Additive Manufacturing & Circular Economy Research

Abstract

Additive manufacturing (AM) is a transformative technology capable of revolutionizing manufacturing processes across various industries through its layer-by-layer production method. However, traditional manufacturing approaches face challenges related to the triple bottom line perspective. While AM is gradually being adopted in different sectors, it remains unclear how effectively this technology contributes to environmental, social, and economic aspects of sustainability. Additionally, the means by which companies leverage AM to achieve their sustainability goals are not well understood. In this report, a bibliometric analysis is deployed to explore the application of circular economy (CE) principles within AM. It analyzes sectors where CE principles are integrated into AM practices to identify areas requiring further research. By examining publication trends, identifying key themes, and assessing the potential impact of CE applications in AM, this study aims to shed light on the current state of research and suggest future directions. Ultimately, this analysis seeks to contribute to the literature on both CE and AM, bridging knowledge gaps and promoting the development of more sustainable and resource-efficient additive manufacturing practices.

Chapter 1: Background

1.1 Introduction

Additive manufacturing (AM), commonly referred to as 3D printing or rapid prototyping, represents a revolutionary shift in manufacturing processes by constructing objects layer-by-layer from three-dimensional digital models. This method contrasts sharply with traditional subtractive manufacturing techniques, such as machining, which involve removing material from a larger block (Gibson et al., 2015). Since its inception in the 1980s with Chuck Hull's invention of stereolithography, AM has undergone significant technological evolution. For instance, the development of selective laser sintering (SLS) in the 1990s expanded AM capabilities to include a wider range of materials, including metals and ceramics (Wohlers & Gornet, 2014). Other significant advancements include fused deposition modeling (FDM), which extrudes thermoplastic filaments, and electron beam melting (EBM), which uses electron beams to fuse metal powders (Gibson et al., 2015).

AM offers many advantages, including significant reductions in material waste, the ability to produce highly customized products, and the facilitation of decentralized production (Walter & Marcham, 2020). These benefits enable rapid prototyping and on-demand manufacturing, greatly enhancing efficiency and innovation across various industries, from aerospace and automotive to healthcare and consumer goods. However, despite these advantages, AM faces several challenges that impede its widespread adoption. Environmentally, certain metal-based AM techniques, such as Selective Laser Melting (SLM) and EBM, can be highly energy-intensive. A study by (Baumers et al.,2011) found that the specific energy consumption of SLM can range from 29 to 82 kWh/kg of processed material, depending on machine utilization. Additionally, the use of fine metal powders can lead to potential health and environmental hazards due to particle emissions. This study(Stephens et al.,2013) reported that desktop 3D printers using ABS filaments can emit ultrafine particles and volatile organic compounds, raising concerns about indoor air quality.

Socially, the shift towards automation and localized production could lead to loss of jobs in traditional manufacturing sectors, highlighting the need for workforce retraining and skill development. Conversely, AM can also contribute positively to social and economic sustainability by enabling the production of customized medical implants and prosthetics, which improve healthcare outcomes and quality of life for patients (Javaid & Haleem, 2018). Economically, AM fosters innovation and entrepreneurship by lowering barriers to entry for small-scale manufacturing. (Weller et al.,2015) argue that AM can lead to increased product variety and customization, potentially creating new market opportunities and business models. Furthermore, localized production can reduce transportation costs and associated emissions, contributing to both economic and environmental sustainability (Gebler et al., 2014).

Additionally, the high initial costs associated with AM equipment and materials, limited scalability for mass production, and uncertainties regarding long-term total cost of ownership and return on investment present significant barriers to widespread adoption (Deloitte, 2019). Additionally, the lack of consistent standards and regulations affects various aspects of AM, including material properties, process parameters, and quality assurance, potentially hindering interoperability across different AM systems (Monzón et al., 2015).

Despite these challenges, integrating AM with circular economy (CE) principles presents a promising avenue for promoting sustainable manufacturing practices. The CE paradigm emphasizes the efficient use of resources, waste minimization, and the creation of closed-loop systems where materials are continuously reused and recycled. However, much of the innovation in AM has focused on advancing the technology itself, with relatively little emphasis on aligning AM with CE principles to support broader sustainability goals (Mariia Kravchenko et al., 2020). This gap underscores the need for research into the implementation of CE within AM to explore its potential for fostering more sustainable manufacturing practices. By examining the intersection of CE and AM, this study aims to contribute to the development of resource-efficient and environmentally responsible manufacturing processes, ultimately supporting the transition towards a more sustainable industrial paradigm.

1.2 Research Scope

This research focuses on the application of CE principles within the context of AM. By conducting a bibliometric analysis, this study aims to identify the extent to which these principles have been incorporated into AM practices, as well as the impacts on sustainability across different sectors. The research will cover academic publications from the Scopus database, focusing on articles published between 2000 and 2024. Analyzing trends, themes, and gaps in the existing literature. The sectors examined will include, but are not limited to, aerospace, automotive, healthcare, and consumer goods. These sectors were chosen due to their significant adoption of AM technologies and their potential for integrating CE principles to enhance sustainability.

1.3 Research Question

To clarify a research question, Clough and Nutbrown (2012) use the Russian doll principle. This involves refining the initial broad research question until it captures the core of the research idea without any irrelevant words or intentions. By removing unnecessary layers (the larger outer dolls), the clearly defined research question (the smallest doll) should provide a focused start. Dudau's (2016) AbC rule further advises that a good research question should include:

- One / two clearly stated Abstract concepts.
- The Context in which the research is conducted.

The central research question guiding this study is: "To what extent are circular economy principles applied in additive manufacturing, and how do these applications impact the sustainability of manufacturing processes?". Here the abstracts being "Additive Manufactring" and "Circular Economy" and the Context is "Sustainability Practices".

This overarching question will be supported by several sub-questions:

1. What are the main research themes at the intersection of AM and CE?

2. Which industry sectors are leading in the application of CE principles to AM?

3. What are the key challenges in implementing CE principles in AM?

4. What are the potential future research directions in this field?

1.4 Research Aim and Objectives

The primary aim of this research is to investigate the potential of AM for achieving sustainability through CE principles. This will be achieved through the following objectives:

1. To conduct a systematic bibliometric analysis of the literature on CE principles in AM.
2. To identify the publication trends in the field of CE in AM
3. To identify the prominent authors and institutions contributing to this field.
4. To identify and analyze the main research themes and clusters in this field.
5. To assess the sustainability impacts of CE applications in AM across different sectors.
6. To identify research gaps and propose future research directions to enhance the sustainability of AM practices.

1.5 Report Structure

Chapter 1: Introduction
This chapter provides an overview of the dissertation, including background information on the research topic, the rationale for the study, and a clear statement of the research question. It outlines the specific aims and objectives that will guide the research process.

Chapter 2: Methodology
This chapter details the research methodology, including the philosophical approach, research design, and data collection methods. It justifies the chosen approaches and explains how they align with the research objectives.

Chapter 3: Literature Review
This chapter presents a comprehensive review and critical evaluation of existing literature relevant to the research question. It identifies key themes, gaps in current knowledge, and potential limitations that inform the research direction.

Chapter 4: Data Collection and Analysis
This chapter describes the process of data collection and presents a detailed analysis of the bibliometric data. It includes descriptive statistics, publication trends, author and institutional contributions, and geographical distribution of research.

Chapter 5: Discussion
This chapter interprets and discusses the findings from the literature review and data analysis. It evaluates the significance of the results in relation to the research question and objectives and identifies gaps in the current research.

Chapter 6: Conclusion and Recommendations
This final chapter summarizes the key findings of the research, assesses the extent to which the research objectives have been met, and provides recommendations for future research directions. It also reflects on the limitations of the study and its implications for the field of circular economy in additive manufacturing.

Chapter 2: Research Methodology

2.1 Introduction

This chapter outlines the methodological approach employed to investigate the integration of circular economy (CE) principles in additive manufacturing (AM). The research design is guided by the (Saunders et al.,2019) Research Onion framework, which provides a systematic approach to developing a comprehensive research methodology. Each layer of the Research Onion is addressed to ensure a robust and coherent research strategy.

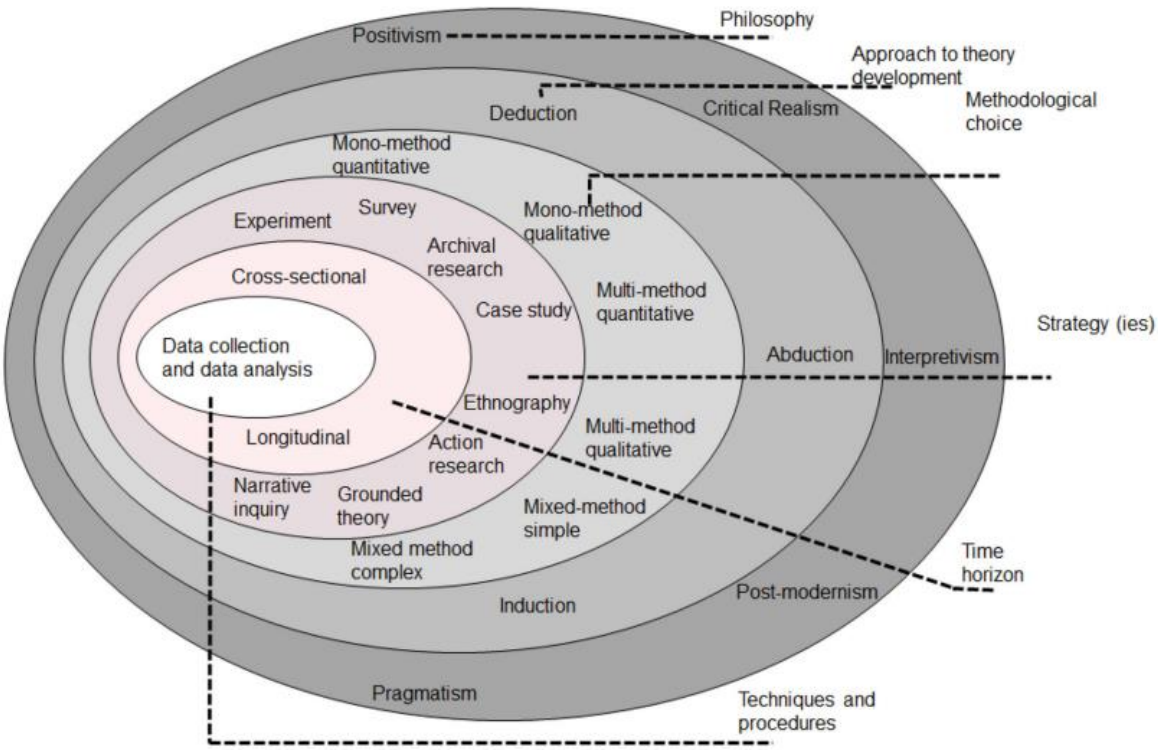

Fig 1: The 'Research Onion'

***Note*:Source:** 2022 Mark NK Saunders; developed from Saunders et al.2019

2.2 Research Philosophy: Pragmatism

This research adopts a pragmatic philosophy to investigate the integration of circular economy (CE) principles in additive manufacturing (AM). Pragmatism is particularly suitable for this study as it focuses on practical outcomes and real-world applications (Morgan, 2014), which aligns well with the goal of understanding how CE principles can be effectively implemented in AM processes. The pragmatic approach allows for the reconciliation of both objective technical aspects of AM and subjective interpretations of sustainability practices in CE (Kelemen & Rumens, 2008). This is crucial when examining the multifaceted nature of CE implementation in AM, which involves not only technological considerations but also economic, environmental, and social factors. The research problem—how to effectively integrate CE principles into AM practices—drives the methodological choices, as emphasized in pragmatic inquiry (Saunders et al., 2019).

2.3 Research Approach: Abductive

The research approach adopted for this study on integrating circular economy (CE) principles in additive manufacturing (AM) is abductive, which allows for a flexible interplay between theory and data (Suddaby, 2006). This approach is suitable for exploring the complex and evolving field of CE in AM, where existing theories may not fully explain all observed phenomena. The abductive approach enables the research to move iteratively between the established theories of CE and AM and the empirical data collected through bibliometric analysis and literature review. This iterative process allows for the identification of unexpected patterns in the integration of CE principles in AM practices, which can then be explored further to develop new theoretical insights (Van Maanen et al., 2007).

2.4 Methodological Choice: Mixed Methods

This study follows a mixed methods approach to investigate the integration of circular economy (CE) principles in additive manufacturing (AM). The mixed methods design allows for a comprehensive exploration of this topic by combining quantitative and qualitative data collection and analysis techniques (Creswell & Plano Clark, 2017). Specifically, a sequential explanatory design is adopted, where quantitative bibliometric analysis is first conducted to identify broad trends and patterns in the research landscape of CE in AM. This is followed by a qualitative thematic analysis of key publications to gain deeper insights into specific strategies and challenges of implementing CE principles in AM practices. The quantitative phase provides a macro-level view of the research field, identifying influential authors, publications, and emerging themes. The subsequent qualitative phase allows for a more detailed understanding of these themes, exploring the context and practical implications of CE integration in AM.

2.5 Research Strategy: Bibliometric Analysis and Systematic Literature Review

The archival and documentary research strategy is particularly well-suited for this project on integrating circular economy principles in additive manufacturing. This approach allows for an in-depth analysis of existing literature, reports, and journals, which is crucial for understanding the current state of knowledge and practices in this evolving field (Saunders et al., 2019). This method aligns well with the cross-sectional time horizon, enabling efficient data gathering without the need for extensive fieldwork or experimentation (Mills et al., 2010). The flexibility of this approach supports both quantitative bibliometric analysis and qualitative thematic analysis, enabling a mixed methods approach (Creswell & Creswell, 2018). For emerging fields like circular economy in additive manufacturing, where practical implementation might be limited, this strategy helps identify theoretical frameworks, proposed models, and potential applications that may not yet be widely implemented in industry.

