



A CONCEPTUAL CAM-5 FRAMEWORK FOR CIRCULAR ADDITIVE MANUFACTURING IN ENGINEERING AND TEXTILE APPLICATIONS

Scientific paper
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ABSTRACT: The growing demand for sustainable manufacturing has accelerated the adoption of circular economy (CE) principles across engineering and industrial sectors. Among advanced manufacturing technologies, additive manufacturing (AM) has emerged as a key enabler of sustainable production due to its ability to minimize material waste, optimize resource utilization, support product customization, and facilitate decentralized manufacturing. Simultaneously, both engineering and textile industries are undergoing a transition toward circular production systems driven by increasing environmental concerns, resource efficiency requirements, and digital transformation. This paper presents a critical review of the role of circular economy principles in additive manufacturing, with particular emphasis on sustainable engineering and textile applications. The study analyzes the integration of circular economy strategies throughout the additive manufacturing lifecycle, including sustainable material selection, digital product design and simulation, resource-efficient manufacturing, circular product lifecycle management, and recycling within closed-loop manufacturing systems. Current opportunities, technological challenges, and future research directions are also discussed to provide a comprehensive overview of recent developments in this rapidly evolving field. Based on the findings obtained from the literature review, the authors propose the CAM-5 (Circular Additive Manufacturing – Five Pillars) conceptual framework, which integrates five complementary pillars for implementing circular economy principles in additive manufacturing: Sustainable Materials, Digital Design & Simulation, Resource-Efficient Additive Manufacturing, Circular Product Lifecycle, and Recycling & Closed-Loop Manufacturing. The proposed framework provides a systematic perspective for integrating sustainability principles into additive manufacturing while demonstrating its potential contribution to engineering and textile applications. The proposed CAM-5 framework may serve as a conceptual foundation for future research focused on sustainability assessment, industrial case studies, and the practical implementation of circular manufacturing strategies within engineering and textile production systems.



Keywords: Additive manufacturing; Circular economy; Sustainable manufacturing; CAM-5 framework; Sustainable engineering; Textile industry.

KONCEPTUALNI CAM-5 OKVIR ZA CIRKULARNU ADITIVNU PROIZVODNJU U INŽENJERSKIM I TEKSTILNIM PRIMENAMA

APSTRAKT: Sve veća potreba za održivom proizvodnjom ubrzala je primenu principa cirkularne ekonomije (CE) u inženjerskim i industrijskim sektorima. Među savremenim proizvodnim tehnologijama, aditivna proizvodnja (AM) izdvojila se kao jedan od ključnih pokretača održive proizvodnje zahvaljujući mogućnosti smanjenja otpada materijala, optimizacije korišćenja resursa, podrške prilagođenoj proizvodnji i decentralizovanih proizvodnih procesa. Istovremeno, inženjerska i tekstilna industrija prolaze kroz tranziciju ka cirkularnim proizvodnim sistemima, podstaknutu rastućim ekološkim zahtevima, potrebom za efikasnijim korišćenjem resursa i procesima digitalne transformacije. U ovom radu prikazan je kritički pregled uloge principa cirkularne ekonomije u aditivnoj proizvodnji, sa posebnim osvrtom na održive primene u inženjerstvu i tekstilnoj industriji. Analizirana je integracija strategija cirkularne ekonomije kroz celokupan životni ciklus aditivne proizvodnje, uključujući izbor održivih materijala, digitalno projektovanje i simulaciju proizvoda, resursno efikasnu proizvodnju, upravljanje cirkularnim životnim ciklusom proizvoda i reciklažu u okviru zatvorenih proizvodnih sistema. Takođe su razmotrene aktuelne mogućnosti, tehnološki izazovi i budući pravci istraživanja kako bi se pružio sveobuhvatan pregled savremenih dostignuća u ovoj brzo razvijajućoj oblasti. Na osnovu rezultata pregleda literature, autori predlažu konceptualni okvir CAM-5 (Circular Additive Manufacturing – Five Pillars), koji integriše pet komplementarnih stubova za primenu principa cirkularne ekonomije u aditivnoj proizvodnji: održivi materijali, digitalno projektovanje i simulacija, resursno efikasna aditivna proizvodnja, cirkularni životni ciklus proizvoda i reciklaža u okviru zatvorenih proizvodnih sistema. Predloženi okvir pruža sistematski pristup integraciji principa održivosti u aditivnu proizvodnju, istovremeno ukazujući na njen potencijal za primenu u inženjerstvu i tekstilnoj industriji. Predloženi CAM-5 okvir može predstavljati konceptualnu osnovu za buduća istraživanja usmerena na procenu održivosti, industrijske studije slučaja i praktičnu primenu strategija cirkularne proizvodnje u inženjerskim i tekstilnim proizvodnim sistemima.

