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Circular economy in the manufacturing sector: Digital transformation and sustainable practices

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Abstract

The transition from a linear economy to a circular economy (CE) represents a profound shift in resource management practices, emphasizing sustainability and waste reduction as core principles. This review paper explores how digital transformation technologies, including Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data, are integrated with circular economy principles within the manufacturing sector. It examines their roles in promoting sustainable manufacturing practices by optimizing resource use, improving efficiency, and reducing environmental impact. Through a comprehensive review of current literature and case studies, this paper elucidates the benefits, challenges, and future directions of adopting a circular economy approach in manufacturing, highlighting opportunities for innovation and sustainable growth.

Keywords: Circular Economy; Digital Transformation; Internet of things (Iot); Artificial Intelligence (AI); Blockchain; Big Data; Sustainable manufacturing practices

1. Introduction

The traditional linear economy model, characterized by its 'take-make-dispose' approach, has been foundational to global industrialization and economic growth over the past century [1]. This model operates on the premise of extracting resources, manufacturing products, and discarding waste, leading to significant environmental degradation, resource depletion, and escalating pressures on ecosystems worldwide. The consequences of this linear approach, including climate change, pollution, and biodiversity loss, have underscored the urgent need for a more sustainable and resource-efficient economic paradigm [2].

In response to these challenges, the concept of the circular economy (CE) has emerged as a transformative alternative [3]. The circular economy aims to redefine the way materials and resources are used within the economy by closing the loop of resource consumption, maximizing the value extracted from resources, and minimizing waste generation [4, 5]. At its core, the circular economy advocates for designing out waste and pollution, keeping products and materials in use for as long as possible through strategies such as reuse, remanufacturing, and recycling, and regenerating natural systems [6, 7].

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Central to the circular economy philosophy is the concept of decoupling economic growth from resource consumption and environmental degradation [8]. By promoting sustainable production and consumption patterns, the circular economy offers a pathway towards achieving environmental sustainability, economic resilience, and social well-being [9]. This paradigm shift not only aims to preserve natural capital and ecosystem services but also fosters innovation in sustainable product design, resource efficiency, and waste management practices [10].

In the context of manufacturing, which accounts for a significant share of global resource consumption and waste generation, digital transformation technologies play a pivotal role in advancing circular economy principles. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data are revolutionizing manufacturing processes by enhancing operational efficiency, optimizing resource utilization, and enabling closed-loop material flows [11]. These technologies facilitate real-time monitoring and control of production processes, predictive maintenance of equipment, and data-driven insights into resource flows and environmental impacts [12].

This paper explores the synergies between digital transformation technologies and circular economy practices within the manufacturing sector. By synthesizing current literature, analyzing case studies, and examining industry best practices, this paper seeks to provide a comprehensive understanding of how these technologies are being integrated to promote sustainable manufacturing practices. Furthermore, the review will discuss the benefits, challenges, and future directions of adopting circular economy principles in manufacturing, highlighting opportunities for innovation, cost savings, and environmental stewardship in the pursuit of a more sustainable industrial future [13].

2. Circular Economy

2.1. Circular Economy Principles

The circular economy is an economic model that aims to eliminate waste and promote the continual use of resources [14]. Unlike the traditional linear economy, which follows a 'take-make-dispose' approach, the circular economy seeks to keep products, materials, and resources in use for as long as possible [15]. It emphasizes strategies such as designing for longevity, reuse, remanufacturing, and recycling to minimize waste generation and environmental impact [16].

2.1.1. Design for Longevity

Designing products for longevity is a pivotal strategy within the framework of the circular economy, which aims to minimize waste and maximize resource efficiency throughout a product's lifecycle [17]. This approach prioritizes several key principles that collectively enhance sustainability and environmental stewardship [18].

Firstly, products designed for longevity emphasize durability and quality, utilizing robust materials and construction methods that withstand prolonged use and environmental stressors [19]. By reducing the frequency of replacements, these products minimize resource consumption and contribute to a more sustainable production cycle [20]. The modular design principles enable products to be easily disassembled into components or modules that can be repaired, replaced, or upgraded independently [21]. This not only extends the overall lifespan of the product but also facilitates more efficient maintenance and repair processes. Consumers benefit from the ability to adapt products to changing needs and technological advancements without the need to discard entire units, thereby promoting resource conservation [22].

Designing for ease of maintenance and repair further enhances product longevity by incorporating accessible components, standardized parts, and user-friendly repair instructions [23]. This empowers consumers to perform repairs themselves or seek professional assistance without requiring extensive technical knowledge or specialized tools. By supporting repairability over replacement, manufacturers reduce the environmental impact associated with discarded products and foster a culture of sustainability [24].

Products designed for circularity also consider end-of-life scenarios from their initial conception, ensuring they can be efficiently disassembled and their materials recovered for recycling or reuse in new products [25]. This approach, known as design for disassembly, minimizes waste generation and promotes closed-loop recycling systems. It helps to reduce the demand for virgin resources and mitigates environmental pollution associated with resource extraction and manufacturing processes [26].

Integrating lifecycle assessment (LCA) into the design process allows manufacturers to evaluate the environmental impacts of products across their entire lifecycle—from raw material extraction and manufacturing to distribution, use, and disposal [27]. This comprehensive analysis informs decisions that optimize resource efficiency, reduce greenhouse gas emissions, and minimize environmental degradation associated with various stages of product lifecycle.

Consumer education and engagement are essential components in promoting sustainable consumption practices and driving behavior change towards a circular economy mindset [28]. Manufacturers play a crucial role in educating consumers about the benefits of durable products, providing guidance on proper product care and maintenance, and offering repair services or spare parts to extend product lifespan [29]. By empowering consumers to make informed choices and participate actively in sustainable practices, manufacturers contribute to fostering a more sustainable and resilient economy.