The main research strategy includes using bibliometric analysis along with a systematic literature review. Bibliometric analysis uses a quantitative approach to map the intellectual structure of a research field (Zupic & Čater, 2015). This method is especially useful for identifying key authors, publications, and trends in the fast-changing field of CE in AM. The systematic literature review provides a thorough and transparent method for combining existing research, ensuring comprehensive coverage of relevant studies (Tranfield et al., 2003).

2.6 Time Horizon: Cross-sectional

The time horizon selected for this study is cross-sectional, which involves examining the integration of circular economy (CE) principles in additive manufacturing (AM) at a specific point in time. This approach is particularly suitable given the time constraints typically associated with academic research projects (Saunders et al., 2019). Cross-sectional studies capture a "snapshot" of a phenomenon, allowing researchers to analyze the current state of CE integration in AM without the extended time commitment required for longitudinal studies. Although a longitudinal study could offer valuable insights into how CE integration in AM evolves over time, the cross-sectional design allows for a focused and timely investigation, capturing the current landscape and identifying immediate challenges and opportunities (Mills et al., 2010). However, if needed, a longitudinal approach may be considered.

2.7 Ethical Considerations

While this study primarily involves the analysis of secondary data and does not involve human participants, ethical considerations remain important. Proper attribution of all sources and accurate representation of research findings will be ensured throughout the study (Wager & Kleinert, 2011).

2.8 Strengths and Limitations

<u>Strengths</u>

- Comprehensive Data Collection: The mixed methods approach allows for a thorough exploration of the research topic, combining quantitative and qualitative insights.
- Robust Analytical Framework: Bibliographic analysis provides a quantitative foundation, while thematic analysis offers depth and context.
- Flexibility: The abductive approach allows for iterative refinement of theories based on emerging data.

<u>Limitations</u>

- Language Bias: The focus on English-language publications may exclude relevant studies in other languages.
- Bibliometric Limitations: Bibliometric analysis may not capture the full complexity of the research impact and may be influenced by publication biases (Wallin et al.,2005).
- Some of the research papers included were handpicked based on my judgment about the topic.

2.9 Ensuring Research Quality and Methodological Rigor

While traditional concepts of reliability and validity are more applicable to empirical studies, ensuring the quality and trustworthiness of research remains crucial in systematic literature reviews and bibliometric analyses (Linnenluecke et al., 2020). This study employs several strategies to maintain methodological rigor and enhance the credibility of its findings.

Systematic Approach and Transparency

This research adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a robust framework for conducting and reporting systematic reviews (Moher et al., 2009). This ensures a transparent and replicable process, enhancing the study's dependability. The search strategy, including the use of the Scopus database, search terms, and inclusion/exclusion criteria, is clearly documented to allow for potential replication and to demonstrate the comprehensiveness of the literature coverage (Snyder, 2019).

Comprehensive Data Collection

To ensure a thorough representation of the field, the Scopus database is utilized as the sole source for literature retrieval. This approach minimizes the risk of overlooking relevant studies and enhances the credibility of the findings by focusing on a comprehensive and high-quality database (Miha Dominko et al., 2021). The time frame for the literature search is clearly defined, and any language restrictions are explicitly stated and justified.

Rigorous Data Analysis

The bibliometric analysis is conducted using established software tools such as VOSviewer and Bibliometrix R Package, Biblioshiny, which provides a systematic and objective approach to analyzing publication patterns and research trends (van Eck & Waltman, 2010). The process of data cleaning and normalization is thoroughly documented to ensure transparency and replicability. For the qualitative thematic analysis, a clear coding framework is developed and applied consistently across all included studies.

Contextual Applicability

While the generalizability of findings from literature reviews can be limited, this study provides detailed descriptions of the context (circular economy in additive manufacturing) and the characteristics of included studies. This allows readers to assess the transferability of findings to other contexts or related fields (Snyder, 2019). By implementing these strategies, this study aims to ensure a high level of methodological rigor, enhancing the trustworthiness and value of its findings in contributing to the understanding of circular economy principles in additive manufacturing.

2.10 PRISMA Framework

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework is widely used to enhance the quality of systematic reviews. It consists of three main phases: identification, screening, and eligibility.

2.10.1 Identification

The identification phase involves searching multiple databases to gather a comprehensive list of potentially relevant studies.

Search Strategy:

- Database: Scopus
- Search Terms: Selected Keywords along with boolean operators were used respectively, ("Additive manufacturing" OR "3D printing” OR ”Rapid Prototyping”) AND ("Circular Economy" OR " closed-loop systems " OR " Resource Efficiency," OR " Environmental Impact ") n=1451 documents.
- Document type: Articles, conference papers, Review
- Search within Article title, Abstract, Keywords
- Publication Stage: Final
- Search Period: Publications from 2000 to 2023.
- Language: English.

The initial search yielded a total of 1451 documents, and after applying the above filters, a total of 594 documents.

2.10.2 Screening and Eligibility

The screening phase involves reviewing the titles and abstracts of the identified studies to exclude irrelevant articles.

Using the Filter Duplicates option on Excel,0 duplicates were removed.(n=594)

Inclusion Criteria:

- Studies discussing the integration of CE principles in AM.
- Peer-reviewed journal articles, conference papers, and reviews.
- Handpicked 77 papers that were relevant to the topic.
- Studies focusing on environmental, social, or economic impacts of AM in a CE context in any sector.

<u>Exclusion Criteria:</u>

- Articles not focused on the intersection of AM and CE.
- Studies without full-text availability.
- Citations should be > 5 (200 documents removed)

After screening, the total number of documents included in the analysis was 471.

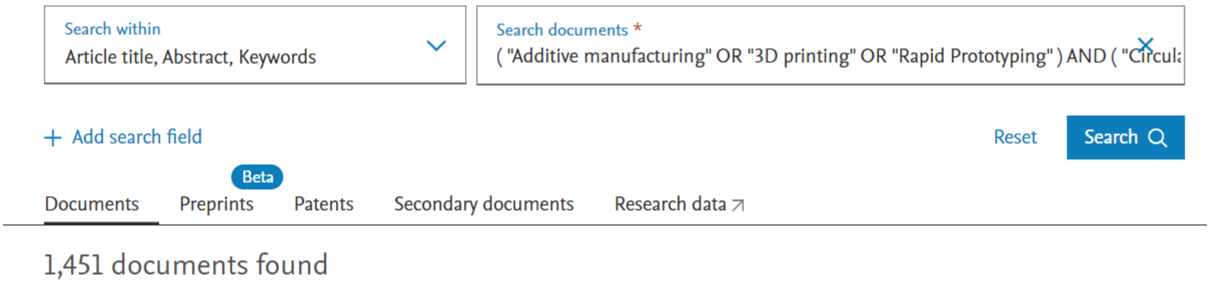

Fig 2: Initial search without filters set

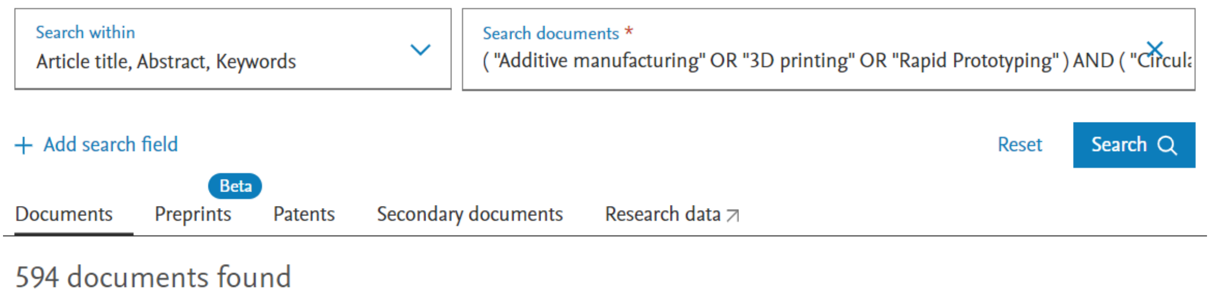

Fig 3: Dataset before Screening

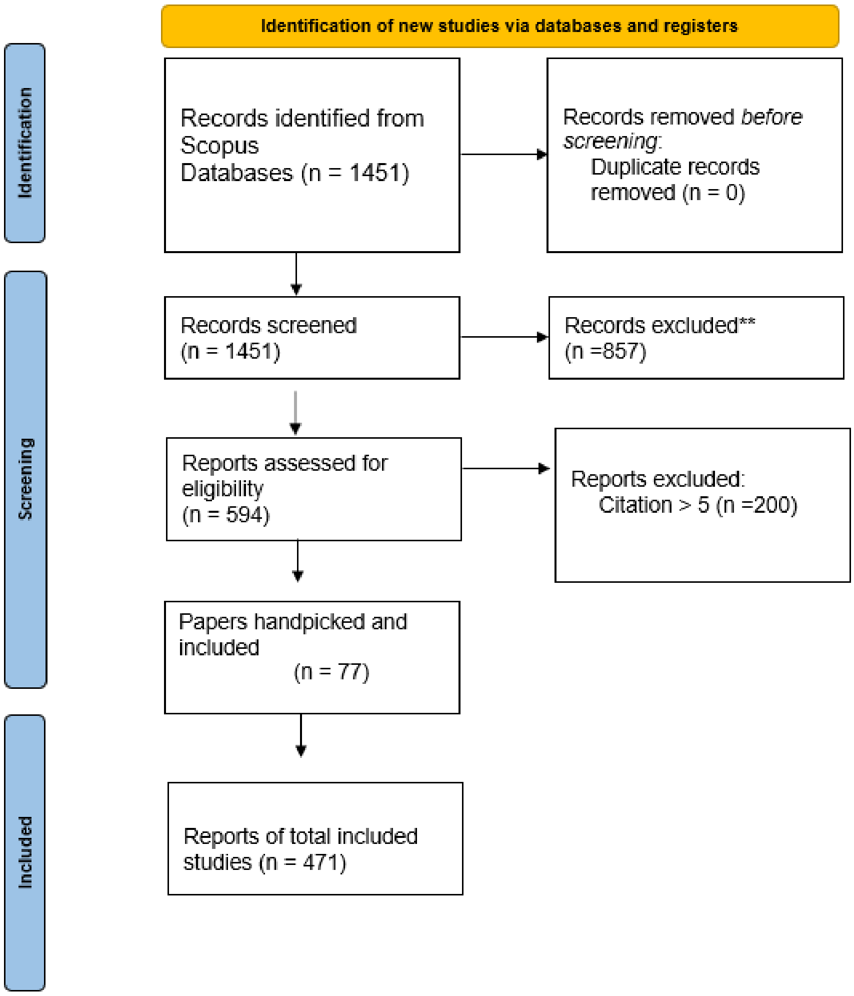

Fig 4: PRISMA Flowchart

2.11 Conclusion

The selected research methodology is summarized in the table below:

Research Methodology	Chosen option
Research Philosophy	Pragmatic
Research Approach	Abductive
Research Strategies	archival and documentary
Research Choice	Mixed Methods
Time Horizon	Cross-Sectional

Table 1: Research Methodology Overview

Chapter 3: Literature Review

3.1 Introduction

This chapter focuses on the potential for AM to contribute to sustainability and environmental impact reduction. This review examines a broad spectrum of strategies, methodologies, and technologies related to the integration of CE principles in AM processes. By critically analyzing current literature, this chapter aims to provide a comprehensive understanding of how AM can enhance sustainability practices within a circular economy framework. The themes discussed below were obtained by using the PRISMA framework and upon analysis using the Bibliometrix R package, Biblioshiny. The results of this analysis are mentioned in Chapter 4.

3.2 Additive Manufacturing: An Overview

Additive manufacturing (AM), commonly known as 3D printing, represents a revolutionary approach to industrial production. It enables the creation of complex, lightweight, and durable components by the addition of material layer by layer, directly from digital models. This method contrasts with traditional subtractive manufacturing, which involves cutting material to achieve the desired dimensions. AM encompasses a range of technologies, including Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM), each offering unique advantages and material compatibilities (Kumar & Chohan, 2021).

Design Flexibility and Rapid Prototyping

One of the most significant benefits of AM is its unparalleled design flexibility. Engineers and designers can create intricate geometries that are often impossible to achieve with conventional manufacturing techniques. This capability is valuable in industries such as aerospace and automotive, where lightweight and complex structures can lead to improved performance and fuel efficiency (Satish, Nancharaih, & Rao, 2018). Additionally, AM allows for rapid prototyping, enabling faster design iterations and reducing the time to market for new products. This rapid prototyping capability is essential for innovation, allowing for more iterations and refinements in the design process (Damir et al., 2023).

Applications in Aerospace

The aerospace industry has been a frontrunner in adopting AM technologies, leveraging them for various applications. AM is used to produce engine components, where performance and weight savings are crucial. For instance, 3D printing allows the creation of cooling channels in turbine blades, enhancing engine efficiency (ThomasNet, 2023). Additionally, lightweight structural components such as brackets and interior fittings are manufactured using AM to optimize strength-to-weight ratios, contributing to reduced fuel consumption (Kumar K & AcherjeeB, 2023). Moreover, AM facilitates rapid tooling and prototyping, allowing for the efficient production of fixtures and replacement parts, thereby reducing downtime (Spatial, 2023).

Applications in Healthcare

In the healthcare sector, AM has made significant strides, particularly in the production of patient-specific medical devices. Custom prosthetics, implants, and anatomical models can be tailored to individual patient anatomy, improving fit and function. This customization enhances patient outcomes and represents a significant advancement in personalized medicine (Kumar & Chohan, 2021). Furthermore, AM is being explored for bioprinting applications, where living cells are printed to create tissue-like structures, potentially leading to breakthroughs in regenerative medicine (University of Cambridge, 2024).

