canada with three articles. It can be seen in full in Figure 4.

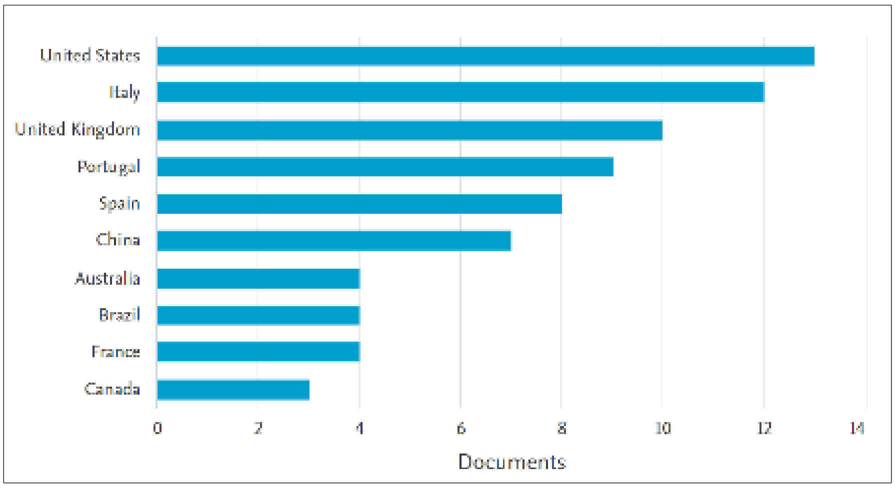

Figure 4 Publication by Country

3.1.5 Publication by Subject Area

The subject area with the most published articles is environmental science, with 56 articles, followed by engineering with 48 articles; energy with 37 articles, and social science with 28 articles. Other subject areas have fewer than 20 published articles. It can be seen in full in Figure 5.

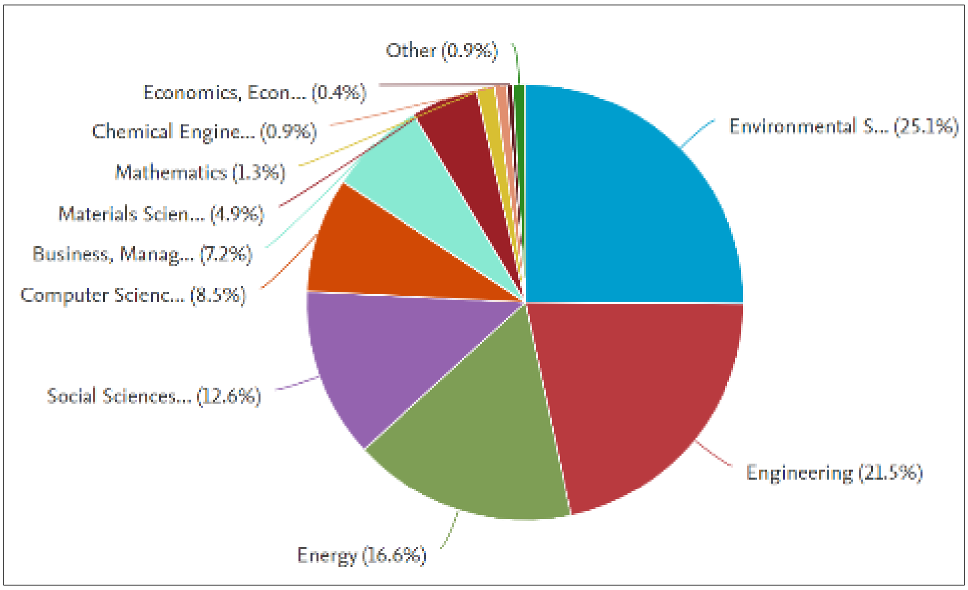

Figure 5 Publication by Subject Area

3.2 Vosviewer Analysis

3.2.1 Co-Authorship Networks

Co-authorship networks aim to analyze the collaboration networks among authors in a research study. At this stage, it is possible to identify productive authors, collaboration relationships, and groups or clusters of authors who collaborate regularly. Figure 6 displays the findings of the co-authorship analysis.

