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A review on literature: How information and communication technology (ICT) supports circular economy for sustainable development

Nicky Arnezti[1,*], Putri Maziya Ikhsanti[1], Denisya Ziva Alika[1], Faridatul Ummah[1], Muhammad Akbar Saputra[1], Muhammad Faisal[1], R. Candra Ahmad Syaukani[1], Muhammad Addif Rayza[1], Zamsyah Dwi Hushaini Ramadhan[1]

[1] *Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.*

*Correspondence: nickyarnezti42@gmail.com

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ABSTRACT

Background: Information and Communication Technology (ICT) plays a crucial role in enabling the transition to a circular economy. By optimizing supply chain management and fostering innovative circular business models, ICT empowers businesses to reduce waste, conserve resources, and create more sustainable value chains. This research aims to explore the specific ways in which ICT supports the circular economy, including enhanced visibility and traceability, optimized resource allocation, improved collaboration, and the development of circular business models such as product-as-a service and sharing economy. **Methods:** This paper is qualitative research using Systematic Literature Review (SLR) from 275 papers that contained the relationship between ICT and circular economy as data, included 23 papers reviewed with SLR method. **Findings:** The result of this research is agreed that ICT has a role in circular economy. This research has explained that ICT can support circular economy through some aspects such as the advance, sustainability, efficiency through technology, etc. **Conclusions:** By leveraging ICT, businesses can transform their supply chains into circular systems, reducing waste, conserving resources, and creating long lasting value. **Novelty/Originality of this article:** Combining research from supply chain management and circular business model and the use of SLR method which is still little used.

KEYWORDS: information and communication technology (ICT); circular economy; supply chain management; circular business model.

1. Introduction

In recent decades, the world has become increasingly aware of the negative impact of overconsumption on the environment. This is because global material consumption and annual waste production is expected to increase by 70 percent by 2050, according to a World Bank report (What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050). This is also followed by rapid urbanization and a population that continues to grow year after year, global annual waste production is expected to jump to 3.4 billon tons over the next 30 years, up from 2.01 billion tons in 2016, according to the findings in the report. Therefore, the transition to a more sustainable system is receiving increasing attention from

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governments, practitioners, and researchers. In response, the concept of circular economy (CE) emerges as a promising alternative to address environmental concerns and limited resources (LCDI, 2020). The circular economy (CE) is considered a sustainable economic system through the reduction and recirculation of natural resources. CE is a model that seeks to extend the life cycle of products, raw materials, and resources so that they can be used for as long as possible (LCDI, 2020). CE is critical in designing business policies and strategies, and prioritizing evidence-based sustainable solutions that result in reduced material consumption to improved environmental, economic, or social impacts. The principles of the circular economy include reducing waste and pollution, keeping products and materials in use for as long as possible, and regenerating natural systems (Ellen Macarthur Foundation, 2016). Various strategies have been proposed to move from a linear economy to a circular economy. These strategies are mostly carried out by industry players. The concepts behind such strategies include sustainable and eco-friendly design, energy and material efficiency measures, strategies set within the three-R waste hierarchy (reduce-reuse-recycle), business model innovation, industrial symbiosis, etc.

At the same time, new digital technologies (DTs) are arising, such as the internet of things (IoT), big data analytics (BDA), artificial intelligence (AI), and 3D printing, which are changing the way products are made, shipped, sold, and consumed. Digital technology is a transition from operations that no longer use a lot of human labor but rather using human labor but is more likely to use an operating system that is fully automated and sophisticated by using a computer system. Referred to as industry 4.0, the new industrial stage not only changes the way of production, but also causes versatile organizational transformation. With emerging technologies, devices can communicate with other devices and services through the internet to achieve various purposes, such as automated manufacturing, home automation, and smart waste management. The adoption of DT is considered a promising way to overcome CE transition barriers. It can create CE opportunities for the manufacturing industry, such as remodeling equipment, improving worker efficiency and motivation, building smart factories based on resource efficiency, and designing closedloop manufacturing process chains.

Digitalization is as important as circular development for the long-term benefits of manufacturers in achieving sustainability. Digital information and technology in Industry 4.0 (IDT in Industry 4.0), refers to the application of advanced technologies that extend beyond organizational boundaries and leverage machine intelligence throughout the product lifecycle to offer faster, more flexible and more stable services. For example, utilizing technologies such as the internet of things (IoT) and big data analytics (BDA) in supply chain management (SCM) can help stakeholders share information effectively and increase flexibility. Under these circumstances, IDT in Industry 4.0 facilitates supply chain resilience with tools that are more agile and cheaper than ever before. Moreover, SCM is an inherently dynamic process, with flows of logistics, information, and capital between to various participants to meet their requirements and maximize their respective benefits (Rehman et al., 2022). Supply Chain Management (SCM) is a science that discusses suppliers and customers from upstream to downstream to get lower costs and superior value for customers. Supply Chain Management is also defined as the strategic and systematic coordination of traditional business functions that facilitate distribution networks among customers, and internal company activities. Practices in the supply chain greatly affect the performance of a company or organization where competitive advantage indicates that the supply chain is correct, because it includes supplier management, customer management, inventory (Gecevska et al, 2010).