Applications in Automotive

The automotive industry is increasingly adopting AM for the production of complex components that enhance vehicle performance and efficiency. AM enables the use of lightweight parts, crucial for enhancing fuel efficiency and reducing emissions.. Additionally, AM enables the customization of interior components, providing manufacturers with the flexibility to offer tailored solutions to consumers (Kingsbury, 2023). The technology is also used for rapid prototyping, allowing automotive companies to accelerate the development and testing of new models (Formlabs, 2023).

Challenges to Mass Adoption

Despite these advantages, the widespread adoption of AM in mass production faces challenges. The speed of production and scalability are primary concerns, as current

AM technologies are generally slower than traditional methods. However, ongoing research aims to solve these limitations by developing faster printing techniques and more efficient processes (Merissa et al., 2024). Another challenge is the limited variety of materials available for AM, particularly in terms of mechanical properties and durability. Researchers are actively working to expand the material palette, exploring new polymers, metals, and composites that can withstand rigorous industrial applications (Monroe Engineering, 2020).

Environmental Impact and Sustainability

Environmental considerations also play a crucial role in the adoption of AM. The process is inherently more sustainable than traditional manufacturing, as it minimizes waste by using only the material necessary for the final product. This efficiency reduces material costs and the environmental footprint of production (Merissa et al., 2024). Moreover, the ability to manufacture parts on-demand and locally can reduce the need for transportation and inventory, further enhancing sustainability (Monroe Engineering, 2020).

Future Prospects

Looking ahead, the future of AM holds great promise. As technology advances, it is expected to become more integrated into mainstream manufacturing processes, offering solutions to current limitations and expanding its applications. Innovations in multi-material printing, hybrid manufacturing, and smart materials are likely to drive the next wave of growth in the field (Pascal Schmitt et al., 2021). As these developments unfold, AM plays a pivotal role in shaping the future of manufacturing, offering unparalleled opportunities for customization, efficiency, and innovation (Damir Godec et al., 2023).

3.3 Circular Economy: An Overview

The circular economy represents a transformative approach to economic development that prioritizes sustainability by extending the lifecycle of resources, materials, and products. Unlike the linear economy, which follows a "take-make-dispose" principle, the circular economy aims to reduce waste and make the most of existing resources by rethinking and redesigning products and business processes (European Investment Bank, 2023). This approach not only conserves resources but also reduces environmental impact, fosters sustainable economic growth, and generates new jobs (Pauline Deutz, 2020).

<u>Defining the Circular Economy</u>

At its core, the circular economy is about reforming the current linear economic model into a system where disposal is minimized. The Ellen MacArthur Foundation defines it as an economic model that decouples growth from the consumption of finite resources, focusing on positive societal benefits. It is restorative and regenerative by design, aiming to eliminate waste and pollution, circulate products and materials, and regenerate nature (Ellen MacArthur Foundation, 2023).

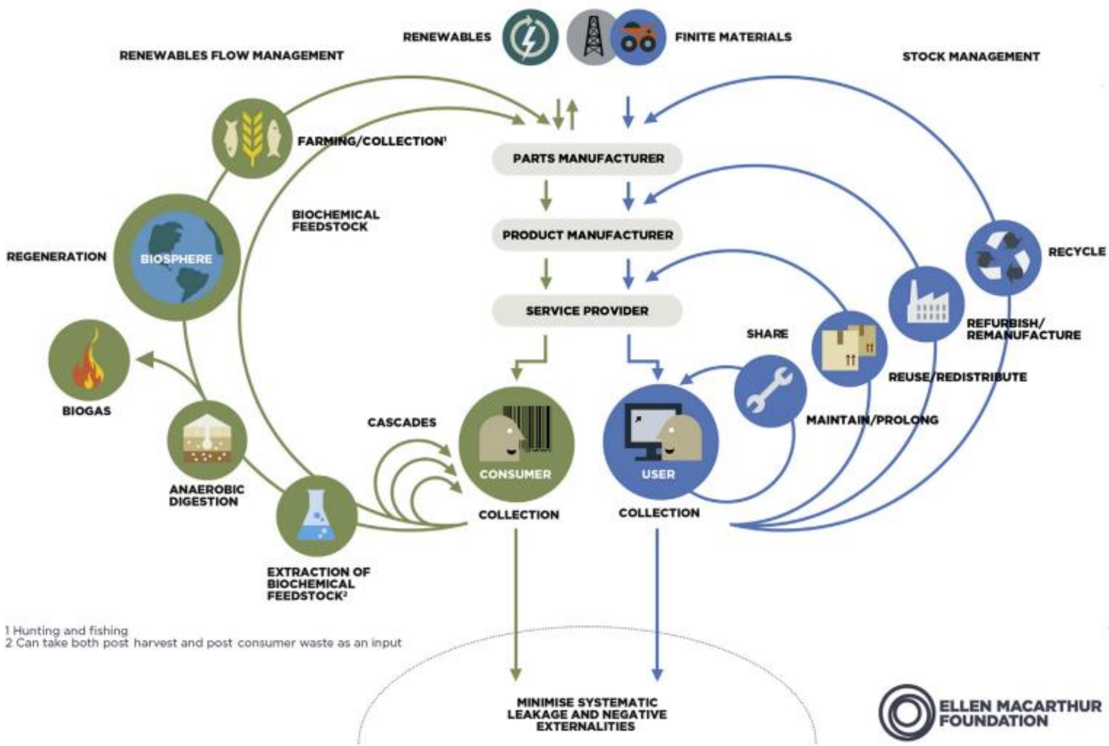

Fig 5: The Ellen MacArthur Circular Economy Diagram

Note: Source: Ellen Macarthur Foundation

Environmental and Economic Benefits

The transition to a circular economy offers significant environmental and economic benefits. By reducing material and energy consumption, waste generation, and greenhouse gas emissions, the circular economy helps mitigate climate change and protect biodiversity (European Commission, 2020). It is estimated that circular economy strategies in key areas such as cement, steel, and plastics could eliminate almost half of global greenhouse gas emissions from production by 2050 (European Investment Bank, 2023). Economically, circular businesses can reduce material, energy, and waste management costs, resulting in higher yields and competitive advantages.

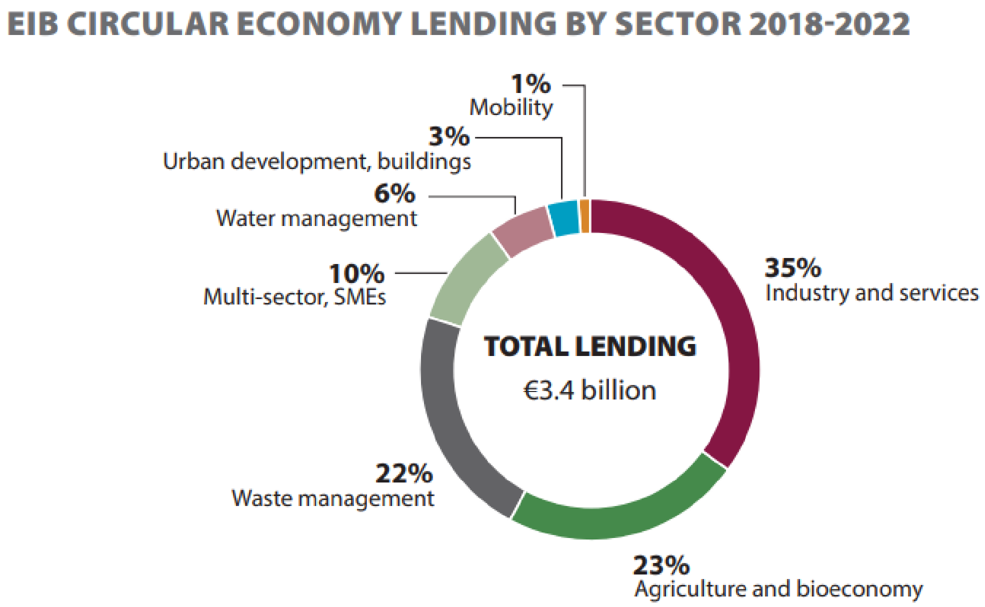

Fig 6: Contributions Of Circular Economy by each Sector.

Note: Source: European Investment Bank, Circular economy OVERVIEW 2023

Applications in Various Sectors:

Industry and Manufacturing

The circular economy has profound implications for industry and manufacturing. By adopting circular practices, companies can redesign production processes to minimize waste and maximize resource efficiency. This includes using recycled materials, designing products for longevity and repairability, and implementing closed-loop systems where waste is reused as input for new production (Ellen MacArthur Foundation, 2023).

Agriculture and Bioeconomy

In agriculture, the circular economy promotes sustainable practices such as nutrient recycling, precision farming, and the use of bio-based materials. These practices help reduce reliance on chemical inputs, enhance soil health, and improve crop yields, contributing to a more sustainable food system (European Commission, 2020).

Waste Management and Urban Development

Circular economy principles are integral to waste management and urban development. By prioritizing recycling, composting, and energy recovery, cities can reduce landfill use and lower their environmental footprint. Urban areas can act as catalysts for circular economy transitions by efficiently sharing resources and goods (Pauline Deutz, 2020).

Challenges and Opportunities

Despite its benefits, the transition to a circular economy faces challenges, including technological limitations, regulatory barriers, and the need for significant behavioral change among consumers and businesses (European Investment Bank, 2023). However, the potential for innovation and growth is substantial. The International Labour Organization estimates that transitioning to a circular economy could increase global employment by 7-8 million jobs by 2030 (European Investment Bank, 2023).

Future Prospects

The circular economy is poised to play a crucial role in achieving global sustainability goals. As awareness grows and more businesses and governments adopt circular principles, the potential for positive environmental and economic impacts will continue to expand. The European Union's Circular Economy Action Plan, a key component of the European Green Deal, exemplifies the commitment to making sustainable products the norm and achieving climate neutrality by 2050 (European Commission, 2020).

3.4 Additive Manufacturing as an Enabler for Circular Economy

Additive manufacturing (AM), commonly known as 3D printing, serves as a powerful enabler for the circular economy by transforming traditional manufacturing processes and promoting sustainability. The circular economy aims to reduce resource consumption and waste while enhancing business innovation and sustainability (CECIMO, 2023). AM supports this by offering novel paradigms for design, manufacturing, and business models, ultimately contributing to a more sustainable economic system.

Fig 7: Advantages of adopting Circular Economy in Additive Manufacturing

Note: Source: Stephanie Hendrixson, Additive Manufacturing,2020

Resource Efficiency and Waste Reduction

One of the primary ways in which AM supports the circular economy is through resource efficiency and waste reduction. Traditional manufacturing processes often result in significant material waste, as excess material is removed to shape the final product. In contrast, AM builds objects layer by layer, using only the material necessary for the final product, thus minimizing waste (Design Society, 2023). This efficiency not only reduces material costs but also decreases the environmental footprint of production (Prima Additive, 2023).

Repair, Remanufacturing, and Longevity

AM also enhances the circular economy by facilitating repair and remanufacturing activities. The technology allows for the production of replacement parts on demand, extending the product span and decreasing the need for new resources (CECIMO, 2023). This ability is valuable in industries such as aerospace and automotive, where maintaining equipment and machinery is crucial for operational efficiency (Additive Manufacturing Media, 2023). Additionally, AM enables the design of products with modular components that can be easily repaired or upgraded, further promoting product longevity (Biman Darshana et al., 2022).

Sustainable Production and Energy Efficiency

AM contributes to sustainable production by reducing energy consumption compared to traditional manufacturing methods. The technology eliminates the need for multiple production stages and reduces transportation requirements by enabling localized production (Prima Additive, 2023). This localized production capability is advantageous for reducing the carbon footprint linked with the long-distance transportation of goods (Design Society, 2023).

Innovation in Design and Business Models

The flexibility of AM in design and production processes encourages innovation in business models that align with circular economy principles. By enabling the creation of complex geometries and customized products, AM allows companies to explore new markets and offer tailored solutions to consumers (Prima Additive, 2023). This innovation is not only limited to product design but also extends to supply chain management, where AM can enhance supply chain flexibility and performance (Biman Darshana et al., 2022).

Table 1 Ten practices for loop closing within a circular economy.

	Practice	*Definition*	*Example*
	"Short" loops	*Can be seen as consumer activities, though all could also be applied to producers or others in the supply chain*	
R0	Refuse*	Consumption is avoided—either altogether or a low-material form selected (e.g., avoided packaging)	Keeping a mobile phone beyond the end of initial contract
R1	Reduce	Avoiding the generation of waste—applies more to producers, for consumers may imply application of one of the other practices	More material-efficient design of product
R2	Resell/reuse	Extending product life by the original or another own using it for the original purpose with little or no intermediary activity (which would imply one of the activities later); might or might not involve a monetary transaction between previous and subsequent users	Using someone else's out of contract phone
R3	Repair	Extending product life by fixing a product to restore previous function or appearance; product may or may not remain with the original owner	Having a new screen fitted on a mobile phone
"Medium" loops		Business-led activities, though possibly aimed at consumers	
R4	Refurbish	Similar to repair but refers to larger or more complex products, such as buildings or vehicles; may involve a product "upgrade"; less likely to be undertaken by an individual	Buildings being restored with improvements to insulation/ plumbing
R5	Remanufacture	Recovery of product/components (with cleaning, repair as required) retaining original purpose; may be sold directly to consumer or installed as component of larger product before sale	Car engines/tyres recovered from otherwise end of life vehicles
R6	Repurpose	Conversion of a product or component to enable a different use; this could be at a "craft" scale, or a commercial operation	Apartments made from disused warehouses
"Long" loops		Focus of formal waste management activities, likely to remain significant options	
R7	Recycle	Recovery and reprocessing of materials to be used in the manufacture of a new product—includes, but not limited to, municipal collection of postconsumer residues	Municipal collection of paper
R8	Recover (energy)	While "recovery" is a general term covering R2–R9, here it refers to processes such as incineration from which energy generation is the primary output (materials such as ash may also be produced)	Energy from waste plant

Fig 8: Implementation Conditions for Closed Loop System

Note: Source: Based on definitions in Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0?