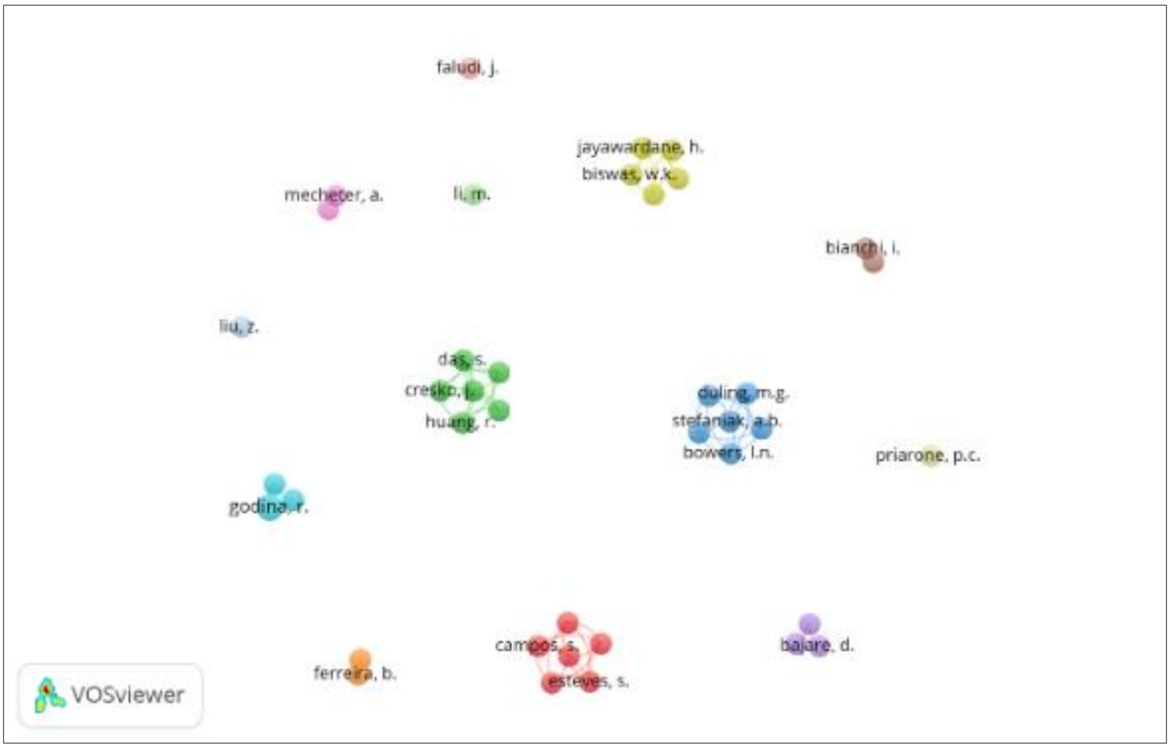

Figure 6 Co-Authorship Networks

From Figure 6, 39 items and 13 clusters were produced. Cluster one, cluster two, and cluster three each have six interconnected researchers. Cluster one includes Campos, S., Esteves, S., Matos, J.R., Oliveira, L., and Pinto, S.M. Cluster two consists of Cresko, J., Das, S., Graziano, D., Huang, R., Masanet, E., and Nimnalkar, S. Cluster three comprises Bowers, L.N., Duling, M.G., Kneep, A.K., Lebouf, R.F., Martin, S.B., and Stefaniak, A.B. Cluster four has five interconnected researchers: Biswas, W.K., Davies, I.J., Gamage, J.R., Jayawardane, H., and John, M. Clusters five and six each have three interconnected researchers, including Bajare, D., Korjakin, A., and Sinka, M. for cluster five, and Godina, R., Kokare, S., and Oliveira, J.P. for cluster six. Clusters seven to nine each have two interconnected researchers, while clusters ten to thirteen have no connections among the researchers.