Ključne reči: Aditivna proizvodnja; Cirkularna ekonomija; Održiva proizvodnja; CAM-5 okvir; Održivo inženjerstvo; Tekstilna industrija.

1. INTRODUCTION

The transition towards sustainable manufacturing has become one of the main priorities of modern industry due to increasing environmental concerns, resource depletion, climate



change, and stricter environmental regulations. Manufacturing companies are expected to reduce their environmental footprint while maintaining productivity, product quality, and economic competitiveness. As a result, the concept of the circular economy (CE) has gained significant attention as an alternative to the traditional linear production model, promoting the efficient use of resources, waste minimization, material recovery, and product life-cycle extension [1,7,10]. Unlike previous review studies that primarily discuss circular economy principles or additive manufacturing independently, this paper integrates these concepts within a unified perspective applicable to both engineering and textile industries. Furthermore, the study proposes the CAM-5 conceptual framework as a systematic representation of the key pillars supporting circular additive manufacturing. Unlike conventional manufacturing systems based on the "take–make–dispose" approach, circular economy principles encourage the continuous circulation of materials and products through strategies such as reducing material consumption, reusing components, repairing products, remanufacturing, and recycling end-of-life materials. The implementation of these strategies contributes not only to environmental protection but also to improved resource efficiency, lower production costs, and increased industrial resilience [3,4].

Among emerging manufacturing technologies, additive manufacturing (AM) has been recognized as one of the key enablers of sustainable production. By producing components layer by layer directly from digital models, additive manufacturing significantly reduces material waste compared with conventional subtractive manufacturing processes. In addition, AM supports decentralized production, rapid prototyping, product customization, spare-part manufacturing, and the utilization of recycled or bio-based materials, making it an important technology within circular manufacturing systems [5,6,8,11].

In parallel, the textile industry is undergoing a profound transformation driven by sustainability requirements, circular economy policies, and digital manufacturing technologies. The sector is facing increasing pressure to reduce textile waste, improve material efficiency, decrease energy and water consumption, and adopt environmentally responsible production practices. Consequently, innovative manufacturing technologies, including additive manufacturing, are attracting growing interest for their potential to support sustainable product development, customized textile accessories, wearable products, rapid tooling, spare parts for textile equipment, and engineering solutions integrated into textile production systems [4,12].

Although additive manufacturing and textile production represent different industrial domains, they share common objectives related to sustainable manufacturing, efficient resource utilization, digitalization, and circular material management. Additive manufacturing should therefore be viewed not as a replacement for conventional textile production, but as a complementary technology capable of supporting the development of more flexible, sustainable, and resource-efficient engineering and textile manufacturing systems.

The aim of this paper is to review recent developments related to circular economy strategies in additive manufacturing and to discuss their contribution to sustainable engineering and textile applications. Particular attention is given to material efficiency, circular design principles, recycling opportunities, sustainable materials, and future



directions that may facilitate the integration of circular economy concepts into advanced manufacturing systems.