Challenges and Opportunities

Despite its potential, the integration of AM into the circular economy faces challenges, including technological limitations, high initial costs, and the need for new skills and capabilities (Biman Darshana et al., 2022). However, the opportunities for innovation and sustainability are substantial. As AM technology continues to advance, it is expected to play a pivotal role in accelerating the transition to a circular economy by providing sustainable solutions across various industries (Additive Manufacturing Media, 2023).

Future Prospects

The future of AM as an enabler of the circular economy looks promising. As more industries adopt AM technologies, the potential for positive environmental and economic impacts will continue to expand. The ongoing development of new materials and processes will further enhance the capabilities of AM, making it an integral part of the circular economy framework (CECIMO, 2023).

3.5 Motor Themes Cluster – (Circular Economy, Recycling, Fusion Deposition Modelling)

CE Strategy	Description	Reference No.
Recycling and Re-manufacturing	Focuses on recycling end-of-life materials to create new products, reducing waste and extending material lifecycle.	4, 51, 41,15, 62
Utilization of Waste Materials in Production	Utilizes industrial or agricultural waste to create new materials, enhancing sustainability and reducing waste.	68,19,7
Distributed Recycling for Additive Manufacturing	Implements strategies for recycling complex polymer composites and integrating them into AM processes.	70

Table 2: CE Strategies Summary and Document Grouping

3.5.1. Recycling and Re-manufacturing

Several documents emphasize the recycling and re-manufacturing of materials as a key Circular Economy (CE) strategy.

Pdf 9 explores the recycling of glass fiber-reinforced polymers (GFRPs), particularly from end-of-life wind turbine blades, for use in additive manufacturing. The strategy involves mechanically recycling these materials to create new products, thus reducing waste and promoting sustainability by extending the lifecycle of materials (Alessia Romani et al.,2020).

(Mauricio et al.,2020)discusses the development of an open-source filament extruder for recycling acrylonitrile butadiene styrene (ABS). This approach emphasizes material reuse and waste reduction, aligning with CE principles by enabling the recycling of ABS into new filament, thus prolonging the material's lifecycle.

(Konstantina et al.,2023) focuses on the recycling of composite materials using solvolysis methods to recover carbon fibers and resin. This strategy, part of the EuReComp project, incorporates a comprehensive R-6 strategy—Reuse, Repair, Refurbish, Remanufacture, Repurpose, and Recycle—which aims to enhance sustainability in various industries by reintroducing recovered components into additive manufacturing processes.

(Heshan et al.,2023) highlights the broader CE strategies of recycling, remanufacturing, repairing, reusing, and refurbishing waste plastics. The document discusses the conversion of end-of-life products into new or usable items, emphasizing the importance of these 'R' strategies in reducing waste and improving resource efficiency.

(David et al.,2023) addresses the mechanical recycling of polylactic acid (PLA) 3D printing waste. The focus is on sorting and separating PLA waste to enhance the quality of the recycled material, which aligns with CE principles by improving material reuse and reducing waste.

(P.Wuamprakhon wt al.,2023) details a strategy for recycling plastic waste into high-value products through additive manufacturing. This approach aims to reduce reliance on virgin plastics and promote the upcycling of waste, thereby addressing environmental concerns associated with plastic waste and supporting CE goals.

3.5.2 Utilization of Waste Materials in Production

Some documents discuss utilizing waste materials in production processes as a CE strategy.

(Dhrutiman et al.,2022) describes the use of industrial waste materials in 3D concrete printing. The strategy involves incorporating high-volume supplementary cementitious materials (SCMs) derived from industrial waste to enhance sustainability and reduce environmental impacts associated with concrete production.

(Roberto et al.,2023)explores the creation of biodegradable composites from agricultural waste, specifically tomato plant residues. This approach aligns with CE principles by valorizing waste materials and enhancing sustainability through the development of green composites.

(Antonella Patti et al.,2022) examines the recycling of biobags into 3D printing materials. The recovered polymer shows promise for use in additive manufacturing due to its good printability and comparable properties to virgin PLA. This strategy promotes material reuse and reduces plastic waste, contributing to the broader goals of a circular economy.

3.5.3 Distributed Recycling for Additive Manufacturing

(Samantha et al.,2020igation) discusses a distributed recycling strategy for additive manufacturing (DRAM), focusing on recycling complex polymer composites, such as windshield wiper blades. The document explores various technical pathways for recycling, including mechanical grinding and filament production. This strategy aims to provide economic incentives for consumers to recycle and integrate these materials into AM processes, promoting a circular economy approach.

3.6 Relevance Degree Cluster-(Manufacturing, Life Cycle Assessment (LCA), Sustainability)

(References used:89,47,34,5,31,8,48)

Ref no.	**Manufacturing Techniques**	**Life Cycle Assessment (LCA)**	**Sustainability**	**Future Scope**
89	Various AM processes (LENS, DMD)	Evaluates AM impacts, focusing on energy use and GWP	- AM can reduce waste; mixed sustainability results	Further research on environmental impacts; optimizing energy efficiency
47	AM enhances efficiency; uses recycled/biobased materials	Cradle-to-gate approach; case-by-case impact evaluations	AM extends product lifecycles; reduces waste	- Addressing high energy consumption; exploring local sourcing

34	FDM, SLS, BJ, and hybrid systems for NFCs	Reduced carbon footprint; challenges in recycling NFCs	NFCs are more sustainable; integration in various industries	Develop new materials; explore hybrid composites; assess market presence
31	3D printing for construction; compared with traditional methods	LCA shows lower impact with 3D printing in material use	Significant resource and cost savings with 3D printing	Optimize materials and methods; apply to broader construction scenarios
5	- CNC milling vs. MEX technology (3D printing)	Cradle-to-gate LCA; MEX generally has lower impact	MEX reduces waste; more sustainable for cultural heritage	Refine environmental efficacy; explore socio-economic implications
7	Thermoforming vs. DLP for dental aligners	Direct 3D printing has lower impact than thermoforming	Direct printing reduces waste and energy use	- Research in other biomedical applications; consider economic factors
8	FFF for bioplastic pots; material composition (PLA, soy by-products)	Bioplastics reduce carbon footprint; traditional plastics have high impact	Bioplastics improve plant health and reduce pollution	Optimize pot design; long-term studies; explore other materials
48	3D printing in automotive industry; compared with traditional methods	Importance of material recovery models; assess sustainability index	Reduces waste; promotes recycling and reuse	Develop strategies for recycling; improve supply chain for

				recycled materials

Table 3: Summary of Relevance Degree Cluster

3.6.1 Manufacturing Techniques

The papers examined under this cluster highlighted the following additive manufacturing processes. Key points related to each technique with respect to sustainability are discussed.

- Laser Engineered Net Shaping (LENS) and Direct Material Deposition (DMD): These AM techniques are examined for their specific energy consumption (SEC), which is very high compared to traditional methods. Due to their high SEC, they also show significant contributions to Global Warming Potential(GWP) (Zhichao Liu et al.,2018).
- Wire-arc Additive Manufacturing (WAAM) is noted for its high material efficiency and cost-effectiveness, and it has a detailed Process-Based Cost Model (PBCM) (Manuel Dias et al.,2022).
- Fused Deposition Modeling (FDM): This technique is used for natural fiber composites (NFCs). It is known for its affordability and ease of use, which explains its widespread adoption by industries (Irshad et al.,2023).
- Material Extrusion (MEX): Compared with CNC milling, showing lower material waste and environmental impacts (Alessio et al.,2023).

3.6.2 Sustainability Aspects

Reduced Waste techniques such as WAAM and MEX are noted for their high material efficiency and reduced waste generation compared to traditional methods (Manuel Dias et al.,2022) and (Alessio et al.,2023).WAAM and 3D printing technologies are shown to reduce production costs significantly compared to conventional methods, hence supporting economic viability (Hadeer et al.,2021). The use of bioplastics and NFCs contributes to sustainability by reducing reliance on petroleum-based materials and offering improved biodegradability (Irshad et al.,2023) & (Arup Dey et al.,2023).

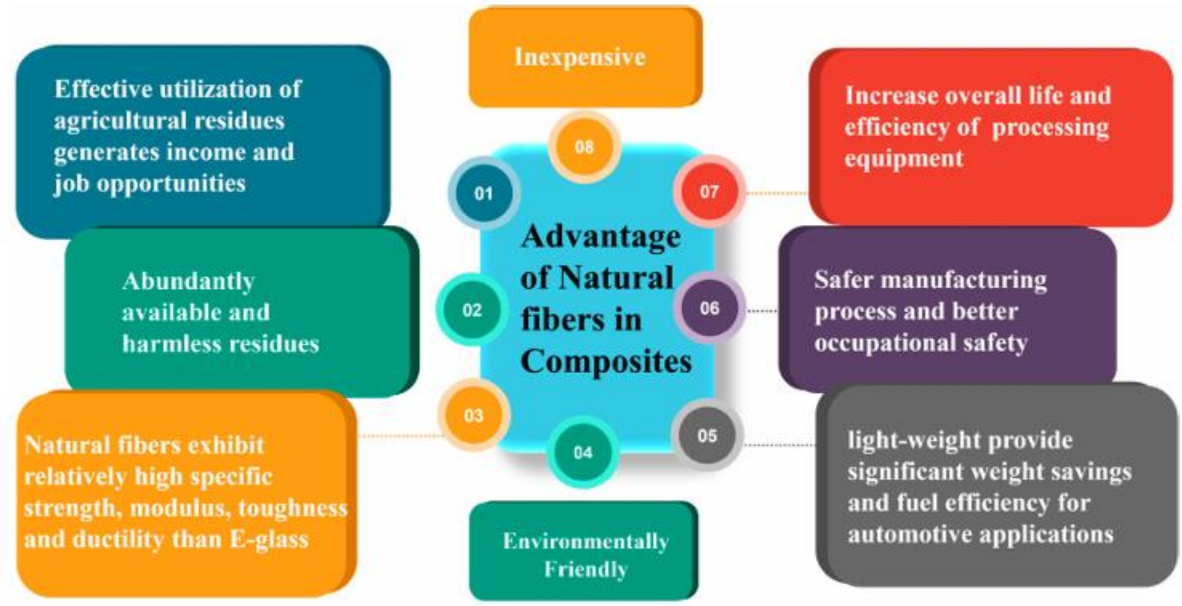

Fig 9: Advantages of using Natural fibers in composites

Note:Source: Natural Fiber Composite Filaments for Additive Manufacturing: AComprehensive Review.*Sustainability*

3.6.3. Future Scope

The integration of AM with other technologies like machining and metal forming enhances production capabilities (Manuel Dias et al.,2022). Continued research to improve AM technologies, including material and process optimization (Arup Dey et al.,2023).Potential for AM technologies to be applied to various fields, including construction and healthcare (Hadeer et al.,2021)&(Alessio et al.,2023).The need for integrated environmental and economic assessments to fully understand the impacts and benefits of AM.

3.7 Development Degree Cluster – (Environmental Impact, 3D Printers, AM)

References Used: (3,52,13,26,24,44,69,80,46)

3.7.1 Environmental Impact

<u>General Environmental Benefits of Additive Manufacturing (3,52,13,26,24,80)</u>

Additive Manufacturing (AM) has been highlighted for its potential to reduce environmental impacts compared to conventional manufacturing methods. AM technologies can save materials and energy, contributing to a lower environmental footprint. For instance, the study from (Alejandro et al.,2023) notes the material and energy savings that AM technologies offer, while (Floriane et al.,2019) emphasizes the importance of reducing resource consumption, including model and support materials, and electrical energy during the manufacturing process.

Specific Environmental Impact Assessments

- Positive Environmental Impacts

- Eco-innovation and Greenhouse Gas Reduction (Russell et al.,2022): Eco-innovation through AM can lower greenhouse gas emissions and reduce the CO2 footprint of manufacturing activities.
- Material Footprint and Energy Consumption (Frank et al.,2017): AM significantly reduces material waste and primary energy consumption compared to conventional machining and welding processes. For example, the material utilization rate for AM can be as high as 83%, compared to 21% for conventional methods.

- Potential Reductions in Negative Impacts

- Laser Polishing (Laura et al.,2022): Laser polishing can eliminate the negative environmental impacts associated with conventional finishing techniques, which often rely on abrasives.
- Local and On-Demand Production (Cristina Elena & Raluca,2022): In the textile industry, AM reduces material waste, decreases the use of water-intensive materials, and facilitates recycling, thus lowering the overall environmental impact.

3.7.2 Additive Manufacturing Technologies Involved

Technologies Highlighted in Various Studies

- Big Area Additive Manufacturing (BAAM) and Wire Arc Additive Manufacturing (WAAM) (Alejandro et al.,2023): These technologies allow for the creation of large geometries with subsequent hybrid machining required for precision.

- Laser Powder Bed Fusion (LPBF) (Laura et al.,2022): This technology provides high design freedom but often requires post-processing to meet application standards.
- Fused Deposition Modeling (FDM) and Material Jetting (Floriane et al.,2019): FDM is noted for material efficiency and lower ecological impacts at high utilization rates, while Material Jetting is used for creating intricate designs.