3.2.2 Keyword Co-Occurrence

Keyword co-occurrence is a bibliometric analysis method used to identify and visualize the relationships between keywords that appear together in a collection of scientific documents. The main function of this analysis is to reveal patterns and trends in a specific research field by examining how keywords relate to one another. By mapping the co-occurrence of keywords, researchers can identify key themes and topics that are often studied together and reveal emerging subfields of research. This is very useful for understanding the conceptual structure of a discipline and for identifying areas that are currently the focus of research. The results of the keyword co-occurrence in this study can be seen in Figure 7.

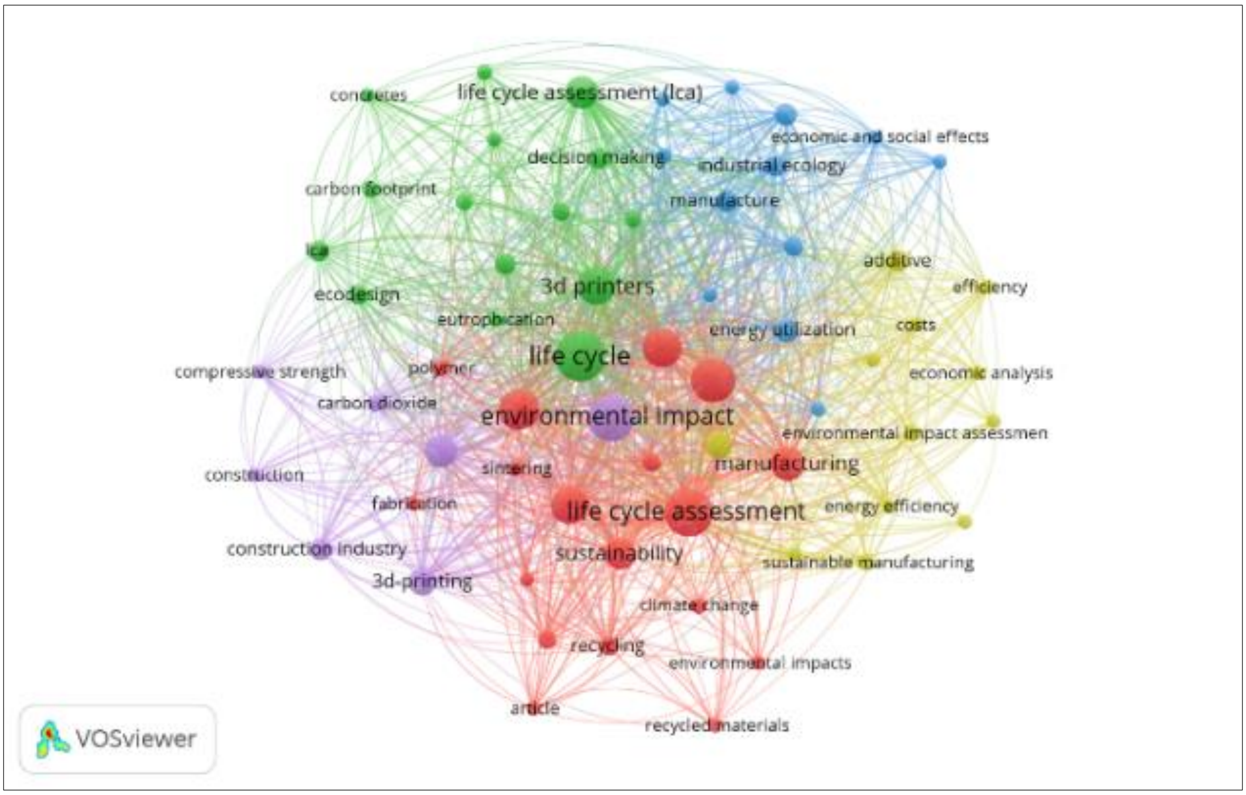

Figure 7 Visualization of the Author's Network

The keyword co-occurrence resulted in five clusters and 64 items. The division of clusters in keyword co-occurrence analysis aims to identify and group keywords that are closely related to each other based on their co-occurrence in scientific publications. Researchers can uncover subfields or specific themes within a discipline by grouping keywords that frequently appear together. Each cluster represents a group of closely related concepts or topics, making it easier to understand the structure and dynamics of research in that field.