2.1.2. Resource Efficiency

Resource efficiency lies at the core of the circular economy, advocating for the judicious use of resources to achieve sustainable development goals [30]. This principle starts with sourcing materials sustainably and employing production processes that minimize resource inputs and waste generation [31]. By embracing innovative technologies such as artificial intelligence (AI), Internet of Things (IoT), and advanced analytics, businesses can optimize resource utilization, enhance operational efficiency, and reduce their environmental footprint [32]. These efforts not only drive economic benefits through cost savings and improved resource management but also contribute significantly to environmental stewardship by reducing greenhouse gas emissions, conserving natural resources, and promoting circularity in resource flows.

Furthermore, integrating resource efficiency practices across industries fosters resilience against resource scarcity and regulatory changes while enhancing competitiveness in a global marketplace increasingly focused on sustainability [33]. Businesses that prioritize resource efficiency not only align with consumer preferences for environmentally responsible products but also build stronger relationships with stakeholders by demonstrating a commitment to sustainable practices. Embracing resource efficiency as a strategic imperative not only enhances corporate sustainability profiles but also contributes to building a more resilient and sustainable economy that meets the needs of present and future generations [34].

2.1.3. Recycling and Reuse

Recycling and reuse are fundamental pillars of the circular economy, aimed at closing the loop of resource consumption and minimizing waste throughout the lifecycle of materials and products [35]. Recycling involves the process of converting waste materials into new products, thereby conserving natural resources and reducing the environmental impact associated with extraction and processing of raw materials. By implementing effective recycling programs and technologies, businesses can divert materials from landfills, mitigate pollution, and lower their carbon footprint.

Similarly, reuse extends the lifespan of products through refurbishment, remanufacturing, or redistribution, thereby maximizing their value and reducing the need for new production [36]. This approach not only conserves resources but also promotes sustainable consumption patterns by encouraging consumers to choose durable, repairable products that can be reused multiple times. By integrating recycling and reuse strategies into their operations, businesses contribute to a circular economy that prioritizes resource efficiency and environmental stewardship. These efforts not only support sustainable development goals but also foster economic resilience by reducing dependency on finite resources and enhancing supply chain efficiency through closed-loop systems [37].

2.2. Product as a Service

Product-as-a-Service (PaaS) models represent a transformative approach within the circular economy, shifting the traditional paradigm of product ownership to service-based consumption models [38]. Under PaaS, customers access products through leasing, renting, or subscription arrangements rather than purchasing them outright. This shift promotes resource efficiency by extending product lifecycles, optimizing utilization rates, and reducing overconsumption and waste generation [39].

By leasing or renting products instead of owning them, customers benefit from access to high-quality goods without the long-term commitment of ownership. Manufacturers, in turn, are incentivized to design durable, modular products that can be easily maintained, repaired, and upgraded throughout their lifecycle. This approach not only enhances product longevity but also fosters a circular economy mindset by encouraging manufacturers to take responsibility for product performance and end-of-life disposal [40].

PaaS models also promote sustainable consumption patterns by aligning economic incentives with environmental outcomes. Businesses can optimize resource use, minimize material inputs, and streamline logistics through efficient product servicing and return processes. This reduces environmental impacts such as carbon emissions and resource depletion, while offering customers flexibility and affordability in accessing products as needed [41]. Ultimately, embracing Product-as-a-Service not only supports economic growth and competitiveness but also advances environmental sustainability goals by promoting a more efficient and resource-conscious approach to product consumption [42].

2.3. Digital Transformation Technologies

Digital transformation technologies such as Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and Big Data are driving significant advancements across industries by revolutionizing how businesses operate, innovate, and interact with their environments.

IoT enables seamless connectivity and data exchange between devices, facilitating real-time monitoring and predictive maintenance in industrial settings. AI empowers machines to learn from data, make decisions, and perform tasks autonomously, thereby enhancing operational efficiency and optimizing processes. Blockchain ensures secure and transparent transactions by decentralizing data storage and validating information across a distributed network, which is particularly valuable in ensuring trust and accountability in supply chains and financial transactions. Big Data harnesses large volumes of structured and unstructured data to derive insights, inform strategic decisions, and drive innovation in areas ranging from customer analytics to operational optimization [43, 44].

2.3.1. Internet of Things (IoT)

Internet of Things (IoT) technologies revolutionize industries by enabling interconnected devices to gather and exchange data, leading to enhanced operational efficiencies and sustainability improvements. One key application of IoT is in smart monitoring and predictive maintenance. IoT sensors deployed in equipment and machinery continuously collect real-time data on performance metrics such as temperature, vibration, and usage patterns. This data allows predictive analytics algorithms to forecast potential failures, enabling proactive maintenance interventions that prevent breakdowns and extend the operational lifespan of assets. By minimizing unplanned downtime and optimizing maintenance schedules, businesses reduce costs and improve overall productivity [45].

Another significant IoT application is resource tracking across supply chains. IoT devices equipped with sensors and RFID tags monitor the movement and status of materials and products throughout their lifecycle. This real-time visibility enables businesses to optimize inventory management, track shipments, and ensure efficient allocation of resources. By enhancing traceability and transparency in supply chain operations, IoT facilitates better decision-making, reduces operational inefficiencies, and minimizes waste. Ultimately, IoT-driven resource tracking contributes to sustainability goals by promoting resource conservation, reducing carbon footprints, and supporting the transition towards more sustainable business practices [46].

2.3.2. Artificial Intelligence (AI)

Artificial Intelligence (AI) plays a transformative role in industries through its advanced capabilities in optimization algorithms and predictive analytics. AI-driven optimization algorithms enhance production processes by analyzing vast amounts of data to identify inefficiencies and optimize workflows [47]. These algorithms can fine-tune manufacturing operations, reduce energy consumption, and minimize waste by optimizing resource allocation and scheduling. By continuously learning from data patterns and historical performance, AI systems improve operational efficiency and reduce costs while maintaining or enhancing product quality. Predictive analytics powered by AI models forecast demand and supply trends with high accuracy, enabling businesses to anticipate market fluctuations and adjust production levels accordingly. This capability enhances inventory management by ensuring optimal stock levels, reducing inventory holding costs, and minimizing the risk of stockouts or overstock situations. AI's ability to analyze complex datasets in real-time allows businesses to make proactive decisions based on actionable insights, improving overall responsiveness and agility in dynamic market environments [48].