Specific Applications

- Textile Industry (Cristina Elena & Ralca,2022): Technologies such as Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), and Polyjet technology are used for producing intricate designs in fashion and clothing.
- Gas Turbine Burners (Frank et al.,2017): Laser Beam Melting (LBM) is used for fabricating metal parts with high material efficiency.
- Biomedical, Aerospace, and Automotive Industries (Mazyar et al.,2018): Various AM techniques, including FDM and Material Jetting, are applied across these sectors for sustainable manufacturing practices.

3.7.3 Barriers for Implementation

General Challenges

- Surface Quality and Design Adaptations (Alejandro et al.,2023): AM processes like WAAM produce parts that require post-processing for surface quality, presenting a barrier in terms of time and design complexity.
- Lack of Implementation Tools and High Costs (Russell et al.,2022): The absence of tools, high implementation costs, and unavailability of accessible data hinder the adoption of AM technologies.

Technology-Specific Barriers

- Powder Quality and Recycling (M.Lutter et al.,2018): Issues like spatter formation during Laser Beam Melting (LBM) affect powder quality, making recycling difficult and impairing the overall feasibility of AM processes.

- Complex Polishing Requirements (Laura et al.,2022): Conventional polishing methods face limitations with complex geometries, functional edges, and concave surfaces, leading to high time and cost consumption.
- Cost of Metal Powder and Recycling Challenges (Frank et al.,2017): The high cost of metal powder, particularly for superalloys, and the need for effective recycling are significant barriers.
- Knowledge Gaps and Lack of Guidelines (Floriane et al.,2019): Users often lack the knowledge required to optimize the use of AM machines, leading to inefficient resource consumption.

Industry-Specific Barriers

- Textile Industry (Cristina Elena & Raluca,2022): Producing wearable garments that meet strength, flexibility, and comfort standards remains a challenge. The technology's expense, limited material choices, and public resistance to digitalization further impede its implementation.

Reference papers with 150 citations were selected and individually analyzed to study commonalities, revealing a clustered pattern. The results indicated a predominant focus on quantified Environmental Impacts. A summarized result of the same is shown in the table below:

Ref No.	Environmental Impact	Industry Type	AM Technique Used	Barriers
3	Positive but not quantitatively assessed	Aeronautical tooling	Big Area Additive Manufacturing (BAAM), Wire Arc Additive Manufacturing (WAAM)	Surface quality and design adaptations
69	Lowers GHG emissions, reduces CO2 footprint	General	Additive Manufacturing (AM)	Lack of implementation tools, high costs, inaccessible data
44	Negative from conventional methods; potential reduction with laser polishing	General	Laser Powder Bed Fusion (LPBF)	Limitations of conventional polishing, time and cost concerns, environmental impact of abrasives

Ref No.	Environmental Impact	Industry Type	AM Technique Used	Barriers
46	Not explicitly discussed	General	Laser Beam Melting (LBM)	Quality concerns with powder recycling, spatter formation
24	Reduces resource consumption and energy usage; detailed LCA analysis	Various (biomedical, aerospace)	Material Jetting, Fused Deposition Modeling (FDM), others	Lack of knowledge, need for guidelines, integration complexity
26	Reduces material footprint, primary energy demand, and CO2 emissions	Gas turbine burners	Laser Beam Melting (LBM)	Material limitations, cost of metal powder, recycling challenges
13	Reduces material waste, water usage, and facilitates recycling	Textile industry	Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Polyjet	Complexity in producing wearable garments, technology expense, limited expertise, public resistance
11	Multifaceted impacts: energy use, material waste, toxicity	General	Fused Deposition Modeling (FDM), Inkjet/Polyjet	High energy consumption, material limitations
52	Limited research, need for predictive models for environmental impacts	Various (biomedical, aerospace)	Fused Deposition Modeling (FDM), Material Jetting	Lack of comprehensive inventory data
80	High energy demand, sustainability assessed using exergetic analysis	General	Direct Laser Metal Deposition (DLMD)	Lack of comprehensive studies, real-time monitoring challenges

Table 4: Summary of Development Degree Cluster

3.8 Basic Themes Cluster – (Construction, Concrete, Binders)

References used : (28,19,48,73)

3.8.1 3D Printing in Construction: Overview

3D printing in construction presents numerous opportunities but also faces several technical challenges. Current high-performance cement-based materials are unsuitable due to inadequate rheological and stiffening properties. Active Rheology

Control (ARC) and Active Stiffening Control (ASC) are proposed as solutions to extend the material palette (Greet et al.,2018). Digitally manufactured concrete (DFC) is expected to change stakeholder dynamics and cost structures in construction, potentially enhancing cost-effectiveness compared to conventional methods (Greet et al.,2018).

3.8.2 Sustainable Materials for 3D Concrete Printing

The use of sustainable materials is crucial for 3D concrete printing (3DCP). Various binder systems, including traditional Portland cement and supplementary cementitious materials (SCMs) like fly ash, silica fume, and slag, are reviewed for their environmental impact and performance (Shantanu et al.,2021). Industrial wastes, such as fly ash and slag, can be incorporated to reduce carbon footprints and enhance sustainability (Dhrutiman Dey et al.,2022).

3.8.3 Environmental and Economic Analysis

Life Cycle Assessments (LCA) are necessary to evaluate the sustainability of 3D printed structures (Greet et al.,2018). Cost analyses indicate that 3D printing mixes are generally more expensive than traditional concrete, but the potential for reduced labor costs and material waste is notable (Maria et al.,2020). Using SCMs and alternative binders can significantly improve the sustainability of 3D printed structures (Shantanu et al.,2021).

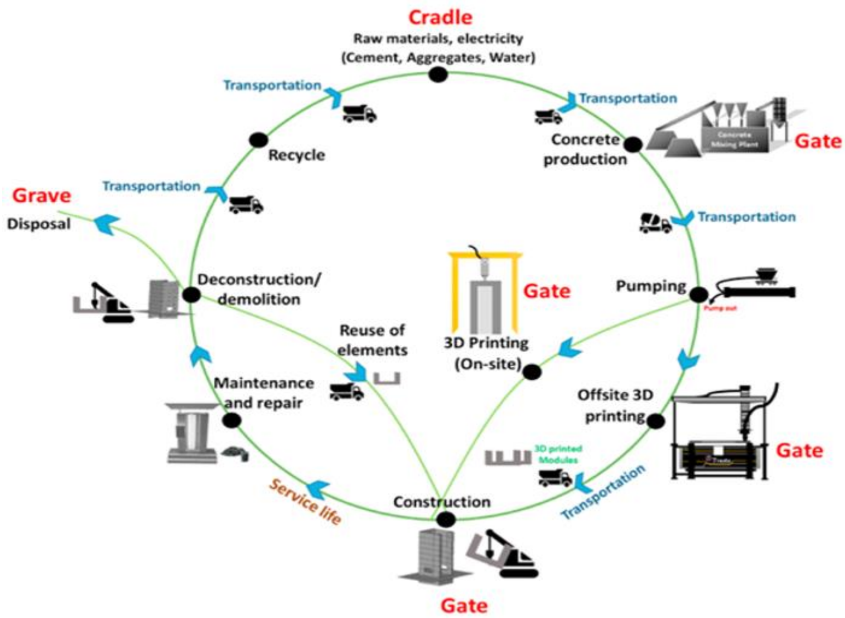

Fig 10: Life Cycle of a 3D printed structure

Note:Source: Sustainable materials for 3D concrete printing. *Cement and Concrete Composites*.

3.9 Emerging Cluster – (Geometry, Closed loop Systems, Robotics)

References used : (37,35,64)

3.9.1 Geometry in Additive Manufacturing and 3D Printing

Mineral Foam 3D Printing: The integration of mineral foam 3D printing (F3DP) with concrete casting aims to address sustainability concerns by reducing the cement content in concrete structures. This approach is crucial for lowering carbon emissions from building materials and aligning with sustainable development goals(Patrick et al.,2023).

- Methodology: A workflow was developed using F3DP to create formwork elements for a ribbed concrete slab. The technique allows for complex and cost-effective geometric designs, reducing material use and weight.
- Material and Fabrication: Mineral foams, which are lightweight and fire-resistant, are printed using a robotic arm. These foams serve as formwork for casting ultra-high-performance fiber-reinforced concrete (UHPFRC), significantly reducing material usage (72% less concrete) and mass (70% lower).
- Future Directions: Further research is suggested on environmentally friendly concrete mixes and machine learning for real-time process adjustments.

3D Printing in Soil Science: 3D printing is emerging as a transformative tool in soil science. It helps in creating agricultural equipment, laboratory devices, and new construction materials while enhancing geotechnical soil characterization(Javier A et al.,2020).

- Challenges and Limitations: Major challenges include the need for biocompatible materials, accurate representation of soil's porous structure, and high spatial resolution in printed models.

- Opportunities for Research: 3D printing can facilitate the development of customizable soil models for research into carbon and nutrient cycling, biomass production, and biodiversity.

3.9.2. Robotics and Machine Learning in Additive Manufacturing

Data Stream Merging: Integrating machine learning to enhance data stream merging aims to stabilize and optimize manufacturing processes by improving productivity and resource efficiency. A machine learning-based approach automates the merging of heterogeneous data streams, using domain expert knowledge to create valid data streams for process optimization. The technology was implemented in an industrial setup, and the case study using the Random Forest model showed notable performance, hence opening new opportunities in broadening CE in AM(Jan Zenisek et al.,2022).

3.10 Niche Themes Cluster – (Geoploymers and Inorganic Polymers)

References used : (61,56,88)

Geopolymers and inorganic polymers have emerged as significant niche themes within the broader fields of additive manufacturing (AM) and circular economy (CE). These materials offer unique advantages that align well with the principles of sustainability and resource efficiency, making them highly relevant for future research and application.

3.10.1 Environmental Benefits

Geopolymers present a notable environmental advantage by potentially reducing carbon emissions compared to traditional Portland cement. This reduction is primarily due to the use of aluminosilicate-rich precursors, which are often derived from industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and liquid sodium silicate (LSS). The utilization of these waste materials not only minimizes the need for virgin resources but also contributes to waste reduction, thereby supporting the goals of a circular economy (Oceane Lya et al.,2021).

3.10.2 Material Composition

The incorporation of industrial by-products into geopolymer formulations is a key factor in their sustainability. For instance, fly ash and GGBS are commonly used in geopolymer production, which helps in diverting these materials from landfills and reducing the environmental footprint of construction activities. The use of these by-products aligns with CE principles by promoting the recycling and reuse of materials within the production cycle (Mohsen Rezaei et al.,2023).

3.10.3 Ease of Use

One-part geopolymer formulations have been developed to simplify the production process, making them more accessible for various applications, including 3D printing. These formulations typically involve the use of a single dry mix that can be activated with water, eliminating the need for multiple components and complex mixing procedures. This ease of use can facilitate the broader adoption of geopolymers in AM, thereby enhancing their potential to contribute to sustainable manufacturing practices (Yazeed A et al.,2023).

3.10.4 Comparative Analysis

While geopolymers offer significant environmental advantages, it is essential to consider their suitability for specific applications. Comparative studies have shown that CEM III-based formulations might be more appropriate for certain 3D printing applications due to their mechanical properties and ease of processing. This suggests that while geopolymers are a promising alternative, the choice of material should be tailored to the specific requirements of the application to achieve optimal performance and sustainability (Oceane Lya et al.,2021).

3.11 Conclusion

Overall, this literature review underscores the significant potential of AM to support circular economy goals and enhance sustainability across various industries. The insights gained from this review provide a strong foundation for further research and real-world applications in integrating AM with circular economy principles.The next chapter gives the results that were obtained from the PRISMA framework which gave the solid base for conducting the systematic literature review.

Chapter 4: Data Collection and Analysis

4.1 Introduction

This chapter details the methodologies and strategies employed for data collection and analysis within the scope of this research. The primary aim is to systematically explore the intersection of Circular Economy (CE) principles with Additive Manufacturing (AM) through a comprehensive bibliometric analysis. By leveraging data from academic publications, this chapter seeks to uncover trends, identify key contributors, and analyze thematic patterns in the literature spanning from 2000 to 2023. The insights gained from this analysis will provide a robust foundation for understanding the current landscape of CE applications in AM, highlighting both advancements and areas requiring further investigation.

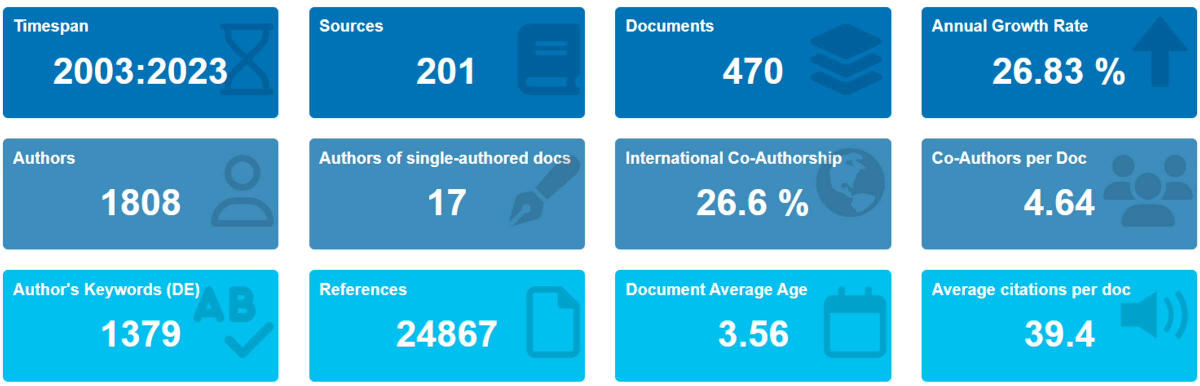

Fig 11: Main Information Overview obtained by Biblioshiny App

4.2 Bibliometric Analysis

4.2.1 Descriptive Analysis

A descriptive analysis was performed to understand the publication trends over time, identify the most prolific authors, institutions, and countries, and map the citation landscape.

