JOURNAL OF ADVANCED ENGINEERING AND INNOVATION
Volume 2, Issue 2, December 2024 | pp. 72-81
https://doi.org/10.54518/jaei.2.2.2024.1297

Circular Economy in Sustainable Engineering Material Development: A Literature Review

Ahmad Fadhilah Rivaldi[1]

Sekolah Tinggi Teknologi Terpadu Nurul Fikri, Indonesia[1]

ABSTRACT

The development of sustainable engineering materials has become an essential strategy for reducing natural resource consumption, minimizing waste generation, and supporting the transition toward more resource-efficient production systems. The circular economy introduces a new paradigm by optimizing material utilization throughout its life cycle through reduction, reuse, repair, remanufacturing, and recycling strategies. This article aims to review recent advances in the application of the circular economy to sustainable engineering material development based on scientific publications from 2019 to 2023. A Systematic Literature Review (SLR) approach was employed using literature collected from Google Scholar and selected according to topic relevance and publication quality. The findings indicate that circular economy implementation has accelerated the development of recycled materials, biomaterials, geopolymers, and environmentally friendly composites supported by advances in manufacturing technologies, additive manufacturing, artificial intelligence, and sustainability assessment methods such as Life Cycle Assessment and Material Flow Analysis. Despite challenges related to material standardization, recycled material quality, technological readiness, and economic feasibility, the circular economy offers significant potential to improve resource efficiency, reduce environmental impacts, and promote the development of more sustainable engineering material systems.

Keywords: *Circular Economy, Life Cycle Assessment, Sustainable Engineering Materials, Systematic Literature Review, Sustainable Materials*

CORRESPONDING AUTHOR:
Ahmad Fadhilah Rivaldi
Sekolah Tinggi Teknologi Terpadu Nurul Fikri, Indonesia

ARTICLE HISTORY
Received : July 15, 2024
Final Revised : August 28, 2024
Accepted : October 23, 2024
Published : December 30, 2024

1. | INTRODUCTION

The increasing demand for materials to support infrastructure development, manufacturing, transportation, energy, and various industrial sectors has driven the intensive exploitation of natural resources in recent decades. The linear economic model, based on a take-make-dispose pattern, has resulted in high consumption of primary materials, increasing waste volumes, and significant greenhouse gas emissions (Barón et al., 2023). These conditions not only reduce the availability of natural resources but also increase pressure on the environment through the accumulation of solid waste, pollution, and decreased material use efficiency. Therefore, a new paradigm is needed in the development of engineering materials that is not only oriented towards technical performance but also considers sustainability aspects throughout the material's life cycle.

One rapidly developing approach is the circular economy, an economic system that aims to maintain the value of materials, products, and resources for as long as possible through strategies of material reduction, reuse, repair, reconditioning, remanufacturing, and recycling. This approach seeks to replace the linear system with a circular system that minimizes waste generation while increasing the efficiency of resource use (Harsono, 2023). In materials engineering, this concept encourages the development of materials with a longer lifespan, easy recovery, recyclability, and a lower environmental impact than conventional materials.

The implementation of a circular economy in materials engineering focuses not only on the final stage of recycling but also encompasses the entire material life cycle, from raw material selection, design, manufacturing, use, maintenance, and end-of-life management. This approach encourages the application of the principles of design for durability, design for disassembly, and design for recycling, ensuring that materials maintain their economic value within a sustainable production system (Harsono, 2023). In line with these developments, various types of materials, such as biomaterials, industrial waste-based materials, geopolymers, environmentally friendly composites, and recycled materials, are increasingly being developed as alternatives to reduce dependence on primary resources.

Meanwhile, advances in manufacturing technology are accelerating the implementation of a circular economy. Technologies such as additive manufacturing, artificial intelligence, digital twins, material tracking, and advanced recycling processes enable the optimization of material use, reduction of production waste, and increased efficiency of material recovery processes. Furthermore, the application of sustainability evaluation methods, such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Life Cycle Cost (LCC), and circularity indicators, has become an important tool for measuring environmental impacts and resource efficiency throughout a material's life cycle.

Despite significant research on the circular economy and sustainable materials, most publications still focus on specific material types, industrial sectors, or specific technologies (Edinov et al., 2023). Studies integrating the development of circular economy concepts, engineering materials innovations, supporting technologies, sustainability evaluation methods, and implementation challenges into a comprehensive discussion are still relatively limited. This gap necessitates a literature synthesis that provides a comprehensive overview of the relationship between circular economy principles and the development of sustainable engineering materials as a basis for research and implementation in various industrial sectors (Edinov et al., 2023).