2. CIRCULAR ECONOMY AS A FOUNDATION FOR SUSTAINABLE MANUFACTURING

2.1. Circular Economy Principles

The circular economy has evolved into one of the most influential frameworks for achieving sustainable industrial development by promoting the continuous use of materials, products, and resources throughout their life cycle. Unlike the traditional linear economy, which relies on extracting raw materials, manufacturing products, and disposing of them after use, the circular economy aims to preserve the value of materials for as long as possible while minimizing waste generation and environmental impacts [7,10].

The implementation of circular economy principles is commonly based on value-retention strategies that seek to extend product life, reduce dependence on virgin resources, and improve resource efficiency. While different frameworks have been proposed in the literature, manufacturing systems frequently adopt the 4R concept, consisting of Reduce, Reuse, Recycle, and Recover, as a practical approach for implementing circular manufacturing strategies. In additive manufacturing, these principles are directly associated with material optimization, product redesign, remanufacturing, polymer recycling, and energy recovery, making the 4R framework particularly suitable for evaluating sustainability performance.

- Reduce focuses on minimizing raw material consumption, production waste, and energy use through optimized product design and manufacturing processes.
- Reuse aims to extend the service life of products and components by enabling repeated use with minimal additional processing.
- Recycle involves converting end-of-life materials into secondary raw materials that can be reintroduced into new manufacturing processes.
- Recover refers to extracting value from materials that cannot be reused or recycled, primarily through energy recovery or other recovery technologies.

Recent studies emphasize that successful implementation of circular economy principles requires more than material recycling alone. Effective circular manufacturing integrates product design, digital technologies, reverse logistics, remanufacturing, and lifecycle management into a comprehensive production strategy. Consequently, circular economy should be considered a systemic transformation of manufacturing rather than a collection of isolated environmental practices.

Table 1: Overview of the 4R principles in sustainable manufacturing

Principle	Objective	Example in Additive Manufacturing	Potential Textile Application
Reduce	Minimize material and energy consumption	Optimized part design, lightweight structures	Material-efficient product design

Reuse	Extend product life	Reuse of tooling and fixtures	Reusable textile accessories
Recycle	Return materials into production	Recycled PLA/PETG filaments	Recycled textile-polymer composites
Recover	Recover value from waste	Energy recovery from polymer waste	Recovery of textile production waste

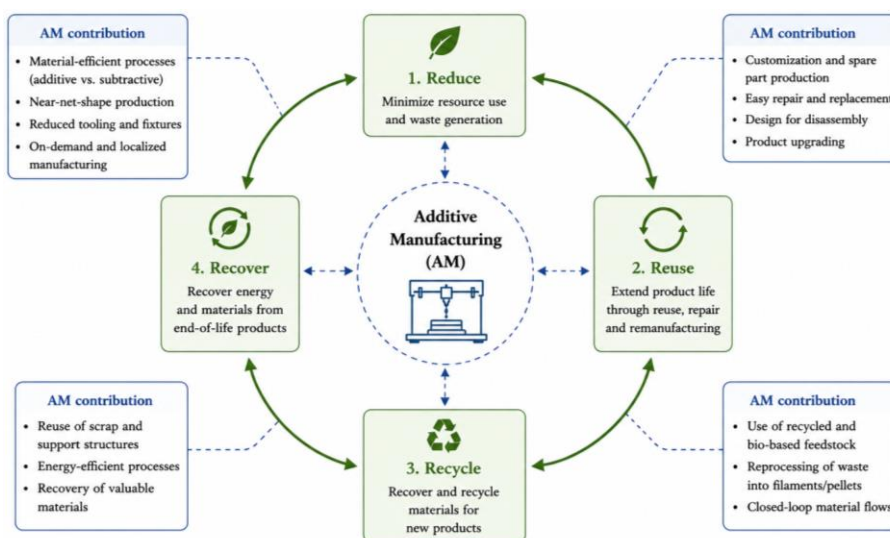


Figure 1: Relationship between the 4R principles of the circular economy and the contribution of additive manufacturing to sustainable resource management