<u>Publication Trends: Analysis of the number of publications per year to identify growth patterns.</u>

Figure 11 shows the publication trends in the field of circular economy and additive manufacturing from 2000 to 2023. The data indicates a significant increase in the number of publications starting around 2015, which could be related to the growing awareness and adoption of sustainable manufacturing practices. This trend reflects the increasing academic and industrial interest in integrating circular economy principles into additive manufacturing processes. The peak in publications

in 2020, may be linked to a heightened global focus on sustainability, likely driven by

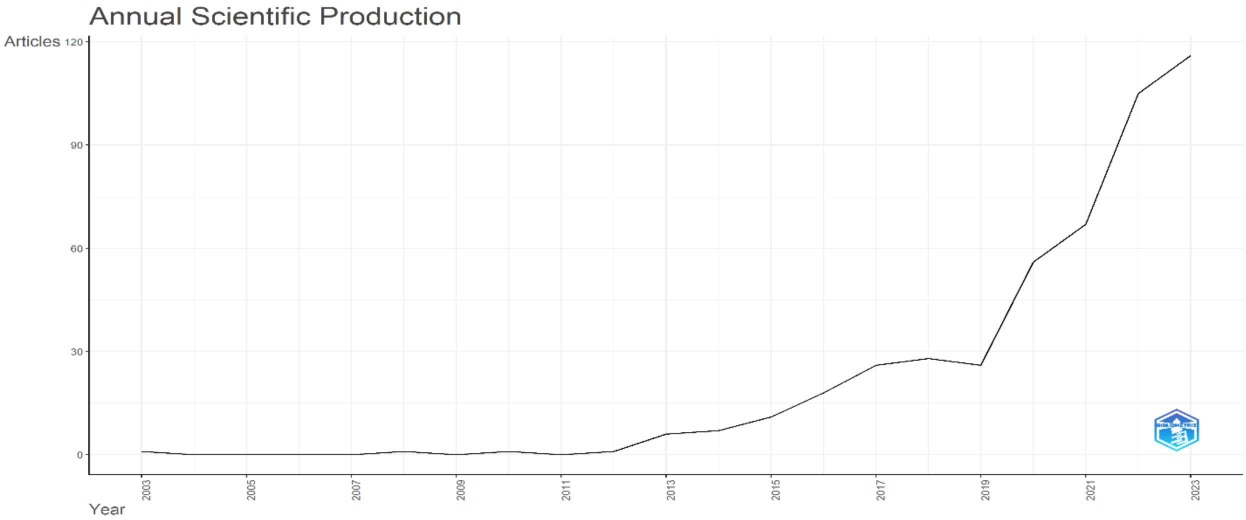

Fig 12: Annual Scientific Publications from the year 2000 to 2023

international policy shifts and increased funding for environmental research.

Deeper Analysis: The peak in 2020, as indicated by a sharp increase from 2019 to 2021, might be due to several factors. The heightened global focus on sustainability during this period could have driven research output. Additionally, the COVID-19 pandemic, which caused significant disruptions globally, may have accelerated interest in resilient and sustainable manufacturing practices. This surge could also be attributed to an increase in remote working and digital collaboration tools, making research more accessible.

Figure 12: Average citations from 2000 to 2023, In addition to the publication trend, the citation data provides further insights into the impact of this research field. According to the information provided, the average number of citations per year per document is 39.4%. This relatively high citation rate suggests that papers in this field are being well-received and frequently referenced by other researchers. The sudden rise and fall from 2019 to 2021 could indicate that the pandemic did have an impact, potentially due to declines in funding, changes in policies, rules, and regulations. An

in-depth analysis of these factors is beyond the scope of this paper but warrants future investigation.

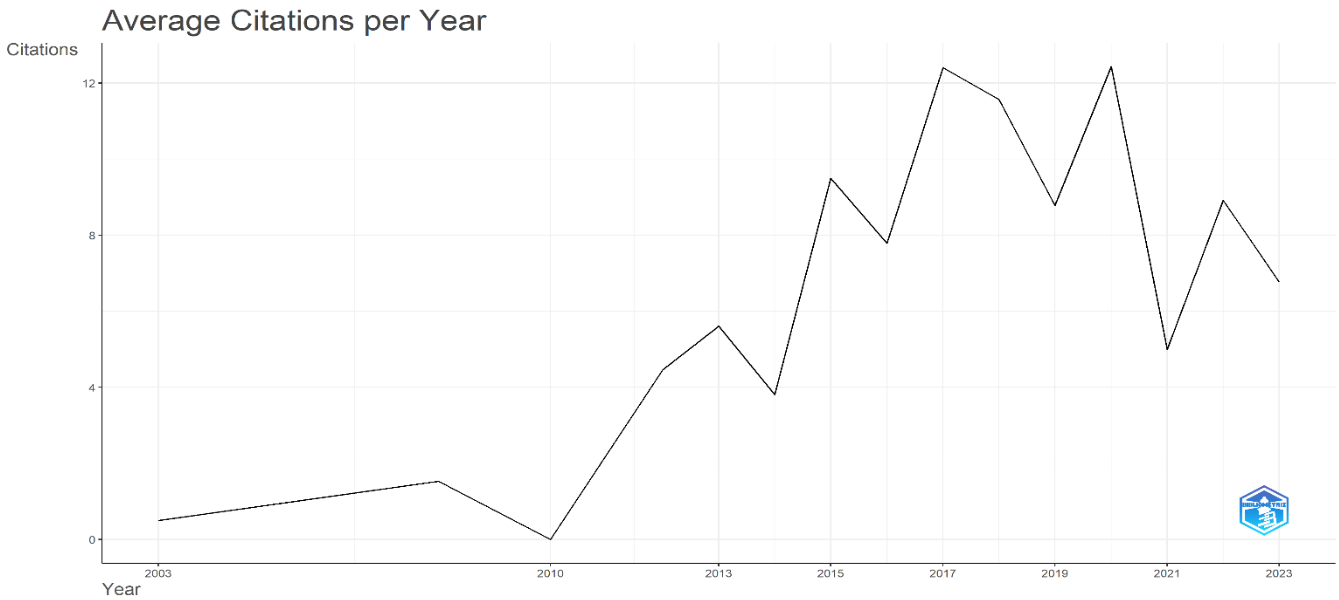

Fig 13: Average Citations per year ranging between 2000 to 2023

Prolific Authors and Institutions: Identification of key contributors to the field.

SL.No.	Authors	Articles	Articles Fractionalized
1	PEARCE JM	16	4.62
2	HERRMANN C	7	1.41
3	LEVI M	6	1.70
4	AURICH JC	5	1.48
5	GODINA R	5	1.18
6	INGARAO G	5	1.03
7	LI M	5	1.16
8	ROMANI A	5	1.45
9	WOERN AL	5	1.58
10	ZHANG H	5	0.89

Table 5: List of most prolific authors by the number of publications and fractionalized contributions.

"Table 2 lists the most prolific authors in the field of circular economy and additive manufacturing, based on the number of articles they have published. The 'Articles Fractionalized' column accounts for co-authorship, giving a more detailed view of each author's contribution.

- **J.M. Pearce**: Leading author with 16 articles (4.62 fractionalized). His work focuses on open-source technologies for sustainable development and additive manufacturing.
- **C. Herrmann**: Published 7 articles (1.41 fractionalized), primarily on sustainable manufacturing and lifecycle engineering.
- **M. Levi**: Authored 6 articles (1.70 fractionalized), emphasizing material efficiency and waste reduction in additive manufacturing.

SL.No	Affiliation	Articles
1	MICHIGAN TECHNOLOGICAL UNIVERSITY	34
2	POLITECNICO DI MILANO	26
3	DELFT UNIVERSITY OF TECHNOLOGY	23
4	UNIVERSIDADE DO PORTO	21
5	TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG	20
6	GHENT UNIVERSITY	18
7	UNIVERSITY OF PALERMO	18
8	UNIVERSITÉ DE LORRAINE	18
9	BIRLA INSTITUTE OF TECHNOLOGY AND SCIE	17
10	UNIVERSITÀ POLITECNICA DELLE MARCHE	16

Table 6: List of top institutions by the number of publications.

"Table 3 highlights the top institutions contributing to research in circular economy and additive manufacturing. Michigan Technological University leads with 34 publications(focus on sustainable manufacturing practices and interdisciplinary research), followed by Politecnico di Milano with 26 publications(material innovation and sustainable design in circular economy contexts), and Delft University of Technology with 23 publications(lifecycle assessment and sustainable manufacturing).

Geographical Distribution: Analysis of the countries leading in research on CE in AM.

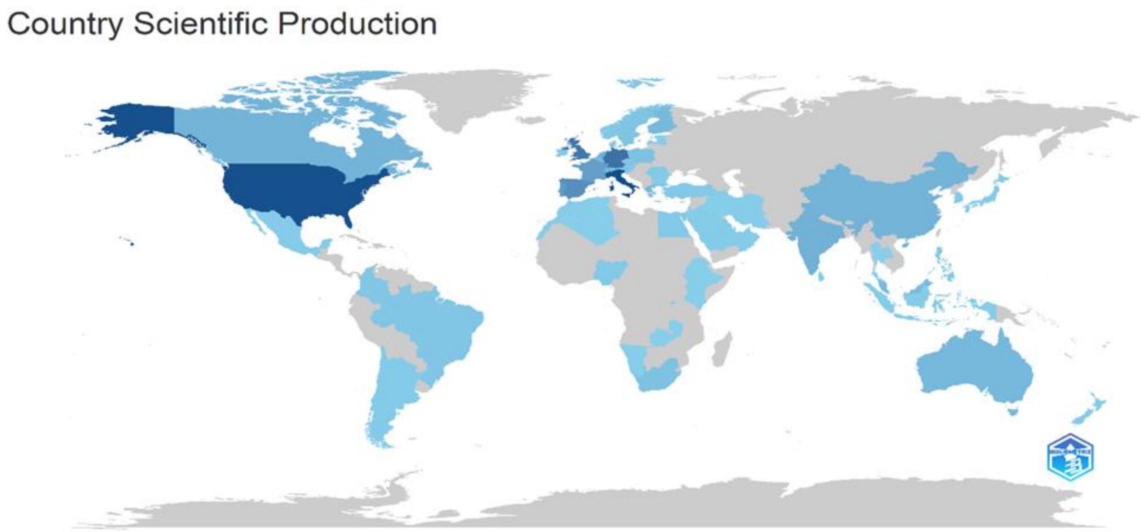

Fig 14: World Map Showing Geographical Distribution of Publications

SL.No.	Country	Freq
1	ITALY	290
2	USA	282
3	GERMANY	203
4	UK	190
5	SPAIN	135
6	PORTUGAL	110
7	FRANCE	102
8	NETHERLANDS	65
9	INDIA	60
10	CHINA	57

Table 7: Geographical Distribution of Publications in Circular Economy and Additive Manufacturing

Table 4 and Figure 13 illustrate the geographical distribution analysis,it shows a strong concentration of research activities in North America, Europe, and Asia. European countries,show a high level of research output, likely due to the EU's strong policy focus on circular economy and sustainability.

- **Italy (290 articles):** Italy's leading position can be attributed to its strong emphasis on sustainable manufacturing practices and the presence of prominent research institutions like Politecnico di Milano.

- **USA (282 articles):** The USA's significant contribution is driven by its robust research infrastructure and leading universities such as Michigan Technological University.
- **Germany (203 articles):** Germany's focus on engineering and technology, supported by institutions like Technische Universität Braunschweig, has resulted in substantial research output.

4.2.2 Thematic Analysis

A thematic analysis was conducted using two powerful bibliometric tools: the Bibliometrix R package (Biblioshiny) and VOSviewer.As detailed in Chapter 2: Methodology, Rigorous data analysis was chosen over mitigation bias since this is an individual project. Hence, the same CSV file obtained from the Scopus database was used for analysis in both applications. This consistency in the dataset ensures that the findings are directly comparable and methodologically rigorous. The results from both Biblioshiny and VOSviewer were found to be similar, reinforcing the validity of the identified themes and trends.

Justification for Tools: Biblioshiny and VOSviewer were chosen for their robust capabilities in handling large bibliometric datasets and their complementary strengths. Biblioshiny, with its interactive web interface, allows for detailed and flexible bibliometric analysis, while VOSviewer excels in visualizing complex bibliometric networks and thematic maps.

- Keyword Co-occurrence: The analysis of keyword co-occurrence was performed to identify prominent themes within the literature. By examining the frequency and co-occurrence of keywords, we were able to pinpoint the main areas of focus and the interconnections between different research topics.