Based on this background, this article aims to examine the development of circular economy applications in the development of sustainable engineering materials through a synthesis of literature published between 2019 and 2023. The discussion focuses on the basic concepts of the circular economy, types of engineering materials that support sustainability, technologies that facilitate their implementation, methods for evaluating material sustainability, implementation challenges, and future research directions. The results of this study are expected to provide a comprehensive scientific foundation for the development of more efficient, innovative, and sustainability-oriented engineering materials.

2. | RESEARCH METHOD

This study employed the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize research findings on the application of the circular economy to the development of sustainable engineering materials. The SLR approach was chosen because it provides a systematic, transparent, and replicable review process, reducing the potential for bias in literature selection and producing a more comprehensive knowledge synthesis than conventional literature reviews. The article preparation process adhered to the principles of PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which include literature identification, screening, eligibility, and inclusion (Fathimatuzzahra, 2022). All secondary data was obtained through a Google Scholar search using a combination of the keywords "circular economy," "sustainable engineering materials," "green materials," "recycled materials," "engineering materials," "life cycle assessment," "material recycling," "resource efficiency," and "sustainable manufacturing."

The search was limited to scientific articles published between 2019 and 2023, in English or Indonesian, and published in peer-reviewed scientific journals. Inclusion criteria included articles discussing the concept of the circular economy, innovation in sustainable engineering materials, supporting technologies, sustainability evaluation methods such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Life Cycle Cost (LCC), and circularity indicators, as well as articles directly relevant to the engineering field. Conversely, articles not available in full manuscript form, proceedings with limited information, duplicate publications, or articles not directly related to the development of engineering materials were excluded from the analysis process (Trisakti, 2022). Next, each article meeting the criteria was analyzed qualitatively through a data extraction process that included information on the research objectives, types of materials studied, technologies used, sustainability evaluation methods, key findings, and recommendations for further research.

The extraction results were then synthesized using a thematic analysis approach to identify research development patterns, relationships between concepts, implementation challenges, and opportunities for developing a circular economy in materials engineering. This approach allows for the development of a comprehensive scientific overview of the development of sustainable engineering materials based on empirical evidence published during the period 2019–2023.

3. | RESULTS AND DISCUSSION

The application of the circular economy in the development of sustainable engineering materials has shown very rapid development during the period 2019–2023. Various studies indicate that the transition from a linear economic system to a circular system has become one of the main strategies in reducing primary resource consumption, reducing waste generation, and increasing the efficiency of material utilization throughout its life cycle (Barón et al., 2023). This approach no longer focuses solely on the recycling process after the material becomes waste, but also integrates aspects of design, raw material selection, manufacturing processes, use, maintenance, and end-of-life management of the material. Thus, the circular economy provides a paradigm shift from waste management to material value management so that materials retain their function and economic value for as long as possible. This development is driven by the increasing industrial demand for materials that not only have good mechanical performance but also meet environmental sustainability aspects (Nainggolan et al., 2023). In modern engineering approaches, the success of a material is no longer measured solely by its strength, corrosion resistance, or service life, but also by its resource efficiency, energy consumption during the production process, potential carbon emissions, and the material's ability to be reused and recycled. Therefore, the concept of design for sustainability is beginning to be widely applied in the development of new materials, so that from the design stage, consideration is given to the possibility of disassembly, component separation, reuse, and material recovery.

One important development is the increasing use of recycled materials as a partial replacement for primary materials. Recycled metals, recycled polymers, recycled aggregates, recycled glass, and various industrial wastes have shown significant potential as alternative raw materials. The use of these secondary materials can reduce the need for natural resource exploitation while simultaneously reducing the amount of waste that must be handled through disposal. Various studies also show that with proper process control, the mechanical characteristics of recycled materials can approach or even match conventional materials, making them suitable for various engineering applications.

In addition to recycled materials, biomaterials have also become a major focus of research in recent years. Materials based on biomass, natural fibers, biopolymers, and renewable raw materials have gained attention due to their relatively lower carbon footprint compared to petrochemical-based materials. The use of natural fibers as composite reinforcement, for example, not only reduces dependence on synthetic fibers but also offers opportunities to develop lightweight materials with adequate mechanical properties. Furthermore, biomaterials have the advantage of being biodegradable in certain applications, potentially reducing long-term waste accumulation.