3.2.3 Overlay Visualization Keyword Co-Occurrence

Overlay visualization provides a dynamic visual representation of bibliometric data that allows researchers to observe the temporal evolution and distribution of various elements within a network, such as keywords, authors, or institutions. With overlay visualization, users can display additional information on the network map, such as publication year or citation intensity, making it easier to identify research trends, topic developments, and temporal relationships among elements. This feature helps researchers understand how research fields change over time and identify emerging topics or those that have long been a primary focus, enabling more informed and strategic decision-making in research. The results of the overlay visualization in this study can be seen in Figure 8.

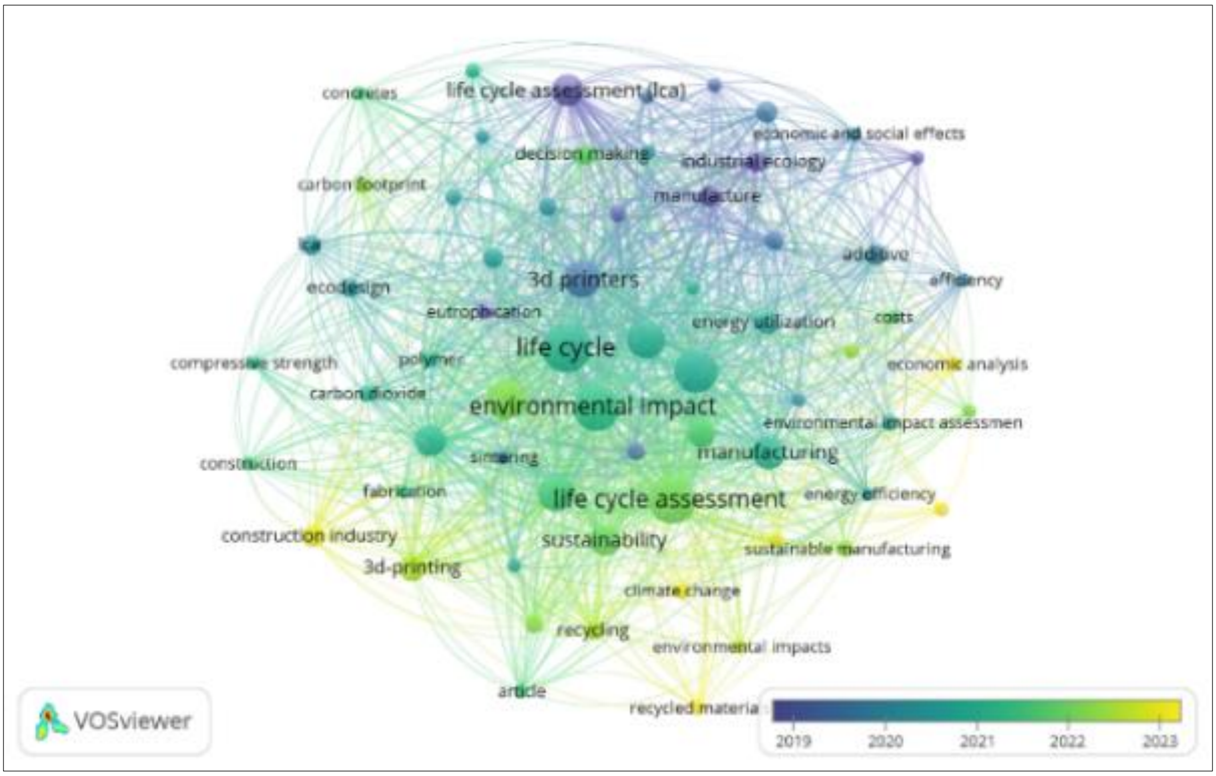

Figure 8 Overlay Visualization

3.2.4 Density Visualization Keyword Co-Occurrence

Density visualization helps visualize the density of elements (such as keywords, authors, or publications) within a bibliometric network. This visualization's primary function is to show dense areas with many interconnected elements, marked by more intense colors, and less dense regions, marked by softer or colourless hues. This helps researchers identify the most active and influential topics or researchers in a particular field and understand the distribution and focus of research within the network. Thus, density visualization provides a clear and intuitive picture of the structure and dynamics of a research field. Density visualization in Figure 9.