2.3.3. Blockchain

Blockchain technology introduces revolutionary capabilities in enhancing transparency, traceability, and operational efficiency across various industries [49]. Blockchain ensures transparency and traceability by creating a decentralized and immutable ledger of transactions and data records. This feature enables stakeholders to track the entire lifecycle of products, from sourcing raw materials to manufacturing, distribution, and end-user consumption. By providing a transparent view of each transaction and verifying the authenticity of data, blockchain enhances trust and accountability in supply chains. This transparency not only mitigates risks such as fraud and counterfeit goods but also supports sustainability efforts by promoting ethical sourcing practices and reducing environmental impacts [50].

Smart contracts, a key innovation enabled by blockchain, automate and enforce agreements between parties without intermediaries. These self-executing contracts are programmed to execute predefined actions when specific conditions are met, facilitating secure and transparent transactions. In the context of circular economy practices, smart contracts can automate processes such as product take-back schemes and recycling initiatives. For example, manufacturers can embed conditions within smart contracts to trigger automated notifications for product returns or initiate payments for recycled materials, thereby promoting closed-loop systems and sustainable resource management [51].

In essence, blockchain technology's integration enhances supply chain transparency, automates trust through smart contracts, and promotes sustainable practices within the circular economy framework. By leveraging blockchain's capabilities, businesses can optimize efficiency, reduce operational costs, and foster greater trust and accountability across their ecosystems.

2.3.4. Big Data

Big Data revolutionizes industries by harnessing vast amounts of data to drive informed decision-making and sustainability initiatives. Data analytics powered by Big Data tools enable businesses to analyze large datasets to uncover valuable insights, patterns, and trends. This analysis informs strategic decision-making processes, enhances operational efficiency, and improves customer experiences. By leveraging predictive analytics and machine learning algorithms, organizations can optimize processes, forecast demand, and improve resource allocation, thereby achieving cost savings and competitive advantages in dynamic market environments [52, 53].

In the realm of sustainability, Big Data facilitates lifecycle assessments (LCA) that evaluate the environmental impact of products throughout their entire lifecycle—from raw material extraction and production to distribution, use, and disposal. By quantifying factors such as energy consumption, carbon emissions, and waste generation, Big Data enables businesses to identify opportunities for reducing environmental footprints and implementing sustainable design and production practices. This holistic approach supports the circular economy by promoting resource efficiency, minimizing waste, and enhancing overall environmental stewardship [54].

In summary, Big Data's capabilities in data analytics and lifecycle assessment empower businesses to drive innovation, optimize operations, and advance sustainability goals. By harnessing the power of Big Data, organizations can navigate complexities, mitigate risks, and capitalize on opportunities to create value while minimizing environmental impacts and promoting sustainable development.

3. Sustainable Practices in Manufacturing

3.1. Sustainable Supply Chain Management

Sustainable practices in manufacturing play a vital role in reducing environmental impact while enhancing operational efficiency [55, 56]. Implementing closed-loop supply chains, where materials are continuously reused within the production cycle, significantly reduces waste and conserves resources. Advanced digital technologies, including the Internet of Things (IoT) and artificial intelligence (AI), facilitate these practices by enabling real-time monitoring and optimization of production processes, which are crucial for effective product lifecycle management. This approach includes designing products from inception for easier disassembly and recycling at the end of their useful life. Additionally, focusing on energy efficiency through the adoption of renewable energy sources and innovative technologies reduces emissions and operational costs [57]. Waste minimization is another critical aspect, achieved by refining production processes and reducing surplus materials. Collectively, these sustainable practices help manufacturers comply with regulatory standards and enhance economic resilience and promote environmental stewardship [58].

3.1.1. Closed-Loop Supply Chains

Closed-loop supply chains represent a significant shift in resource management and operational efficiency in manufacturing. These systems extend the traditional supply chain management practices by integrating the end-of-life processing of products back into the beginning of the production cycle [57]. This approach is pivotal in achieving sustainability by minimizing waste, reducing resource consumption, and decreasing the environmental impact associated with manufacturing [59, 60].

3.1.2. Reverse Logistics

Reverse logistics is a critical component of closed-loop supply chains. It involves the process of moving goods from their typical final destination back to the manufacturer or a specialized recycling center for the purpose of capturing value or proper disposal. Reverse logistics is not merely the reverse flow of products but includes the management of returned merchandise due to damage, seasonal inventory, restock, salvage, recalls, or excess inventory. It also covers the recycling of packaging materials and remanufacturing of products. Effective reverse logistics practices can result in significant cost savings, improved customer satisfaction, and enhanced environmental sustainability by reducing the need for new raw materials and decreasing disposal costs [57, 61].

3.2. Material Recovery

Material recovery, another cornerstone of closed-loop supply chains, refers to the process of retrieving reusable materials from used products or waste streams. This practice is essential for reducing the reliance on virgin raw materials, which often have substantial ecological footprints from extraction and processing [62]. Material recovery involves several strategies, including disassembling products to salvage components, recycling materials back into the same or different products, and refurbishing used products for resale. By recovering materials, manufacturers can reduce production costs, lower their environmental impact, and contribute to a more sustainable economic model. In an effective closed-loop system, material recovery ensures that resources are continually reused within the production cycle, thus minimizing waste and the depletion of finite resources [63].

3.3. Energy Efficiency

Energy efficiency in manufacturing not only reduces environmental impact but also significantly cuts operational costs. It involves optimizing production processes and equipment to use less energy and implementing strategies that curb energy waste. Two key approaches that have been widely studied and implemented in pursuit of energy efficiency are the integration of renewable energy sources and the adoption of energy management systems [64, 65].