Another notable development is the increasing research into geopolymer materials. These materials utilize aluminosilicate-rich materials, including industrial residues, as raw materials to produce materials with high strength and lower carbon emissions than certain conventional materials (Ahmad et al., 2021). This approach reflects the implementation of the waste valorization principle, which transforms residues previously considered waste into value-added resources. This concept is a crucial element of the circular economy because it can extend the life cycle of materials while reducing the need for primary raw materials (Indrayani, 2021).

In the manufacturing sector, the application of more efficient production technologies also significantly contributes to the implementation of a circular economy. Modern manufacturing processes are beginning to integrate the principles of cleaner production, energy efficiency, process waste reduction, and optimization of raw material use. This approach allows for reduced material consumption without compromising product quality. Furthermore, the development of additive manufacturing technology, or three-dimensional printing, provides new opportunities to increase material efficiency because component formation is carried out in stages as needed, significantly reducing material loss due to conventional cutting and forming.

Digital technology also plays a crucial role in supporting the transformation towards a more circular production system. The use of artificial intelligence, machine learning, the Internet of Things, and digital twins enables real-time material condition monitoring, production process optimization, component lifespan prediction, and even timely determination of maintenance and material recovery (Siswanto & Dewi, 2023). The integration of digital technology not only improves operational efficiency but also extends the useful life of materials, thus aligning with the basic principles of a circular economy.

Sustainability evaluation is an integral part of the development of engineered materials. Various studies have shown that the use of the Life Cycle Assessment (LCA) method is increasingly widespread because it can provide an overview of the environmental impact of a material from the raw material extraction stage to the end of its useful life. Through this approach, researchers can compare several material alternatives based on energy consumption, greenhouse gas emissions, water use, and environmental pollution potential. Thus, material selection is not only based on technical aspects but also considers the environmental consequences arising throughout its entire life cycle. In addition to Life Cycle Assessment (LCA), the Material Flow Analysis (MFA), Life Cycle Cost (LCC), and various circularity indicators are also increasingly being applied to provide a more comprehensive picture of material use efficiency (Rasyid, 2023). Material Flow Analysis allows the identification of material flows from extraction, production, distribution, use, and recovery at the end of their useful life. This information serves as the basis for identifying points of material loss that can still be optimized through reuse, remanufacturing, or recycling strategies. Meanwhile, Life Cycle Cost provides an economic perspective by taking into account all costs incurred during the material's life cycle, so that material selection decisions consider not only initial costs but also operating, maintenance, recovery, and end-of-life management costs (Amanda & Prasetyo, 2023). The integration of LCA, MFA, and LCC provides a stronger basis for evaluating the sustainability of a material comprehensively, thus supporting more effective decision-making in materials engineering

Circularity is also increasingly being used as a quantitative indicator to assess the level of circularity of a product or material (Arkananta, 2023). This indicator measures the extent to which a material originates from secondary resources, has a long lifespan, and can be recovered after its useful life. The higher a material's circularity, the less dependent it is on primary raw materials and the greater its potential to remain in the economic cycle. Therefore, circularity indicators are an important evaluation tool in the development of sustainable engineering materials because they complement information obtained through environmental and economic analyses.

Although various innovations have shown promising progress, implementing a circular economy in the development of engineering materials still faces several challenges. One major obstacle is the consistent quality of recycled materials. Not all secondary materials have uniform physical, chemical, and mechanical characteristics due to variations in raw material sources, contamination levels, separation processes, and recovery technologies used (Asiah et al., 2020). This variation can lead to decreased material performance if not accompanied by adequate quality control. Therefore, the development of purification technology, material characterization, and quality standardization are crucial to ensure recycled materials meet technical specifications for various engineering applications.

The next challenge relates to product design. Most products currently on the market are still designed with functionality and production costs in mind, while disassembly, component separation, and reuse are not prioritized. This situation makes the material recovery process more difficult and expensive. Therefore, the application of the principles of design for disassembly, design for repair, and design for recycling needs to be integrated from the early stages of product development. With this approach, each component can be more easily separated, repaired if damaged, or reused without significant loss of material value.