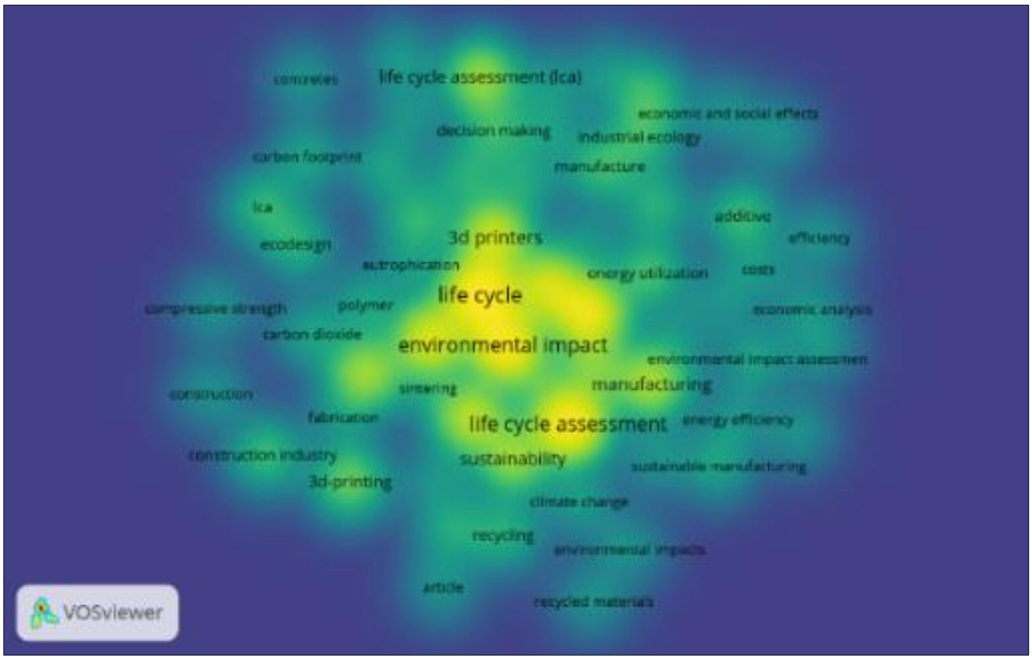

Figure 9 Density Visualization

Figure 9 shows that keywords with a yellow background have a very high element density. In the context of a keyword map or a collaboration network of authors, areas with a yellow background indicate the highest concentration, highlighting the topics that are most researched.

Accordingly, the synthesis derived from Table 1 reveals that recent studies reveal an increasing emphasis on understanding the environmental implications of additive manufacturing (AM), particularly when compared to conventional methods. Much of this research turns to Life Cycle Assessment (LCA) as a means of evaluating energy use, emissions, and material efficiency [21], [22]. There is growing optimism that AM can reduce waste and improve sustainability, especially when applied in decentralized manufacturing contexts or when recycled materials are introduced into the process [23], [24]. That said, many of the works reviewed stop short of offering a full picture. While environmental performance is frequently addressed, economic feasibility and social impact are not consistently examined. Moreover, methodological inconsistencies particularly in how system boundaries and impact categories are defined can limit comparability and generalizability[25]. This issue is compounded by the fact that many assessments remain confined to a cradle-to-gate scope, rather than considering full product life cycles [26].

In the construction and materials sectors, experiments with biocomposites and waste-based inputs show promise, though practical challenges such as material handling or variability in properties continue to complicate large-scale implementation[27], [28]. At the same time, some researchers have begun incorporating life cycle costing and probabilistic models, broadening the discussion beyond environmental metrics alone[29], [30]. New manufacturing approaches, such as WAAM and near-net-shape electrochemical processes, have also entered the discourse, offering notable efficiency gains and suggesting further avenues for future investigation [31], [32].