In addition, ICTs also facilitate the development of circular business models that offer a different approach to value creation. Instead of focusing on producing and selling products, circular business models are more oriented towards providing services and sustainable use of products. ICTs play an important role in supporting the development and implementation of circular business models by facilitating interactions between producers, consumers and other stakeholders. Recent studies show that the implementation of CE principles could increase Europe's Gross Domestic Product (GDP) by as much as 11%, with net benefits of approximately €1.8 trillion by 2030, and material cost savings of up to USD 1 trillion. The CE business model describes a holistic view of a company's business, including the value proposition that attracts customers to choose the company over its competitors (Ranta et al., 2020), supports value creation, offers a delivery system that fulfills the value proposition while increasing circularity through a combination of constricting, slowing, and closing resource flows (Bocken et al., 2016), and implements a value capture mechanism that allows the company to capture a portion of the value created as profit while complying with CE principles (Bocken et al., 2016).

Achieving a true circular economy requires a combination of efficient SCM and innovative business models. ICT is the bridge that connects these two elements. By utilizing ICT, companies can design supply chains that are flexible and responsive to market changes, and develop sustainable circular business models. Through this article, we will discuss in depth how ICT supports circular economy through SCM optimization and circular business model development.

1.1 The circular economy

The circular economy is characterized as a restorative and regenerative economy by design which aims to keep products, components, and materials in its highest utility and value at all times (Ellen MacArthur Foundation, 2019). Circular economy is expected to be a strategy to face challenges of resource scarcity and waste disposal with less pollution generated. During this time, the circular economy had many definitions which were analysed in different factors and dimension. The most highlighted definition and concept, also studied for a long time (since 1950's) of CE is the 3R principles.

Actually, each associate has a different opinion and perspective to define the 3R principle. Some of them stated that 3R is recycled, remanufactured, and reused. The other stated refurbish, remanufacture, and reverse logistics. But, In general and the most stated by many researchers and associates, the 3R principle is reduce, reuse, and recycle. Based on it, the circular economy can be defined as an economic system based on business models replacing the 'end-of life' concept with reducing, reusing, and recycling materials in production or consumption processes (Uluturk et al., 2020).

The use of the circular economy concept in several companies and organizations are for businesses. Even though CE business not only focused on usual business goals (I.e., earnings and profit rate), but also concerned its environmental aspects (I.e., recycled material rate and carbon footprint) (Trevisan et al., 2021). This is the key difference between circular economy and economy concept in general. Circular economy is a greater level of environmental sustainability with more focus on socio-economic aspects.

1.2 Types of ICT applications in the digital era

According to UNESCO's official website, Information and Communication Technology (ICT) is a diverse set of technological tools and resources used to transmit, store, create, share or exchange information. There are several kind of ICT applications, such as: product lifecycle management (PLM). In this day and age, innovation is key to business survival and success, and PLM plays a vital role in helping manufacturers develop products with lower costs and faster time to market. PLM is a process of managing the entire product lifecycle, from initial idea, planning, development, production, to disposal, with the aim of improving efficiency as well as effectiveness in product development and management (Mauersberger et al., 2024). Business approach strategy to effective management and corporate intellectual capital used. PLM system provides a set of business solutions to support collaborative reaction, management, and use of product definition information across the extended enterprise from concept to end of life-integrating people, business systems and information. information technology strategy, PLM establishes a coherent data structure that enables real-time collaboration and data sharing among geographically distributed teams.

Then, Internet of Things (IoT) is a concept where various devices, such as sensors, electronic devices, and other objects, are integrated through the internet network. Through IoT, users can connect to perform various activities, from information retrieval to data processing, without the need for human intervention. IoT technology involves equipping devices with sensors, enabling them to communicate and actively engage within an information network. This allows real- time remote monitoring of product usage, condition, and location. As a result, companies have a valuable opportunity to gain insights into customer behavior, fostering a closer connection with users and transforming the manufacturer- customer relationship from one focused on negotiation to one centered on communication.

Artificial intelligence (AI) is the ability of machines to perform tasks that are considered similar to human intelligence and the use of artificial intelligence technology is currently applied in various fields. Artificial intelligence (AI) first emerged since the development of digital computers in the 1940s and continues to grow today. Artificial intelligence (AI) is a broad term that encompasses various technologies involving models and systems designed to perform cognitive tasks similar to human reasoning and learning. AI facilitates problem-solving through pattern recognition, prediction, optimization, and the creation of recommendations, utilizing data from diverse sources such as videos, images, audio, numerical data, and text.