3. ADDITIVE MANUFACTURING AS AN ENABLER OF THE CIRCULAR ECONOMY

Additive manufacturing has become one of the most promising technologies supporting the transition towards circular manufacturing systems. Unlike conventional subtractive manufacturing, where a significant portion of raw material is removed during machining operations, additive manufacturing fabricates components layer by layer, allowing material to be deposited only where required. This manufacturing approach contributes to improved material utilization, reduced waste generation, and greater production flexibility [5, 6, 8]. One of the major advantages of additive manufacturing from a circular economy perspective is its ability to support localized and on-demand production. Manufacturing products close to the point of use reduces transportation requirements, inventory levels, and associated carbon emissions. Furthermore, digital manufacturing enables rapid design modifications and production without additional tooling, thereby extending product functionality while minimizing unnecessary resource consumption [9,11].

Material circularity represents another important aspect of additive manufacturing. Recent advances in polymer processing have enabled the production of recycled and bio-based filaments suitable for FDM technologies. Materials such as recycled PLA, recycled PETG, recycled ABS, and bio-derived polymers contribute to reducing dependence on virgin raw materials while promoting closed-loop material cycles. However, maintaining consistent mechanical performance and process stability remains one of the primary challenges associated with recycled feedstock materials [2,5].

In addition to material efficiency, additive manufacturing facilitates product repair, redesign, and remanufacturing. Instead of replacing entire products, damaged components can be reproduced individually, extending product life and reducing waste generation. This capability is particularly important for engineering industries, where spare parts often become unavailable after product discontinuation, as well as for textile manufacturing systems requiring customized tooling or replacement components.

Digitalization further strengthens the contribution of additive manufacturing to circular economy implementation. Computer-aided design, topology optimization, simulation tools, and digital inventories reduce unnecessary physical stock while enabling rapid product customization and decentralized manufacturing. Consequently, additive manufacturing is increasingly recognized as a key enabling technology supporting Industry 4.0 and Industry 5.0 concepts within sustainable production systems.

Despite these advantages, several challenges still limit the large-scale implementation of circular economy principles in additive manufacturing. These include limited availability of standardized recycled materials, variability in feedstock quality, energy consumption during printing, insufficient recycling infrastructure, and the absence of internationally accepted sustainability assessment methodologies. Addressing these challenges will be essential for achieving fully circular additive manufacturing systems in future industrial applications.

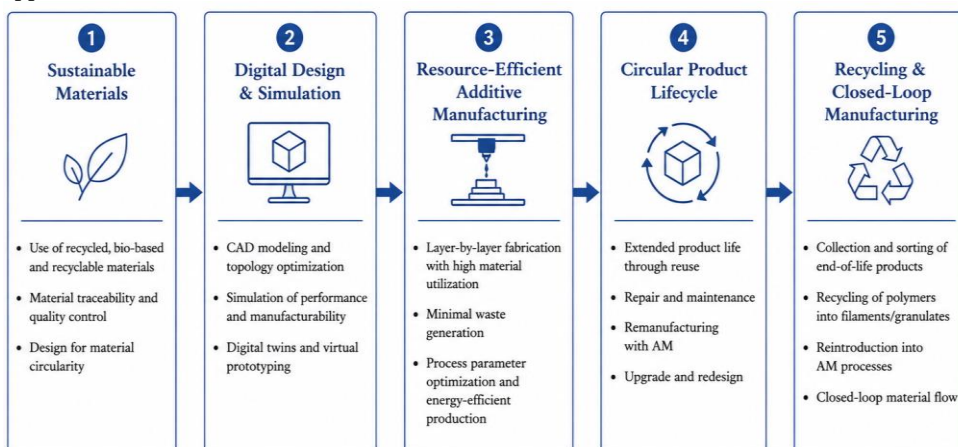


Figure 2: Key sustainability stages through which additive manufacturing supports circular economy implementation



4. ENGINEERING AND TEXTILE APPLICATIONS OF CIRCULAR ADDITIVE MANUFACTURING

The implementation of circular economy principles through additive manufacturing has expanded rapidly across various engineering disciplines, offering innovative solutions for sustainable product development, resource optimization, and waste reduction. Owing to its flexibility, digital workflow, and efficient material utilization, additive manufacturing is increasingly recognized as a valuable production technology capable of supporting both engineering and textile industries in their transition towards more sustainable manufacturing systems [4,8].