3.3.1. Renewable Energy Integration

Renewable energy integration in manufacturing involves replacing conventional energy sources that are often non-renewable and emit high levels of greenhouse gases, with renewable sources like solar, wind, biomass, and hydroelectric power. The use of renewable energy helps manufacturers reduce carbon footprints and comply with global environmental standards and regulations. Solar energy, through photovoltaic cells, is particularly popular in the manufacturing sector due to the decreasing cost of solar technologies and the ability to install large solar arrays on factory roofs or nearby locations [66]. Wind energy can also be harnessed if a manufacturing facility is situated in an appropriately windy area. Biomass energy, derived from organic materials, provides an excellent opportunity for manufacturers to use production waste as a resource to generate energy [67].

3.3.2. Energy Management Systems

Energy management systems (EMS) play a crucial role in enhancing energy efficiency by using advanced technology to monitor, control, and conserve energy in a manufacturing facility. These systems provide real-time data on energy usage patterns and can automatically adjust systems to improve energy efficiency based on predictive analytics and intelligent algorithms. EMS typically focuses on major energy-consuming areas such as HVAC systems, lighting, production lines, and machinery, and seeks to optimize the energy use without disrupting the manufacturing process. By implementing EMS, manufacturers can achieve more predictable energy consumption, reduce energy waste, and increase the overall energy efficiency of operations [68].

3.4. Product Lifecycle Management (PLM)

Product Lifecycle Management (PLM) in manufacturing refers to the systematic approach to managing the entire lifecycle of a product from inception, through design and manufacture, to service and disposal [69]. PLM integrates people, data, processes, and business systems to provide a product information backbone for companies and their extended enterprise. Within the realm of sustainable practices, PLM emphasizes the importance of designing products that are environmentally friendly throughout their lifecycle. Two key concepts within this are Design for Disassembly (DfD) and Modular Design, which are pivotal for enhancing sustainability [70].

3.4.1. Design for Disassembly

Design for Disassembly (DfD) is a design approach that focuses on designing products so that they can easily be taken apart at the end of their useful life. This facilitates easier repair, refurbishment, and recycling, significantly extending the product's life and minimizing waste. DfD aims to simplify and minimize the connections and materials used, making disassembly possible with common tools and without damaging the product components. This practice is particularly beneficial in reducing the environmental impacts associated with waste and landfill use, as well as helping manufacturers recover valuable materials that can be reused in new products. Literature suggests that DfD not only supports environmental goals but also can reduce costs associated with disposal and increase the potential for product refurbishment and material recovery [71,72].

3.4.2. Modular Design

Modular Design refers to an approach where a product is designed in separate modules or components that can easily be connected or disconnected from each other. This design strategy allows for easier maintenance and upgrade of parts instead of replacing the entire product, thereby extending the product’s life and reducing waste [73]. Modular design also supports customization, where customers can tailor products to their needs by choosing specific modules, which can reduce overproduction and excess inventory. In terms of sustainability, modular design can significantly reduce the resource footprint of manufacturing operations, as parts can be independently created, replaced, or upgraded, facilitating better resource use and less material waste. [74-76]

4. Benefits of Integrating Digital Technologies with Circular Economy

4.1. Enhanced Resource Efficiency

Digital technologies are instrumental in driving enhanced resource efficiency within the circular economy framework [77]. Tools like the Internet of Things (IoT) enable real-time monitoring and control of resources throughout the manufacturing process. For example, IoT devices can track the usage rates of raw materials and energy consumption at every stage of production, ensuring that resources are utilized optimally and wastage is minimized. This level of precision in resource management not only contributes to sustainability but also enhances the overall efficiency of production processes, ensuring that materials and energy are used effectively to reduce environmental impact and cost [78-80].

4.2. Increased Transparency

Blockchain technology and IoT contribute significantly to increased transparency in supply chains, a crucial aspect of sustainable practices. Blockchain provides an immutable ledger, where data once entered cannot be altered covertly, making it ideal for tracking the origin and lifecycle of products and materials. This ensures that every stakeholder in the supply chain, from suppliers to consumers, can verify the sustainability credentials of products. Similarly, IoT devices can provide real-time data on the environmental conditions and handling of materials, ensuring compliance with sustainability standards. This level of transparency is essential for verifying that all actors in the supply chain adhere to agreed-upon environmental and ethical standards [81].

4.3. Cost Savings

Integrating digital technologies in circular economy practices leads to significant cost savings. Predictive maintenance, powered by AI and data analytics, allows for the timely maintenance of equipment, preventing costly breakdowns and extending the machinery’s operational life. Additionally, digital tools enable the optimization of production processes by analyzing data to identify inefficiencies and suggesting improvements. This not only reduces operational costs but also decreases waste and energy consumption, further driving down expenses. The reduction in resource use and waste generation through optimized processes also means lower costs related to raw material procurement and waste management [82].

4.4. Regulatory Compliance

Digital tools play a pivotal role in helping manufacturers comply with increasingly stringent environmental regulations and standards. Compliance software and systems can track and manage emissions, waste production, and energy use in real-time, ensuring that all operations stay within the legal limits. Automated reporting features can also streamline the process of reporting to regulatory bodies, reducing the administrative burden and enhancing accuracy. The ability to quickly adjust processes in response to changes in legislation or standards, thanks to agile digital systems, is critical for maintaining compliance and avoiding potential fines or sanctions [83, 84].

4.5. Consumer Trust and Brand Loyalty

The integration of digital technologies into circular economy initiatives significantly boosts consumer trust and brand loyalty. In today's market, consumers are increasingly aware of and concerned about environmental issues and are more likely to trust brands that demonstrate a commitment to sustainability [85]. The transparency afforded by digital technologies like blockchain makes it easier for consumers to verify the sustainability claims of brands, thus enhancing trust. Additionally, brands that actively use advanced technologies to minimize environmental impact are often seen as industry leaders, which can enhance consumer loyalty and attract new customers who prioritize sustainability in their purchasing decisions. This trust and loyalty are invaluable in a competitive market, driving long-term success for brands that invest in these technologies [86].