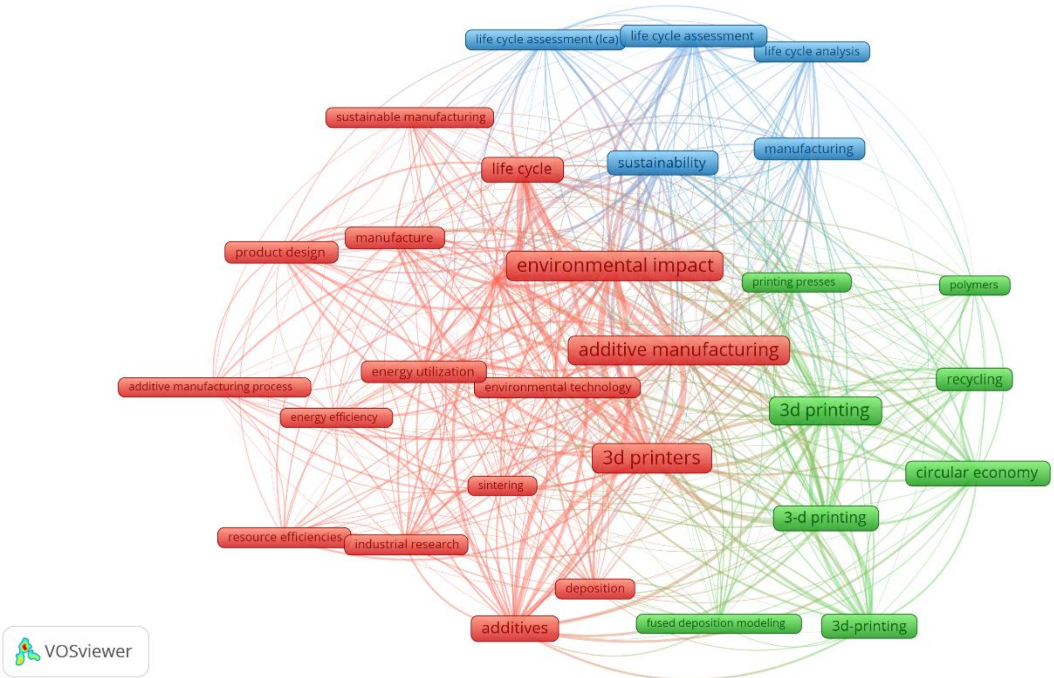

Fig 15: Keyword network visualization using Vosviewer

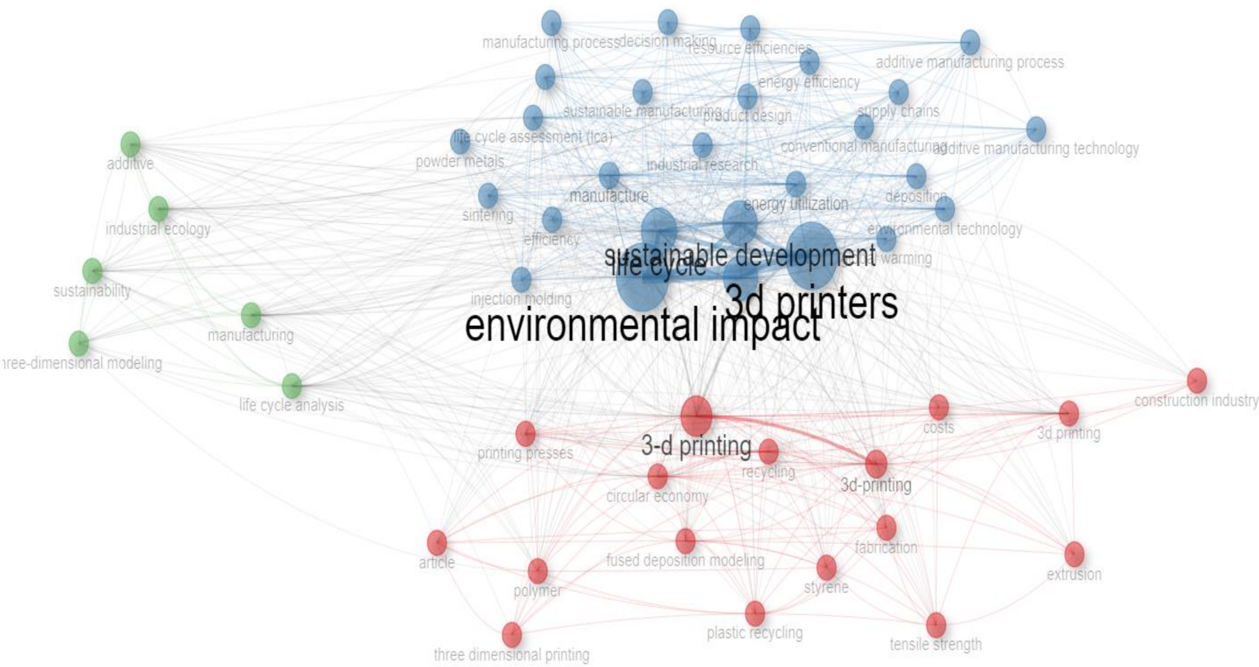

Fig 16: Keyword Co-occurrence network visualization using Biblioshiny

Key Insights from Keyword Network Visualization: The figures above show that both analysis tools produced similar results by forming 3 main clusters.

The keyword network visualizations highlight several prominent themes. Keywords such as "Circular Economy," "Additive Manufacturing," "Sustainability," and "Recycling" appear frequently and are central to the network. These themes connect various subtopics, illustrating the interdisciplinary nature of research in this field. For instance, the connection between "Circular Economy" and "Sustainability" emphasizes the overarching goal of integrating sustainable practices into manufacturing processes

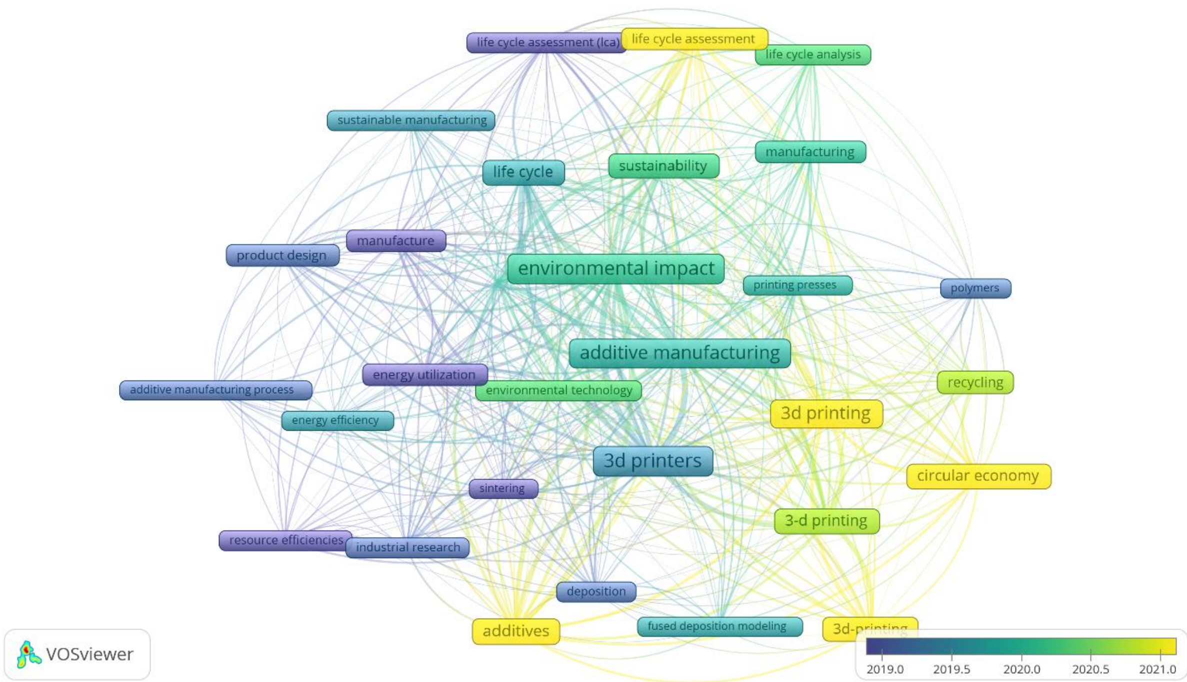

Fig 17: Keyword Co-occurrence overlay Visualization

The map reveals several distinct clusters of keywords, each representing a major theme within the research field:

Interconnections Between Clusters

The map demonstrates strong interconnections between the three main clusters. For example, "additive manufacturing" is linked to both "sustainability" and "circular economy," highlighting the potential of this technology to contribute to a more sustainable future. Additionally, "recycling" and "energy efficiency" connect the technology cluster with the sustainability cluster, emphasizing the importance of resource optimization.

Emerging Trends

The inclusion of keywords like "environmental technology" suggests a growing emphasis on additive manufacturing's environmental impact. Furthermore, the presence of terms like "industrial research" indicates a shift towards practical applications and economic considerations.

Creation of thematic maps to visualize research clusters and emerging trends.

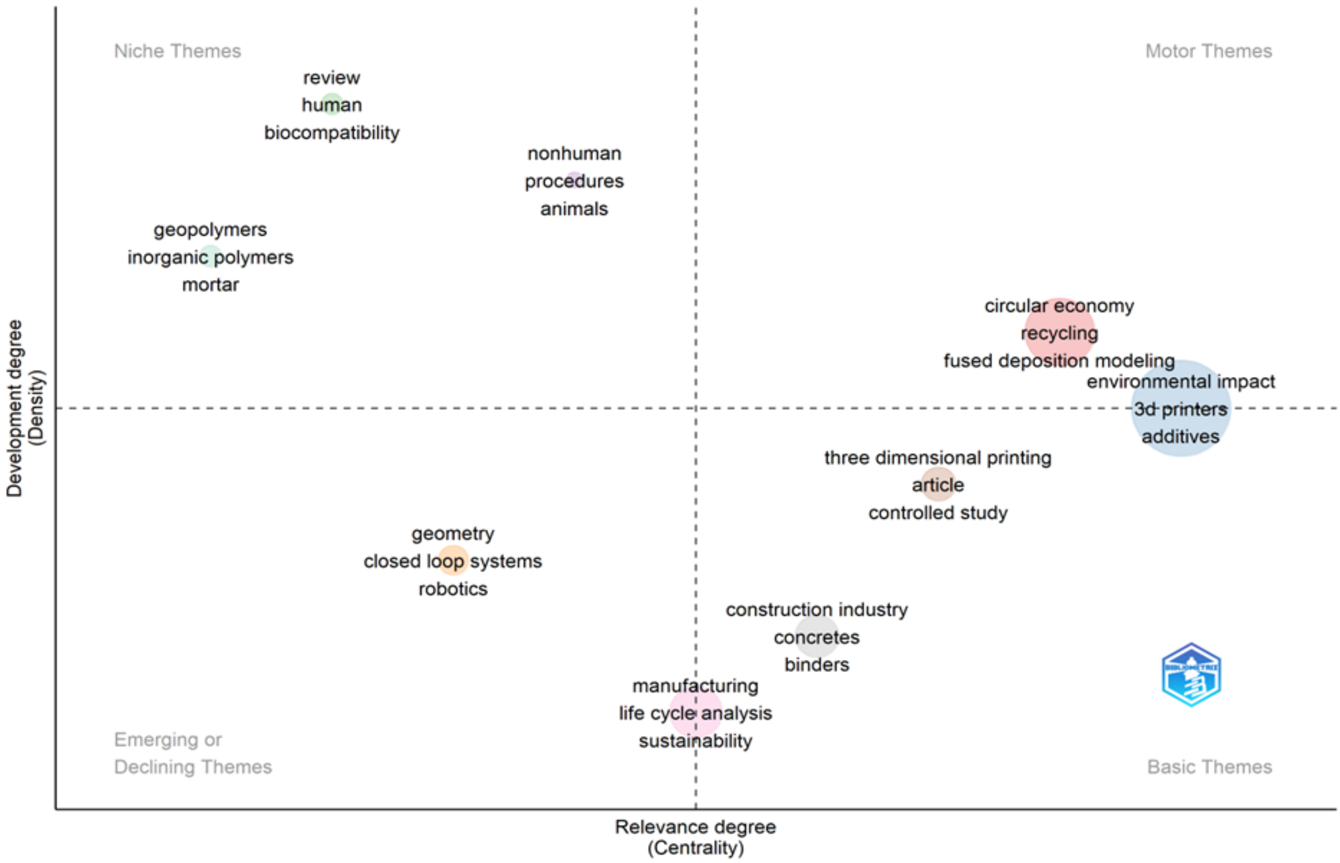

Fig 18: Thematic Visualization Map using Biblioshiny

Understanding the Themes

Niche Themes: These are emerging or specialized topics within the broader field. They often represent areas with high potential for future research. Geopolymers and Inorganic Polymers themes are grouped together as they represent emerging, specialized topics with high potential for future research. Both geopolymers and inorganic polymers are materials that align closely with CE principles:

- Geopolymers are synthesized from aluminosilicate-rich precursors, often utilizing industrial waste products. This aligns with CE by reducing reliance on virgin materials and minimizing waste .
- Inorganic polymers offer superior mechanical properties and thermal stability, making them suitable for specific AM applications in demanding environments.

Emerging or Declining Themes: These themes represent areas that are gaining or losing prominence within the field. Geometry, Closed-Loop Systems, and Robotics,these themes are grouped as they represent areas gaining prominence in the field, focusing on process optimization and automation :

- Geometry emphasizes design optimization in AM processes, leading to enhanced material efficiency and waste reduction.
- Closed-loop systems directly align with CE principles, focusing on recycling and reusing materials within the AM production cycle.
- Robotics represents the integration of automation and AI in AM processes, optimizing sustainability efforts

Motor Themes: These are the core or driving concepts of the field. They are well-established and have a significant influence on other themes. Circular Economy, Recycling, and Fusion Deposition Modelling (FDM),these themes are grouped as the core, driving concepts of the field :

- Circular Economy serves as the overarching framework, emphasizing resource efficiency and waste reduction.
- Recycling focuses on recovering and reprocessing materials for reuse in AM processes.
- FDM is a prevalent AM technique used as a case study for exploring CE integration

Development Degree (Density): This axis measures the level of research activity or development around a theme. Themes with higher density have more research publications. Environmental Impact, 3D Printers, and Additives,these themes are grouped based on their high level of research activity :

- Environmental Impact encompasses the broader ecological consequences of AM.
- 3D Printers focus on the technology itself, including energy efficiency and material compatibility.
- Additives emphasize the importance of material composition and sourcing

Basic Themes: These are foundational concepts that provide the context for the field. They are often broad and general in nature. Construction Industry, Concretes, and Binders, these themes provide the foundational context for the field, particularly in relation to the construction sector :

- Construction Industry highlights a significant application area for CE and AM principles.
- Concretes explore the potential of this common material for AM applications.
- Binders are crucial for the success of AM processes in construction

Relevance Degree (Centrality): This axis measures the importance or centrality of a theme within the research field. Themes closer to the center are typically more central. Life Cycle Assessment (LCA), Sustainability, and Manufacturing, these themes are central to the research field, emphasizing comprehensive assessment and broader context :

- LCA is vital for evaluating the environmental impact of AM processes and products.
- Sustainability encompasses the economic, environmental, and social dimensions of AM.
- Manufacturing highlights the industrial context for AM and CE integration

Sustainability Considerations for Additive Manufacturing-Driven Circular Economy Strategies Centered on Products

The results effectively address sustainability considerations for additive manufacturing (AM) driven circular economy (CE) strategies with a focus on products by investigating various ways in which AM technologies can contribute to circular economy principles through product-oriented approaches. For instance, the study on high modulus biocomposites using cellulose highlights how AM can support sustainable product development through the use of renewable materials. This approach aligns with CE strategies by emphasizing the use of bio-based materials that reduce reliance on non-renewable resources and enhance the sustainability of the products manufactured.