4.1 Engineering Applications

Within engineering industries, additive manufacturing enables the production of lightweight structures, functional prototypes, customized products, tooling, molds, and spare parts with considerably lower material waste than conventional manufacturing processes. The possibility of manufacturing components on demand contributes to shorter supply chains, reduced inventory requirements, and lower transportation-related emissions. Moreover, topology optimization and digital design techniques allow engineers to minimize material consumption while maintaining the required mechanical performance, thereby supporting circular economy objectives [5,11]. Another important contribution of additive manufacturing is the repair and remanufacturing of engineering components. Instead of replacing complete assemblies, damaged parts can be reproduced individually, extending product life cycles and reducing the demand for new raw materials. Such practices align closely with circular economy strategies focused on value retention and resource efficiency.

4.2 Textile Applications

The textile industry is increasingly exploring additive manufacturing as a complementary technology rather than a replacement for conventional textile production. Applications include customized textile accessories, garment fasteners, buttons, buckles, wearable products, smart textiles, rapid prototyping, and the production of spare parts for textile machinery. Additive manufacturing also enables greater product personalization and supports small-batch production, which is becoming increasingly important in modern textile markets characterized by rapidly changing consumer demands [11].

From a sustainability perspective, additive manufacturing contributes to reducing production waste and improving material efficiency in textile-related applications. The adoption of recycled polymers and bio-based materials further supports the development of environmentally responsible products while promoting circular material flows. Furthermore, digital production allows manufacturers to produce components only when required, reducing overproduction and inventory, which are among the major sustainability challenges in the textile sector.

The integration of additive manufacturing with digital design, sustainable materials, and circular economy principles demonstrates considerable potential for supporting future

engineering and textile production systems. As Industry 5.0 concepts continue to evolve, collaboration between advanced manufacturing technologies and sustainable product development is expected to play an increasingly important role in achieving environmentally responsible industrial growth.

Table 2: Potential applications of additive manufacturing supporting circular economy principles

Circular strategy	Engineering applications	Textile applications
Reduce	Lightweight components	Optimized product design
Reuse	Repair of spare parts	Reusable accessories
Recycle	Recycled polymer filaments	Recycled textile-polymer products
Recover	Material recovery	Textile waste valorization

5. PROPOSED CAM-5 CONCEPTUAL FRAMEWORK FOR CIRCULAR ADDITIVE MANUFACTURING

The reviewed literature demonstrates that circular economy implementation in additive manufacturing extends beyond material recycling and requires a comprehensive approach that considers the entire product life cycle. Although numerous studies discuss sustainability, material efficiency, and digital manufacturing independently, limited attention has been given to integrating these concepts into a unified framework applicable to both engineering and textile industries.

The proposed CAM-5 framework consists of five interconnected pillars that collectively represent the essential elements required for implementing circular economy principles within additive manufacturing systems. Rather than describing a sequential manufacturing process, the framework emphasizes the integration of complementary sustainability dimensions that should be considered simultaneously throughout the product life cycle. Based on the findings obtained from the reviewed literature, the authors propose the CAM-5 conceptual framework (Figure 3), which integrates five complementary pillars supporting circular additive manufacturing [2,5,7]. The first pillar, sustainable material selection, focuses on choosing environmentally responsible materials, including recyclable polymers, recycled feedstock, and bio-based materials. Material selection directly affects the environmental impact of manufacturing and determines the potential for future material recovery and recycling.

The second pillar involves digital design and product optimization. Modern computer-aided design (CAD), simulation tools, and topology optimization techniques enable the development of lightweight and material-efficient products before manufacturing begins. This approach minimizes unnecessary material consumption while maintaining the required product functionality.