5. Challenges of Integrating Digital Technologies with Circular Economy

Integrating new technologies into existing systems poses substantial challenges for businesses, particularly for small and medium enterprises due to the high costs and complexity involved. This includes upgrading infrastructure, purchasing new hardware, and training staff, alongside ensuring compatibility with existing systems [87]. Additionally, the reliance on digital technologies raises significant data security and privacy concerns, necessitating robust protection measures and compliance with stringent regulations like the GDPR. The economic viability of adopting such technologies is another hurdle, as the initial investments are significant and the return on investment may not be immediate, which can be particularly deterrent in industries with thin margins [88]. Regulatory and policy barriers also complicate the adoption of circular economy practices, with varying requirements across different regions adding to the complexity and cost. Moreover, cultural and organizational changes are required to shift from a linear to a circular economic model, necessitating a deep-rooted change in company culture and mindset, which can be challenging to implement. These barriers highlight the need for strategic planning and resources but also offer opportunities for innovation and growth in adopting circular economy practices [89, 90].

5.1. Future Directions

Advancements in technology and collaborative efforts are pivotal in driving the adoption of circular economy principles across various sectors [91]. Digital twin technology offers significant benefits by enabling real-time monitoring and predictive maintenance of physical assets, thereby optimizing operations and extending product lifecycles. Similarly, AI and machine learning are enhancing decision-making in manufacturing, improving efficiency in resource use, waste reduction, and energy management. Blockchain technology further contributes by enhancing transparency and traceability in supply chains, ensuring adherence to sustainability practices [92]. Additionally, increased collaboration among industries, governments, and academia fosters innovation and standardization necessary for the circular economy, while supportive policies and regulations by governments incentivize sustainable practices, crucial for facilitating the transition to a circular economy and achieving environmental and economic benefits [93, 94].

6. Conclusion

The integration of digital transformation technologies with circular economy principles presents a viable and promising path toward sustainable manufacturing. While there are challenges to overcome, the benefits such as enhanced resource efficiency, increased transparency, cost savings, and better regulatory compliance make this integration an attractive approach for the future. As digital technologies continue to advance and collaborations expand, the adoption of circular economy practices is expected to grow, driving significant improvements in sustainability and resilience in the manufacturing sector.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Rashid S, Malik SH. Transition from a Linear to a Circular Economy. In Renewable Energy in Circular Economy 2023 Oct 10 (pp. 1-20). Cham: Springer International Publishing.

[2] Mityakov S, Lapaev D, Zakharov P, Zakharova Z, Mityakova O. The methodology for the multi-projection analysis of sustainable development of the regions of the northern sea route. Revista Gestão & Tecnologia. 2023 Jun 13; 23:309-37.

[3] Hobson K, Lynch N. Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. Futures. 2016 Sep 1; 82:15-25.

[4] Kirchherr J, Yang NH, Schulze-Spüntrup F, Heerink MJ, Hartley K. Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resources, Conservation and Recycling. 2023 Jul 1; 194:107001.

[5] Reddy VV, Kumar P, Rao AL, Kumar R, Singh S, Asha V, Kareem SH. Waste to Wealth Generation: Innovative Methodologies in Resource Utilization and Minimization in Circular Economy. InE3S Web of Conferences 2023 (Vol. 453, p. 01035). EDP Sciences.

[6] Kandpal V, Jaswal A, Santibanez Gonzalez ED, Agarwal N. Circular economy principles: shifting towards sustainable prosperity. InSustainable Energy Transition: Circular Economy and Sustainable Financing for Environmental, Social and Governance (ESG) Practices 2024 Feb 8 (pp. 125-165). Cham: Springer Nature Switzerland.

[7] Kaur H, Singhal N. Circular Economy for Energy Materials: State-of-the-Art Initiatives and Regulatory Issues. InEnergy Materials 2024 (pp. 1-24). CRC Press.

[8] Calisto Friant M, Vermeulen WJ, Salomone R. Transition to a sustainable circular society: more than just resource efficiency. Circular Economy and Sustainability. 2024 Mar;4(1):23-42.

[9] Kandpal V, Jaswal A, Santibanez Gonzalez ED, Agarwal N. Circular economy principles: shifting towards sustainable prosperity. InSustainable Energy Transition: Circular Economy and Sustainable Financing for Environmental, Social and Governance (ESG) Practices 2024 Feb 8 (pp. 125-165). Cham: Springer Nature Switzerland.

[10] Sharma R, Malaviya P. Ecosystem services and climate action from a circular bioeconomy perspective. Renewable and sustainable energy reviews. 2023 Apr 1;175:113164.

[11] Matin A, Islam MR, Wang X, Huo H, Xu G. AIoT for sustainable manufacturing: Overview, challenges, and opportunities. Internet of Things. 2023 Aug 10:100901.

[12] Han Y, Shevchenko T, Yannou B, Ranjbari M, Shams Esfandabadi Z, Saidani M, Bouillass G, Bliumska-Danko K, Li G. Exploring how digital technologies enable a circular economy of products. Sustainability. 2023 Jan 21;15(3):2067.

[13] Hegab H, Shaban I, Jamil M, Khanna N. Toward sustainable future: Strategies, indicators, and challenges for implementing sustainable production systems. Sustainable Materials and Technologies. 2023 Jul 1;36:e00617.

[14] Obiuto NC, Ninduwezuor-Ehiobu N, Ani EC, Andrew K. Implementing circular economy principles to enhance safety and environmental sustainability in manufacturing.

[15] Vijai, Wisetsri W. Circular Economy for Sustainable Development in India. InGlobal Sustainability: Trends, Challenges & Case Studies 2024 May 22 (pp. 61-87). Cham: Springer Nature Switzerland.