Economic aspects are also a crucial factor in determining the success of circular economy implementation. In some cases, the costs of collecting, sorting, processing, and recovering materials are still higher than those of using primary raw materials, especially when natural resource prices are relatively low. This situation causes some industry players to still consider the use of secondary materials less economically attractive (Dian, 2023). Furthermore, the initial investment in implementing recycling technology, digitalizing production processes, and material monitoring systems also requires significant costs. Therefore, technological innovations are needed to increase process efficiency and reduce production costs to ensure sustainable materials are more competitive.

From an environmental perspective, implementing a circular economy does not always yield positive impacts if the material recovery process requires high energy consumption or generates additional emissions. Therefore, every material reuse strategy must be evaluated using a life cycle approach to ensure that the environmental benefits truly outweigh the impacts. Such an evaluation is crucial because a recycling process that appears environmentally friendly may not be profitable if all stages require significant energy consumption or generate new, difficult-to-manage waste.

The development of digital technology offers significant opportunities to address these challenges. The integration of Artificial Intelligence (AI) and Machine Learning enables the prediction of material characteristics based on raw material composition and process parameters, thereby minimizing quality variation. Furthermore, the application of the Internet of Things (IoT) enables monitoring of material conditions during the production process and throughout their continuous use. The obtained data can be used to predict component lifespan, determine maintenance schedules, and optimize material recovery strategies before failure occurs. Furthermore, Digital Twin technology enables virtual simulations of material performance and production processes, allowing various design alternatives to be evaluated in advance without the need for repeated physical testing. This approach has the potential to reduce material consumption, accelerate the innovation process, and increase product development efficiency.

In addition to digitalization, the concept of industrial symbiosis is also becoming an increasingly important strategy in implementing a circular economy. Through this approach, residues or byproducts from one industrial process are used as raw materials for another, creating a more efficient resource utilization network. This approach not only reduces the amount of waste disposal but also increases the economic value of previously underutilized materials. This inter-industry synergy demonstrates that the success of a circular economy depends not only on material innovation but also on collaboration between actors in the supply chain.

Overall, the literature synthesis indicates that the development of sustainable engineering materials is no longer solely oriented toward improving mechanical properties, but has evolved toward optimizing the entire material life cycle through the application of circular economy principles (Hidayanti, 2021). The utilization of recycled materials, biomaterials, geopolymers, environmentally friendly composites, modern manufacturing technologies, process digitalization, and sustainability evaluation methods have formed a new foundation for more efficient, adaptive, and environmentally sound materials engineering. While challenges remain in technical, economic, standardization, and industrial implementation, technological advances and increasing attention to resource efficiency demonstrate that the circular economy has significant potential to become a leading paradigm in the development of sustainable engineering materials. This approach not only supports reduced natural resource consumption and waste generation but also encourages the creation of more resilient, innovative, and competitive production systems to support sustainable development.

4. | CONCLUSION

The application of a circular economy has become an increasingly important approach in the development of sustainable engineering materials because it integrates efficient resource use, waste reduction, and increased economic value of materials throughout their life cycle. Based on literature synthesis, the implementation of circular principles focuses not only on recycling activities but also includes designing materials that are easily repaired, reused, remanufactured, and recycled, thereby extending their useful life and reducing dependence on primary resources.

The development of biomaterials, recycled materials, geopolymers, environmentally friendly composites, and the use of industrial waste as alternative raw materials demonstrates that materials innovation plays a strategic role in supporting a more sustainable production system. Furthermore, advances in manufacturing technology, additive manufacturing, artificial intelligence, the Internet of Things, and digital twins further strengthen the implementation of a circular economy through optimizing material use and increasing production process efficiency. Sustainability evaluation using Life Cycle Assessment, Material Flow Analysis, Life Cycle Cost, and circularity indicators is also a crucial tool for assessing the environmental, economic, and technical performance of a material. However, several challenges remain to be overcome, including limited quality of recycled materials, material standardization, technological readiness, investment costs, and industrial supply chain integration.

Therefore, collaboration between researchers, industry, and policymakers is crucial for accelerating the implementation of a circular economy in materials engineering. The development of innovative materials supported by digital technology and a lifecycle-based approach is expected to enable more efficient, adaptive, and sustainable materials engineering systems in the future.

Acknowledgment
We gratefully acknowledge the contributions of individuals who supported the completion of this article.

Funding Information
This research did not receive any funding.

Conflict of Interest Statement
The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement
Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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