The third pillar represents the additive manufacturing process, where components are fabricated using layer-by-layer deposition. Compared with conventional manufacturing processes, additive manufacturing provides improved material utilization, reduced waste generation, rapid product customization, and decentralized production, thereby supporting several circular economy objectives simultaneously.

Following product utilization, the framework incorporates reuse, repair, and remanufacturing strategies. Instead of replacing complete products, damaged or obsolete components can be repaired or reproduced individually using additive manufacturing technologies. This significantly extends product service life while reducing demand for virgin raw materials.

The fifth pillar includes recycling and material recovery, where end-of-life polymer materials are reprocessed into secondary feedstock suitable for new manufacturing cycles. The continuous implementation of these activities establishes a closed-loop manufacturing system capable of improving resource efficiency and reducing environmental impacts.

The proposed CAM-5 conceptual framework demonstrates that successful implementation of circular economy principles cannot rely on material recycling alone. Instead, sustainable additive manufacturing requires the integration of five complementary pillars encompassing sustainable materials, digital product development, resource-efficient production, circular product life-cycle management, and recycling strategies. Although conceptual in nature, the proposed framework may serve as a foundation for future research, industrial implementation, and sustainability assessment within engineering and textile manufacturing systems.

Unlike existing circular economy frameworks, CAM-5 integrates sustainability principles specifically from the perspective of additive manufacturing while simultaneously considering engineering and textile applications.

Table 3: Comparison between conventional manufacturing and circular additive manufacturing

Aspect	Conventional Manufacturing	Circular Additive Manufacturing
Material use	High waste	Optimized material utilization
Production	Mass production	On-demand production
Repair	Limited	Easy repair/remanufacturing
Recycling	End-of-life	Closed-loop recycling
Sustainability	Linear	Circular

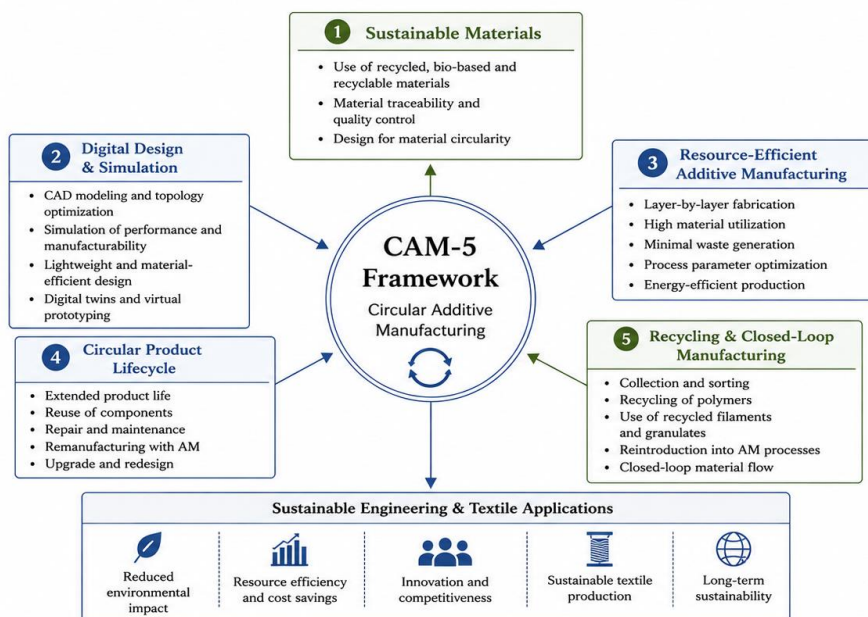


Figure 3: The proposed CAM-5 conceptual framework for integrating circular economy principles into additive manufacturing for sustainable engineering and textile applications (developed by the authors)

6. FUTURE RESEARCH DIRECTIONS

The transition toward sustainable manufacturing requires continuous development of innovative technologies and integrated management strategies that support circular economy implementation. Although additive manufacturing has demonstrated considerable potential for improving material efficiency and reducing production waste, several technological and organizational challenges remain before fully circular manufacturing systems can be achieved [5,7].