Table 1 Systematic Literature Review

Author	Proposed	Key Contribution	Area of application	Limitation
[21]	The paper aims to systematically analyze comparative studies focusing on the environmental impacts of additive manufacturing (AM) and conventional manufacturing (CM).	Comprehensive Literature Review, Identification of Research Gaps, Insights into Decentralized vs. Centralized Systems	Manufacturing and Supply Chain Management, Environmental Impact Assessment, Energy Efficiency in Manufacturing	Research on the environmental impact of transportation between additive manufacturing and conventional manufacturing is still limited. The long-term benefits of decentralized versus centralized manufacturing systems are still unclear. The evaluation of the impact of transportation on additive manufacturing and the environmental performance of decentralized supply chains is also lacking.
[33]	The paper proposes a comprehensive life cycle assessment (LCA) to evaluate the environmental impacts of additive manufacturing (AM) using recycled carbon fibres (CFs) compared to virgin CFs.	Detailed Life Cycle Inventory (LCI), Environmental Impact Analysis, Comparison of Scenarios, Insights into Solvolysis, Promotion of CF Recycling	Sustainable Manufacturing, Composite Materials, Lifecycle Assessment, Material Science and Engineering	The study lacks an economic assessment, data on recovered fibre properties, and adaptations for sizing and composites. The functional unit (a testing coupon) also complicates defining fiber functionality loss.
[34]	The journal proposes a life-cycle assessment (LCA) of 3D concrete printing and traditional casting processes for	Comparative Analysis, Environmental Impact Assessment, Innovative Material Use, Life-Cycle Data	Sustainable Construction, Material Science, Environmental Policy,	The study only considered Portland cement and did not evaluate alternative cement matrices that are more environmentally

	cementitious materials incorporating ground waste tire rubber (GWTR)		Manufacturing Processes	friendly. The authors suggest further research on environmental impacts.
[24]	The publication suggests repurposing marine plastic garbage to create new products by using 3D printing technology.	Innovative Recycling, Sustainability Assessment, Material Development, Economic and Environmental Analysis	Waste Management, Additive Manufacturing, Sustainable Manufacturing, Environmental Policy	Energy and production time of filaments can be reduced with a new approach to waste utilization, such as the use of polymers that can be depolymerized back to their raw materials.
[22]	The paper proposes an investigation into the energy requirements and environmental performance of various additive manufacturing (AM) processes.	Comprehensive Life Cycle Assessment (LCA), Energy Consumption Analysis, Environmental Impact Evaluation, Comparison with Conventional Manufacturing, Recommendations for Improvement	Aerospace, Automotive, Healthcare, Consumer Goods, Industrial Manufacturing	The article does not fully explore the environmental impact of AM under various experimental conditions. The authors acknowledge that further efforts are needed to fully understand the overall environmental impact of AM.
[23]	The paper proposes to investigate the environmental and economic impacts of distributed additive manufacturing (DAM) compared to traditional centralized manufacturing (CM).	Comparative Analysis, Life Cycle Assessment (LCA), Policy and Decision-Making	The primary application area for this research is in the manufacturing industry, particularly in sectors where additive manufacturing technologies are being adopted.	The study does not consider the implications of energy, emissions, and costs of material storage, inventory equipment, and products before distribution. The benefits of material efficiency in AM are also not visible because the level of waste and the importance of lightweight materials may not be as significant in the injection molding industry compared to other sectors.
[27]	The paper proposes using biocomposites composed of agricultural waste products, specifically hemp shives, combined with fast-setting binders such as magnesium, calcium sulphoaluminate (CSA), and gypsum-based binders.	Material Development, Environmental Impact, Mechanical Properties, 3D Printing Feasibility	These biocomposites are primarily applied in the construction industry, particularly for 3D-printing building materials and structures.	Pumping complex materials is challenging due to the easily compressible filler. Reducing the environmental impact of MPC binders needs to be prioritized, and research on the compatibility of CSA binders with bio-based fillers needs to be expanded.
[28]	The paper proposes using large-scale 3D printing technology for constructing houses. It uses a nozzle to add layers of prepared mortar in an extrusion process to build structures.	Environmental Performance, Economic Viability, Eco-Efficiency	The primary area of application for the proposed 3D printing technology is in the construction of residential buildings.	The limits, presumptions, and correctness of the inventory data within the system have an impact on the LCA and LCC outcomes. Since 3D printing technology is still in its infancy, data has been