Similarly, the research on laser ablation of poly(lactic acid) (PLA) sheets for medical microcomponents demonstrates how AM can produce sustainable single-use products. PLA, being a biodegradable material, underscores the potential of AM to support environmental sustainability by creating products that contribute to waste reduction and improve lifecycle management. This approach illustrates a practical application of circular economy principles in producing medical components that are both environmentally friendly and functional.

The investigation into distributed recycling for additive manufacturing, particularly using materials from windshield wiper blades, further exemplifies how AM can integrate recycled products into manufacturing processes. This study highlights the importance of incorporating recycled materials into AM practices, thereby promoting sustainable product design and reducing environmental impact. Overall, these examples collectively show how AM can facilitate product design and manufacturing strategies that align with circular economy principles, focusing on sustainable product life cycles and minimizing environmental impact.

Sustainability Considerations for Additive Manufacturing-Driven Circular Economy Strategies Centered on Materials

In addressing sustainability considerations related to materials, the results effectively cover how AM can utilize and manage various materials within a circular economy framework. The study on ethyl lactate production from post-consumer poly(lactic acid) (PLA) illustrates the link between AM and material recycling strategies. By focusing on the chemical recycling of PLA to produce ethyl lactate, this research highlights how

AM can be connected with strategies that extend the lifecycle of materials and ensure their reuse.

Another significant example is the utilization of agricultural waste, specifically tomato plant residues, to create biodegradable composites. This approach demonstrates how AM can incorporate waste materials into new products, thereby contributing to resource efficiency and sustainability. By transforming agricultural waste into valuable materials for AM, this research supports the principles of circular economy by promoting the use of by-products and reducing overall waste.

The recycling of biobags into 3D printing materials further illustrates how recycled polymers from packaging waste can be utilized in AM processes. This example showcases how AM can facilitate the reuse of materials and reduce dependence on virgin resources, aligning with circular economy goals. These instances collectively demonstrate how AM can drive sustainability through effective material management, focusing on recycling, repurposing, and efficient use of resources.

Sustainability Considerations for Additive Manufacturing-Driven Circular Economy Strategies Focused on Business Models and Product Innovation

The results also address sustainability considerations related to business models and product innovation by exploring the intersection of AM and circular economy principles in these areas. The development of an instrumented open-source filament extruder for research and education explains how AM can influence business models by promoting accessible and adaptable manufacturing technologies. This approach aligns with CE strategies by potentially impacting material reuse and fostering innovation in educational contexts.

Additionally, the research on technical pathways for distributed recycling of polymer composites dives deep into how distributed recycling and AM can be integrated into business models for recycling and product innovation. Specifically, the case study of windshield wiper blades highlights how business models can adapt to incorporate recycling and AM practices, particularly for specialized applications. This research underscores the potential for AM to drive innovative approaches in business models and product development.

Although not explicitly detailing business models, the Colombian sustainability perspective on fused deposition modeling highlights a focus on sustainability in AM practices. This study can inform innovative approaches and strategies within the context of circular economy principles, contributing to the development of sustainable business models and product innovation. Collectively, these examples illustrate how AM and circular economy strategies intersect to influence business models and drive product innovation, ultimately supporting more sustainable manufacturing practices.

4.3 Limitations

This study's limitations include reliance on data from a single database (Scopus), which may not capture all relevant publications. Additionally, the focus on bibliometric analysis means that qualitative insights from interviews or case studies are not included. Future research could address these limitations by incorporating a more diverse set of data sources and methodologies.

4.4 Conclusion

The provided thematic framework effectively captures the key dimensions of the research area. The grouping of themes reflects a logical progression from material focus to technological advancements, core concepts, environmental and technological impacts, industry application, and research methodology.

Chapter 5: Discussion

5.1 - Introduction

This chapter examines the literature review findings, emphasizing their significance, implications, and alignment with the research objectives. The analysis will critically examine the relevance of these findings to the research questions, providing an interpretation that integrates the varied themes identified in the literature.

5.2 - Overview of 3D Printing in Construction

The research findings underscore the multifaceted nature of incorporating 3D printing into the construction industry. This innovation promises to revolutionize construction practices by enhancing efficiency, reducing waste, and promoting sustainability. However, the complexity of integrating 3D printing technologies within existing construction frameworks presents significant challenges.

5.3 - The Role of Geopolymers and Inorganic Polymers

Geopolymers and inorganic polymers are emerging as pivotal materials in the advancement of 3D printing in construction. These materials offer superior environmental benefits due to their lower carbon footprint compared to traditional concrete. The literature highlights their potential to significantly reduce the environmental impact of construction activities. However, widespread adoption is hindered by factors such as cost, material availability, and the need for specialized knowledge.

5.4 - The Integration of Robotics and Closed-Loop Systems

Robotics and closed-loop systems are integral to optimizing 3D printing processes in construction. Robotics enhance precision and efficiency, while closed-loop systems ensure sustainable practices by recycling materials and minimizing waste. The literature indicates that while these technologies are promising, their implementation is fraught with challenges, including high initial investment costs and the need for extensive training and adaptation of current practices.

5.5 - Circular Economy and Recycling in 3D Printing

The circular economy (CE) framework is increasingly relevant in 3D printing, particularly in construction. CE promotes recycling and reusing materials, which aligns well with the sustainable objectives of 3D printing. The literature identifies recycling as a critical component of 3D printing's contribution to CE, but also notes the complexities in establishing effective recycling processes for construction materials. There is a need for more robust systems to facilitate the recycling of 3D printed materials.

5.6 - Environmental Impact and Life Cycle Assessment (LCA)

The environmental impact of 3D printing in construction is a significant focus in the literature. Life Cycle Assessment (LCA) is a crucial tool for evaluating this impact. LCA provides a comprehensive analysis of the environmental consequences of 3D printing, from raw material extraction to end-of-life disposal. The findings highlight the importance of LCA in identifying areas where environmental performance can be improved. However, the literature also points to the need for standardized LCA methodologies tailored to 3D printing in construction.

5.7 - Current Trends

Fusion Deposition Modelling (FDM) and the use of various additives are prevalent trends in 3D printing within the construction sector. FDM is favored for its versatility and relatively low cost. Additives enhance material properties, making them more suitable for specific construction applications. Sustainability remains a core theme, with the literature emphasizing the need for sustainable practices throughout the 3D printing process. The challenge lies in balancing innovation with sustainability, ensuring that new materials and methods do not compromise environmental goals.

5.8 - Challenges and Opportunities in Manufacturing and Construction

Manufacturing and construction industries face numerous challenges in adopting 3D printing technologies. These include technical barriers, such as the need for new design paradigms and the adaptation of construction codes and standards. Opportunities abound, particularly in the potential for cost savings, reduced construction times, and enhanced design flexibility. The literature suggests that overcoming these challenges requires a promising effort from industry stakeholders, policymakers, and researchers.

5.9 - Validity and Reliability of the Research

The research is grounded in a robust analysis of secondary sources, including peer-reviewed journals, books, and reputable industry reports. This ensures both the validity and reliability of the findings. The consistency of perspectives across different sources enhances the credibility of the conclusions drawn.

5.10 - Limitations of the Research

Several limitations were encountered during this research. The reliance on secondary data means that real-world applicability may vary. Additionally, the growing pace of technological advancements in 3D printing means that some findings may become outdated quickly. Time constraints and word limits also restricted the depth of exploration into some topics.

5.11 - Conclusion

This chapter has synthesized the literature reviewed, identifying key themes and their implications for the research objectives. The integration of 3D printing in construction has significant promise but also presents substantial challenges. The findings highlight the importance of sustainability, innovative materials, and advanced technologies in realizing the full potential of 3D printing in construction. Future research should focus on addressing the gaps identified, particularly in areas such as material recycling, consumer behavior, and the role of SMEs in adopting new technologies.

Chapter 6: Conclusions and Recommendations

6.1 Introduction

This chapter summarizes the findings of this research, which aimed to explore the application of circular economy (CE) principles within additive manufacturing (AM) and their impact on sustainability across various sectors. Through a comprehensive bibliometric analysis, this study has identified key trends, themes, and gaps in the existing literature, providing insights into the current state and future directions of this field.

6.2 Critical Reflections

This section reflects on the extent to which the research aims and objectives have been achieved and discusses potential areas for improvement.

The aim of this research was to investigate the potential of AM for achieving sustainability through CE principles. This has been addressed through a systematic bibliometric analysis of relevant literature from the Scopus database, covering the period from 2000 to 2023.

Objectives of the Research

1. To Conduct a systematic bibliometric analysis of the literature on CE principles in AM.

Achieved: The use of Biblioshiny and VOSviewer for bibliometric analysis aligns with this objective. The analysis provided an overview of the existing literature, which was detailed in Chapter 3.

2. To identify the publication trends in the field of CE in AM.

Achieved: Chapter 4 successfully detailed the publication trends, noting significant increases starting from 2015 and a peak around 2020.

3. To identify the prominent authors and institutions contributing to this field.

Achieved: The report identified key authors and institutions and provided a table with detailed contributions that align with this objective.

4. To identify and analyze the main research themes in this field.

Achieved: Thematic analysis was conducted using keyword co-occurrence maps, revealing core themes such as sustainability, recycling, and specific AM techniques.

5. To assess the sustainability impacts of CE applications in AM across different sectors.

Partially Achieved: While the analysis provided an overview, the assessment of sector-specific impacts was not as detailed, detailed sector-specific impacts were less comprehensively covered due to the limitations of bibliometric data.. Future research could benefit from more in-depth case studies focusing on individual sectors.

6. To identify research gaps and propose future research directions to enhance the sustainability of AM practices.

Partially Achieved: Several research gaps were identified, and recommendations for future research were provided but up to what extend and if it’s applicable to all sectors is still not clear.

What could have been better: For a more practical approach, case studies of industries that implemented CE in AM and interviews with manufacturing leads could have given practical insights about the sustainability aspects. A comparison between these method results obtained using theoretical databases and Primary data from manufacturing units would have given a clear picture of the gaps present.

6.3 Conclusion

The research has successfully addressed the primary question: "To what extent are circular economy principles applied in additive manufacturing, and how do these applications impact the sustainability of manufacturing processes?" The findings indicate a growing integration of CE principles in AM, with significant contributions from various sectors such as aerospace, automotive, healthcare, and consumer goods. However, challenges remain, particularly in scaling these practices and addressing infrastructure and policy barriers.

6.4 Recommendations for Future Research

1. Development of standardized metrics for assessing the circularity and sustainability of AM processes and products.

2. Investigation of policy frameworks that can support the transition to CE in AM across different geographical contexts.

3. Examination of the long-term economic and environmental impacts of adopting CE principles in AM at an industry-wide scale.

Appendices:

1. Risk Management

Risk Category	Description	Likelihood	Impact	Mitigation Strategy	Monitoring
Data Availability	Limited access to or availability of relevant bibliometric data from databases like Scopus, leading to incomplete analysis.	Medium	High	Use multiple databases (e.g., Web of Science, Google Scholar).	Regularly check data availability and backup sources.
Data Quality	Poor quality or incomplete data entries in bibliometric datasets, affecting the accuracy of analysis and results.	Medium	High	Implement data cleaning procedures before analysis. .	Conduct periodic quality checks on the dataset.
Analysis Tools	Technical issues or limitations with bibliometric analysis tools like Biblioshiny and VOSviewer that could delay analysis.	Medium	Medium	Ensure software and tools are updated to the latest versions. - Have backup tools or alternative methods ready for analysis	- Test tools before extensive analysis and maintain regular backups.
Interpretation of Results	Misinterpretation of bibliometric analysis results, leading to incorrect conclusions or recommendations	Low	High	Cross-verify findings with subject matter experts. - Conduct a peer review of the analysis section to ensure validity.	Involve external reviewers during key stages of analysis.
Scope Creep	Unplanned changes or expansions in	Medium	Medium	Stick to the defined research	Regularly review project

	project scope, such as adding additional sectors or themes, that increase complexity and workload			scope and objectives. - Document and assess any potential changes to ensure they align with the research goals.	scope and objectives with stakeholders
Time Management	Delays in project timelines due to extended data collection, analysis, or writing phases, potentially missing deadlines	High	High	Develop a detailed project timeline with milestones. - Prioritize tasks and allocate sufficient time for data collection and analysis.	Regularly track progress against the timeline and adjust as needed
Technological Risks	Risk of software or hardware failure during the analysis phase, leading to potential loss of data or time	Medium	Medium	- Regularly back up all data and analysis outputs. - Use reliable and secure hardware systems.	Implement regular data backup procedures and check system health.