One of the most promising research directions involves the development of advanced sustainable materials. Future investigations should focus on improving the quality, mechanical performance, and recyclability of recycled polymer feedstock while expanding the application of bio-based and biodegradable materials suitable for additive manufacturing processes [2,8]. Material traceability and certification systems will also become increasingly important for ensuring reliable circular material flows.

Digitalization is expected to play an essential role in the evolution of circular manufacturing systems. The integration of digital twins, artificial intelligence, machine learning, and real-time process monitoring can significantly improve process optimization,



predictive maintenance, material utilization, and decision-making throughout the manufacturing life cycle. These technologies are closely aligned with the principles of Industry 5.0, which emphasizes sustainable, resilient, and human-centered production systems [4].

Another important research direction concerns the development of comprehensive sustainability assessment methodologies. Future studies should combine environmental, economic, and technical performance indicators to evaluate additive manufacturing processes more objectively. Approaches such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) (Finnveden et al., 2009), and multi-criteria decision-making (MCDM) methods, including AHP, TOPSIS, and PROMETHEE, may provide valuable tools for selecting sustainable materials and manufacturing strategies [13].

Furthermore, greater collaboration between engineering and textile industries is expected to accelerate the implementation of circular manufacturing principles. The increasing use of recycled materials, customized production, smart textiles, wearable technologies, and digital manufacturing creates new opportunities for integrating additive manufacturing into sustainable textile production systems [12].

Finally, future research should focus on validating the proposed CAM-5 conceptual framework through industrial case studies, comparative sustainability assessments, and practical implementation within manufacturing environments [5,7]. Such validation would enable further refinement of the framework and support its application as a decision-support tool for sustainable engineering and textile manufacturing.

The proposed framework may also serve as a foundation for future quantitative studies aimed at evaluating circular manufacturing performance through sustainability indicators and decision-support methodologies.

7. CONCLUSION

The transition from linear production models toward circular manufacturing systems has become one of the key priorities for achieving sustainable industrial development. This paper reviewed the fundamental principles of the circular economy and discussed the contribution of additive manufacturing to improving material efficiency, reducing production waste, extending product life cycles, and promoting resource recovery. The analysis confirms that additive manufacturing represents an important enabling technology for supporting circular economy implementation in both engineering and textile-related applications.

The findings indicate that additive manufacturing contributes to sustainability through optimized material utilization, decentralized and on-demand production, product customization, and the increasing use of recycled and bio-based materials. These characteristics enable manufacturers to reduce environmental impacts while simultaneously improving production flexibility and resource efficiency.

The review also highlights that engineering, and textile industries share common sustainability objectives despite representing different manufacturing sectors. Circular economy strategies, supported by digital manufacturing technologies, provide new

opportunities for reducing waste generation, improving product life-cycle management, and promoting environmentally responsible production practices. Consequently, additive manufacturing should be considered a complementary technology capable of supporting the transition toward more sustainable manufacturing systems.

As the main contribution of this study, the authors proposed the CAM-5 conceptual framework, which integrates five complementary pillars for implementing circular economy principles in additive manufacturing: sustainable materials, digital design and simulation, resource-efficient additive manufacturing, circular product lifecycle, and recycling with closed-loop manufacturing. The proposed framework provides a systematic perspective that may facilitate future integration of sustainability principles into engineering and textile manufacturing systems.

Although the proposed framework is conceptual in nature, it establishes a foundation for future research focused on its practical validation through industrial case studies, sustainability assessment methodologies, and decision-support approaches. Further investigations may also explore the integration of Industry 5.0 technologies, artificial intelligence, digital twins, and life-cycle assessment methods to enhance the sustainability of additive manufacturing processes and strengthen circular manufacturing strategies.

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