				gathered from published works.
[25]	The paper discusses various approaches and methodologies for conducting Life Cycle Assessment (LCA) of additive manufacturing (AM) products.	Identification of Key Environmental Impact Categories, Evaluation of LCA Methodologies, Integration of Externalities	Additive Manufacturing Industries, Environmental Policy Making, Sustainable Manufacturing Research	The simple application of LCA may not be suitable for comparing additive and subtractive technologies. It is necessary to consider certain environmental criteria in addition to economic factors. Some studies do not explain the categories of environmental impact used for assessment.
[26]	The paper investigates the environmental impact, specifically the carbon footprint, of 3D-printed bone tissue engineering scaffolds through a life cycle assessment (LCA).	Life Cycle Assessment (LCA) Application, Comparison of Materials, Detailed Analysis, Recommendations for Improvement	highlighting aspects such as energy consumption, raw material usage, and waste generation	- The study could be expanded to cover the full cradle-to-grave life cycle rather than just cradle-to-gate - Further research is needed on the parameters involved in 3D bone tissue engineering scaffolds to avoid assumptions and improve reliability
[35]	Establish environmental guidelines to help designers make more sustainable choices during the digital fabrication design process.	Digital fabrication can potentially reduce the amount of industrial materials in a project associated with high environmental impacts.	Digital fabrication in architecture and construction.	This study does not consider the end-of-life of the digital fabrication infrastructure (robots, computers, etc), which may have additional environmental impacts due to increased metal consumption.
[36]	They were developing a framework based on the Social Life Cycle Assessment (SLCA) methodology to measure the social impacts of AM products throughout their lifecycle.	To evaluate the social effects of Additive Manufacturing (AM) goods for their life cycle, a Social Life Cycle Assessment (SLCA) framework is being developed. A mathematical model is included in this framework to aggregate indicator scores and establish cut-off scores to distinguish between favorable and unfavorable social consequences. It can be used with case studies to give an overall score that gauges social effect and scores for every stakeholder group and stage of the life cycle that show improvement areas.	Additive manufacturing (AM) technology	This study is limited to stakeholders from UNEP/SETAC, and further validation by experts is needed to apply this framework to real case studies.
[32]	Developing the Near-net-shape Electrochemical	The Near-net-shape Electrochemical	Manufacturing: titanium industry	Near-net-shape Electrochemical

	Metallisation (NEM) Method	Metallization (NEM) process can reduce environmental impact by up to 70%, improve efficiency in time, and offer the potential for further optimization compared to the conventional Kroll-EBM method in titanium manufacturing.		Metallization (NEM) requires a large amount of energy input, especially during titanium's heating and melting stage.
[37]	Analyze any contaminants released while recycling and 3-D printing of ABS and PLA plastics, comparing emissions from recycled and virgin materials and assessing contaminant levels in different environments.	Its detailed evaluation of contaminant emissions during the recycling and 3-D printing of various plastics provides essential data on environmental and health impacts.	Environmental sustainability, occupational health, and the circular economy.	The mechanical and thermal characteristics of polymers were not assessed in tandem with emissions, and the amounts of NF and FF contaminants can vary depending on some variables—limited understanding of how changes in polymer properties due to recycling impact emissions.
[29]	This paper proposes a comprehensive review and meta-analysis of metal additive and conventional manufacturing processes, comparing CNC machining and DMLS from environmental and economic perspectives. It explores how geometry complexity and shape size affect performance, addressing LCC uncertainty through Monte Carlo simulation.	This study compares the economic and environmental effects of AM and CM using LCA and LCC. It investigates how part size and geometry complexity affect the performance of AM and CM, and it uses Monte Carlo sensitivity analysis to pinpoint important cost drivers.	Applicable across various sectors, including aerospace, automotive, and general manufacturing, where the choice of manufacturing technology significantly impacts resource use and environmental footprints.	Focus on specific geometries and sizes that may not encompass all applications of AM and CM technologies. Uncertainty in the LCA and LCC analysis is also a factor, as assumptions can influence the reliability of the findings. The study does not consider the environmental impact of the product's use and disposal stages and is limited to 316L stainless steel material, which restricts the applicability of the findings to other materials. The geographical context used (Qatar) may also affect the relevance of the results in different regions, and the social aspects of the transition from CM to AM are not discussed.
[30]	Evaluate the economic sustainability using life cycle cost (LCC) analysis and the environmental impacts using life cycle assessment (LCA)	MAM reduces the total cost for aeronautical components by 33,2% but increases the cost for industrial machinery parts by 79,3% MAM reduces the potential environmental impact by more than 60% for both	Industrial machinery and aeronautical sectors.	Adopting metal additive manufacturing (MAM) does not lead to cost savings in industrial machinery.