[16] Fontana A, Barni A, Leone D, Spirito M, Tringale A, Ferraris M, Reis J, Goncalves G. Circular economy strategies for equipment lifetime extension: A systematic review. Sustainability. 2021 Jan 21;13(3):1117.

[17] Hummen T, Desing H. When to replace products with which (circular) strategy? An optimization approach and lifespan indicator. Resources, Conservation and Recycling. 2021 Nov 1; 174:105704.

[18] Shirvani G, Ghasemshirazi S. Towards Sustainable IoT: Challenges, Solutions, and Future Directions for Device Longevity. arXiv preprint arXiv:2405.16421. 2024 May 26.

[19] Nwokediegwu ZQ, Ilojianya VI, Ibekwe KI, Adefemi A, Etukudoh EA, Umoh AA. Advanced materials for sustainable construction: A review of innovations and environmental benefits. Engineering Science & Technology Journal. 2024 Jan 24;5(1):201-18.

[20] Sakib MN, Kabir G, Ali SM. A life cycle analysis approach to evaluate sustainable strategies in the furniture manufacturing industry. Science of the Total Environment. 2024 Jan 10; 907:167611.

[21] Amend C, Revellio F, Tenner I, Schaltegger S. The potential of modular product design on repair behavior and user experience–Evidence from the smartphone industry. Journal of Cleaner Production. 2022 Sep 20; 367:132770.

[22] Jin M, Li B, Xiong Y, Chakraborty R, Zhou Y. Implications of coproduction technology on waste management: Who can benefit from the coproduct made of leftover materials?. European Journal of Operational Research. 2023 Jun 16;307(3):1248-59.

[23] Eswaran M, Gulivindala AK, Inkulu AK, Bahubalendruni MR. Augmented reality-based guidance in product assembly and maintenance/repair perspective: A state of the art review on challenges and opportunities. Expert Systems with Applications. 2023 Mar 1; 213:118983.

[24] Lloveras J, Pansera M, Smith A. On 'the Politics of Repair Beyond Repair': Radical Democracy and the Right to Repair Movement. Journal of Business Ethics. 2024 May 15:1-20.

[25] Triguero Á, Moreno-Mondéjar L, Sáez-Martínez FJ. Circular economy and firm performance: The influence of product life cycle analysis, upcycling, and redesign. Sustainable Development. 2023 Aug;31(4):2318-31.

[26] Dumée LF. Circular materials and circular design—review on challenges towards sustainable manufacturing and recycling. Circular economy and sustainability. 2022 Mar;2(1):9-23.

[27] Roberts M, Allen S, Coley D. Life cycle assessment in the building design process–A systematic literature review. Building and Environment. 2020 Nov 1; 185:107274.

[28] Gomes GM, Moreira N, Ometto AR. Role of consumer mindsets, behaviour, and influencing factors in circular consumption systems: A systematic review. Sustainable Production and Consumption. 2022 Jul 1; 32:1-4.

[29] Zhou Y, Xiong Y, Jin M. Less is more: Consumer education in a closed-loop supply chain with remanufacturing. Omega. 2021 Jun 1; 101:102259.

[30] Wamane GV. A "new deal" for a sustainable future: enhancing circular economy by employing ESG principles and biomimicry for efficiency. Management of Environmental Quality: An International Journal. 2023 Jul 3.

[31] Shen SC, Khare E, Lee NA, Saad MK, Kaplan DL, Buehler MJ. Computational design and manufacturing of sustainable materials through first-principles and materiomics. Chemical Reviews. 2023 Jan 5;123(5):2242-75.

[32] Haleem A, Javaid M, Khan IH, Mohan S. Significant Applications of Artificial Intelligence Towards Attaining Sustainability. Journal of Industrial Integration & Management. 2023 Dec 1;8(4).

[33] Wu H, Feng Z, Sun T, Li R, Zhao H. Efficiency, sustainability, and resilience a trifecta for a green economic recovery through natural resource markets. Resources Policy. 2024 Jan 1; 88:104435.

[34] Yusuf N, Lytras MD. Competitive sustainability of saudi companies through digitalization and the circular carbon economy model: a bold contribution to the vision 2030 agenda in Saudi Arabia. Sustainability. 2023 Feb 1;15(3):2616.

[35] Illankoon C, Vithanage SC. Closing the loop in the construction industry: A systematic literature review on the development of circular economy. Journal of Building Engineering. 2023 Jul 13:107362.

[36] Muneeb SM, Asim Z, Hajiaghaei-Keshteli M, Abbas H. A multi-objective integrated supplier selection-production-distribution model for re-furbished products: Towards a circular economy. Renewable and Sustainable Energy Reviews. 2023 Apr 1; 175:113156.

[37] Barros MV, Salvador R, do Prado GF, de Francisco AC, Piekarski CM. Circular economy as a driver to sustainable businesses. Cleaner Environmental Systems. 2021 Jun 1; 2:100006.

[38] Sakao T, Golinska-Dawson P, Duberg JV, Erik S, Hidalgo-Crespo J, Riel A, Peeters J, Green A, Mathieux F. Product-as-a-service for critical raw materials: challenges, enablers, and needed research. Going Green: CARE INNOVATION. 2023 May 9.

[39] Fischer AD. *Circular economy–forging institutions: On how circular business model innovation shapes the circular economy while instigating the new rules of the game* (Doctoral dissertation, Wageningen University and Research).

[40] Atif S, Ahmed S, Wasim M, Zeb B, Pervez Z, Quinn L. Towards a conceptual development of industry 4.0, servitisation, and circular economy: A systematic literature review. Sustainability. 2021 Jun 7;13(11):6501.

[41] Borghi V, Pellizzoni L, Vitale T, SciencesPo P. PaaS: a model for socially and environmentally responsible companies and for an inclusive circular economy?.

[42] Watson RT, Boudreau MC, Chen A, Huber M. Green IS: Building sustainable business practices. Information systems. 2008; 17:17.