		sectors due to reduced material consumption For aeronautical components, the use phase further contributes to environmental and economic benefits through significant fuel and CO2 emissions savings.		
[38]	Integrating recycled materials in 3D printing to increase sustainability and reduce environmental impact.	Combining 3D printing and recycling has the potential to enhance sustainability, reduce waste, and maintain material quality in manufacturing.	Rapid prototyping, customizable consumer products, sustainable construction practices, healthcare, and educational and research institutions.	The study lacks an assessment of the long-term durability and stability of 3D printed objects using recycled materials, has a limited focus on the social implications and broader industrial adoption challenges, and highlights the need for further investigation into innovative recycling techniques, circular design strategies, and comprehensive LCA.
[15]	A life cycle assessment (LCA) approach to evaluate the environmental impact of RT-COF-1 in surface and 3D inkjet printing applications.	Demonstrated the environmental benefits of using RT-COF-1 in 3D inkjet printing compared to surface printing, highlighting significant reductions in energy demand and carbon footprint.	Additive manufacturing, specifically in surface and 3D inkjet printing using covalent organic frameworks (COFs)	Processing challenges related to the patterning of COFs and high chemical consumption during printing.
[31]	Using WAAM to produce Inconel 625 components, reducing material waste and energy use while improving mechanical properties.	Demonstrating the environmental benefits and efficiency of using WAAM over traditional machining for Inconel 625, significantly reducing material waste and energy consumption.	Focused on manufacturing aerospace components, especially high-performance parts that require excellent mechanical properties and resistance to harsh environments.	A comprehensive analysis of long-term mechanical properties, such as fatigue and creep, is lacking under different environmental conditions.
[39]	The project creates green 3D printing samples meeting ASTM E1530:2019 standards, using statistical design, specific printing parameters, thermal post-treatment, and LCA for environmental impact assessment.	Novel 3D printing method for metal parts with environmental benefits and ASTM E1530:2019 compliance.	Manufacturing components for heating, cooling, and heat exchanger systems, including valves, pipes, pumps, and boiler accessories.	No in-depth LCA has been conducted specifically on Fused Deposition Modelling (FDM) manufacturing processes followed by sintering.

4 Conclusion

This study has identified trends and gaps in the literature regarding the environmental impact of additive manufacturing (AM) technology through a bibliometric analysis of 80 documents selected from the Scopus database. This analysis found that although AM technology offers advantages in terms of material efficiency and design flexibility, there are still significant challenges related to energy consumption and emissions generated during production.

There is growing interest in the environmental potential of additive manufacturing (AM), especially when compared to more conventional production methods. Across several studies, AM is associated with reduced material usage, lower energy requirements, and decreased waste generation. These benefits tend to be even more apparent when AM is combined with optimized design strategies or incorporates recycled materials. Nevertheless, many of these discussions still occur in isolation. The environmental dimension is often the primary focus, while the economic and social aspects do not receive the same degree of attention. As a result, we are left with only a partial understanding of what sustainability in AM truly entails.

To obtain a clearer understanding, future research needs to look beyond solely environmental data. Studies would be stronger if they incorporated economic and social analyses, ideally framed across the entire life cycle of a product. It would also be beneficial if there were greater consistency in the application of LCA methods, and if the later stages such as product use or disposal were considered more frequently. As the technology becomes more widespread, this broader evaluation will be essential. It will not only help researchers better comprehend the impact but also assist businesses and policymakers in making more informed decisions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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