[43] Moumtzidis I, Kamariotou M, Kitsios F. Digital transformation strategies enabled by internet of things and big data analytics: The use-case of telecommunication companies in Greece. Information. 2022 Apr 14;13(4):196.

[44] Adhicandra I, Tanwir T, Asfahani A, Sitopu JW, Irawan F. Latest Innovations in Internet of Things (IoT): Digital Transformation Across Industries. Innovative: Journal Of Social Science Research. 2024 May 6;4(3):1027-37.

[45] Ceipek R, Hautz J, De Massis A, Matzler K, Ardito L. Digital transformation through exploratory and exploitative internet of things innovations: The impact of family management and technological diversification. Journal of Product Innovation Management. 2021 Jan;38(1):142-65.

[46] Vermesan O, Bacquet J, editors. Cognitive Hyperconnected Digital Transformation: Internet of Things Intelligence Evolution. River Publishers; 2017 Jun 23.

[47] Javaid M, Haleem A, Singh RP, Suman R. Artificial intelligence applications for industry 4.0: A literature-based study. Journal of Industrial Integration and Management. 2022 Mar 21;7(01):83-111.

[48] Jagatheesaperumal SK, Rahouti M, Ahmad K, Al-Fuqaha A, Guizani M. The duo of artificial intelligence and big data for industry 4.0: Applications, techniques, challenges, and future research directions. IEEE Internet of Things Journal. 2021 Dec 31;9(15):12861-85.

[49] Feng H, Wang X, Duan Y, Zhang J, Zhang X. Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges. Journal of cleaner production. 2020 Jul 1;260:121031.

[50] Aoun A, Ilinca A, Ghandour M, Ibrahim H. A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. Computers & Industrial Engineering. 2021 Dec 1;162:107746.

[51] Esmaeilian B, Sarkis J, Lewis K, Behdad S. Blockchain for the future of sustainable supply chain management in Industry 4.0. Resources, conservation and recycling. 2020 Dec 1;163:105064.

[52] Khan R, Usman M, Moinuddin M. The Big Data Revolution: Leveraging Vast Information for Competitive Advantage. Revista Espanola de Documentacion Cientifica. 2024 Apr 16;18(02):65-94.

[53] Choudhary L, Swami S. Harnessing the Power of Big Data: Revolutionizing Agriculture. Current Journal of Applied Science and Technology. 2023 Aug 5;42(22):40-9.

[54] Modgil S, Gupta S, Sivarajah U, Bhushan B. Big data-enabled large-scale group decision making for circular economy: An emerging market context. Technological Forecasting and Social Change. 2021 May 1; 166:120607.

[55] Abatan A, Jacks BS, Ugwuanyi ED, Nwokediegwu ZQ, Obaigbena A, Daraojimba AI, Lottu OA. The role of environmental health and safety practices in the automotive manufacturing industry. Engineering Science & Technology Journal. 2024 Feb 25;5(2):531-42..

[56] C, Ahmad SF, Ayassrah AY, Irshad M, Telba AA, Awwad EM, Majid MI. Green production and green technology for sustainability: The mediating role of waste reduction and energy use. Heliyon. 2023 Dec 1;9(12).

[57] Mishra A, Dutta P, Jayasankar S, Jain P, Mathiyazhagan K. A review of reverse logistics and closed-loop supply chains in the perspective of circular economy. Benchmarking: an international journal. 2023 Mar 21;30(3):975-1020.

[58] Ottosson E, Oweini R. Developing a closed-loop supply chain to eliminate Single Use Plastic products: Implementing Circular Economy practices driven by EU commission directives.

[59] Aldrighetti R, Battini D, Das A, Simonetto M. The performance impact of Industry 4.0 technologies on closed-loop supply chains: insights from an Italy based survey. International Journal of Production Research. 2023 May 3;61(9):3004-29.

[60] Shaharudin MR, Zailani S, Tan KC, Cross J, Hotrawaisaya C. Fostering closed-loop supply chain orientation by leveraging strategic green capabilities for circular economy performance: empirical evidence from Malaysian electrical and electronics manufacturing firms. Environment, development and sustainability. 2023 Jan 18:1-38.

[61] Shahidzadeh MH, Shokouhyar S. Toward the closed-loop sustainability development model: a reverse logistics multi-criteria decision-making analysis. Environment, Development and Sustainability. 2023 May;25(5):4597-689.

[62] Ramanathan U, He Q, Subramanian N, Gunasekaran A, Sarpong D. Collaborative closed-loop supply chain framework for sustainable manufacturing: Evidence from the Indian packaging industry. Technological Forecasting and Social Change. 2023 Jun 1; 191:122489.

[63] Lara-Guillén J, Méndez-Aparicio MD, Jiménez-Zarco AI. Circular Economy and Closed-Loop Supply Chains in Industry 4.0: Importance to Achieve Sustainable Development. InDigital Transformation for Improved Industry and Supply Chain Performance 2024 (pp. 299-333). IGI Global.

[64] Ibekwe KI, Umoh AA, Nwokediegwu ZQ, Etukudoh EA, Ilojianya VI, Adefemi A. Energy efficiency in industrial sectors: A review of technologies and policy measures. Engineering Science & Technology Journal. 2024 Jan 24;5(1):169-84.

[65] Bosu I, Mahmoud H, Hassan H. Energy audit and management of an industrial site based on energy efficiency, economic, and environmental analysis. Applied Energy. 2023 Mar 1; 333:120619.

[66] Jahanger A, Ozturk I, Onwe JC, Joseph TE, Hossain MR. Do technology and renewable energy contribute to energy efficiency and carbon neutrality? Evidence from top ten manufacturing countries. Sustainable Energy Technologies and Assessments. 2023 Mar 1; 56:103084.

[67] Jung S, Kara LB, Nie Z, Simpson TW, Whitefoot KS. Is additive manufacturing an environmentally and economically preferred alternative for mass production?. Environmental science & technology. 2023 Apr 17;57(16):6373-86.

[68] Digitemie WN, Ekemezie IO. A comprehensive review of Building Energy Management Systems (BEMS) for improved efficiency. World Journal of Advanced Research and Reviews. 2024;21(3):829-41.

[69] Matenga AE, Mpofu K. Blockchain-based product lifecycle management using supply chain management for railcar remanufacturing. Procedia CIRP. 2023 Jan 1; 116:486-91.

[70] Elahi M, Afolaranmi SO, Martinez Lastra JL, Perez Garcia JA. A comprehensive literature review of the applications of AI techniques through the lifecycle of industrial equipment. Discover Artificial Intelligence. 2023 Dec 7;3(1):43.

[71] JAKAB R. *Bridging theory and practice: simulation-based scheduling performance evaluations for Application Lifecycle Management* (Doctoral dissertation, University OF Pannonia).

[72] Abanda FH, Jian N, Adukpo S, Tuhaise VV, Manjia MB. Digital twin for product versus project lifecycles' development in manufacturing and construction industries. Journal of Intelligent Manufacturing. 2024 Jan 31:1-31.

[73] Li N, Feng Y, Liu J, Ye X, Xie X. Research on the Modular Design and Application of Prefabricated Components Based on KBE. Buildings. 2023 Nov 29;13(12):2980.

[74] Panarotto M, Isaksson O, Vial V. Cost-efficient digital twins for design space exploration: A modular platform approach. Computers in industry. 2023 Feb 1; 145:103813.

[75] Karakitie ED, Aralu CE, Fadare AD. Performance charateristics of a conventional spark ignition petrol engine powered by biogas. Fuel Communications. 2022 Mar 1; 10:100032.

[76] Aralu CE, Karakitie DE, Fadare DA. Construction of a pilot scale biogas digester at the University of Ibadan Dairy Farm, Abadina. Fuel Communications. 2021 Dec 1; 9:100033.

[77] Kandasamy J, Venkat V, Mani RS. Barriers to the adoption of digital technologies in a functional circular economy network. Operations Management Research. 2023 Sep;16(3):1541-61.

[78] Kandasamy J, Venkat V, Mani RS. Barriers to the adoption of digital technologies in a functional circular economy network. Operations Management Research. 2023 Sep;16(3):1541-61.

[79] Li Y, Hu Y, Li L, Zheng J, Yin Y, Fu S. Drivers and outcomes of circular economy implementation: Evidence from China. Industrial Management & Data Systems. 2023 Apr 4;123(4):1178-97.

[80] Jemal KM, Kabzhassarova M, Shaimkhanov R, Dikhanbayeva D, Turkyilmaz A, Durdyev S, Karaca F. Facilitating circular economy strategies using digital construction tools: framework development. Sustainability. 2023 Jan 3;15(1):877.

[81] Medaglia R, Rukanova B, Zhang Z. Digital government and the circular economy transition: An analytical framework and a research agenda. Government Information Quarterly. 2024 Mar 1;41(1):101904.

[82] Han Y, Shevchenko T, Yannou B, Ranjbari M, Shams Esfandabadi Z, Saidani M, Bouillass G, Bliumska-Danko K, Li G. Exploring how digital technologies enable a circular economy of products. Sustainability. 2023 Jan 21;15(3):2067.

[83] Gao Y. Unleashing the mechanism among environmental regulation, artificial intelligence, and global value chain leaps: A roadmap toward digital revolution and environmental sustainability. Environmental Science and Pollution Research. 2023 Feb;30(10):28107-17.

[84] Zhao S, Teng L, Arkorful VE, Hu H. Impacts of digital government on regional eco-innovation: moderating role of dual environmental regulations. Technological Forecasting and Social Change. 2023 Nov 1; 196:122842.

[85] Verleye K, De Keyser A, Raassens N, Alblas AA, Lit FC, Huijben JC. Pushing forward the transition to a circular economy by adopting an actor engagement lens. Journal of Service Research. 2024 Feb;27(1):69-88.

[86] Rehman FU, Al-Ghazali BM, Haddad AG, Qahwash EA, Sohail MS. Exploring the reverse relationship between circular economy innovation and digital sustainability—the dual mediation of government incentives. Sustainability. 2023 Mar 15;15(6):5181.

[87] Atieh AM, Cooke KO, Osiyevskyy O. The role of intelligent manufacturing systems in the implementation of Industry 4.0 by small and medium enterprises in developing countries. Engineering Reports. 2023 Mar;5(3):e12578.

[88] Radicic D, Petković S. Impact of digitalization on technological innovations in small and medium-sized enterprises (SMEs). Technological Forecasting and Social Change. 2023 Jun 1; 191:122474.

[89] Khan AA, Laghari AA, Li P, Dootio MA, Karim S. The collaborative role of blockchain, artificial intelligence, and industrial internet of things in digitalization of small and medium-size enterprises. Scientific Reports. 2023 Jan 30;13(1):1656.

[90] Javaid M, Khan S, Haleem A, Rab S. Adoption of modern technologies for implementing industry 4.0: an integrated MCDM approach. Benchmarking: An International Journal. 2023 Dec 1;30(10):3753-90.

[91] Mhatre P, Gedam VV, Unnikrishnan S, Raut RD. Circular economy adoption barriers in built environment-a case of emerging economy. Journal of Cleaner Production. 2023 Mar 15; 392:136201.

[92] Munaro MR, Tavares SF. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. Cleaner and Responsible Consumption. 2023 Mar 1; 8:100107.

[93] Verleye K, De Keyser A, Raassens N, Alblas AA, Lit FC, Huijben JC. Pushing forward the transition to a circular economy by adopting an actor engagement lens. Journal of Service Research. 2024 Feb;27(1):69-88.

[94] Vincent SA, Simolowo OE. Design and Performance Stress Analysis of an Archetype Yam Peeling Machine.