Blockchain technology is a database mechanism that gathers information sharing transparently within a business network. A blockchain database stores data in blocks that are linked together in a chain (Rejeb et al., 2023). The data in AI is chronologically consistent because you cannot delete or change the chain without the consensus of the network and it is real time. Therefore, blockchain technology creates an immutable or fixed ledger to track orders, payments, accounts, and other transactions. As stated by McKinsey & Company, blockchain is a secure database distributed among a network of participants, providing simultaneous access to current information for everyone involved. It enables data and transactions to be recorded in a permanent, unchangeable, and transparent manner

Big data analytics is the process of collecting, processing, and analyzing data needed to identify patterns and trends. This process also enables organizations to make far better and strategic decisions based on actual data evidence. Big Data can be identified through 4 characterizes namely (i) a massive amounts of data generated in a continuous way; (ii) unstructured and distinct formats (I.e., Imaging, texting, etc); (iii) a high data generation frequency; and (iv) a good quality and direct proven application. So, because of the large size and its rapid changes, Big Data cannot be analyzed using traditional database software or techniques. To optimize Big Data's performance, collaborating with analytics is a good choice. Analytics enables to turn company's data into insights, which provide the basis for better decision-making. So, the combination of Big Data and Analytics can positively advance management towards CE, by providing the information needed in sustainability-oriented decision-making processes.

1.3 Correlation of ICT and circular economy

ICT provides a critical infrastructure for monitoring and sustaining circular practices that include various digital tools and platforms that contribute to CE principles (i.e., sustainable design, closed-loop processes, and extended product life cycles) (Pagoropoulos et al., 2017). Through the application of data-driven technologies such as the Internet of Things (IoT), blockchain, and big data analytics, companies can achieve real-time resource tracking, efficient product lifecycle management, and greater transparency across the supply chain. So, ICT and CE will complement each other in order to drive economic sustainability and innovation. Leveraging ICT drives increased efficiency, transparency, and scalability in CE strategies, ultimately supporting the global shift towards a more sustainable and resilient economic system (Chauhan et al., 2022).

In a circular economy, data-driven decisions are essential. ICT enables big data analysis that can be used to analyze consumption, production, and waste patterns. Through apps and online platforms, ICT can raise consumer awareness about the importance of the circular economy and how they can contribute, such as by choosing products that are easy to recycle or supporting sustainability-focused brands. This can help companies to understand the product lifecycle and is also useful in identifying opportunities for improvement or increased recycling. ICT also enables better monitoring, management and optimization of resource use.

In addition, ICT supports in the design of more environmentally friendly products by using CAD (Computer-Aided Design) software that allows designers to create products with circularity in mind, as well as in the ease of recycling or reuse. ICT can assist in the tracking and management of e-waste and other materials. For example, blockchain technology is used to record the recycling of products and materials, ensuring that they can be reused safely and efficiently. ICT also plays a role in developing and utilizing cleaner and more energy-efficient production technologies. Technologies such as automation and artificial intelligence (AI) can optimize production processes, reduce waste, and improve the output of each production cycle.

1.4 Challenges and limitations of ICT's implementation

The use of ICT-based technologies such as the Internet of Things (IoT), big data and blockchain in enabling the Circular Economy (CE) often involves large- scale data collection and analysis. This can increase the risk of data breaches and cyberattacks that threaten users' security and privacy. In complex CE ecosystems, data sourced from multiple actors, including end users and suppliers, can become targets for exploitation or theft. These security issues can undermine trust among stakeholders in CE systems, such as enterprises, governments, and consumers. The failure to maintain data privacy can also lead to legal violations and regulatory sanctions in many regions (Demestichas & Daskalakis, 2020). The application of ICT in the circular economy, especially using technologies such as IoT or blockchain, involves the collection and exchange of large amounts of data. This increases risks related to data security and privacy. Companies must ensure that the data collected is safe from the threat of hacking and misuse.

ICT solutions such as IoT and big data analytics systems require complex and highly scalable infrastructure. These implementations often face technical constraints, such as limitations in expanding capacity or integration with other systems. In Heyes et al. (2018), it is described that Systems that are poorly scalable or difficult to integrate can stall the adoption of ICT based solutions in supporting CE, especially in small and medium-sized enterprises that have limited resources to invest in these complex technologies. One of the main challenges faced by organizations in implementing ICT to support CE is resistance to change. Kirchherr et al. (2018) point out that companies are often reluctant to adopt circularity-based business models due to uncertainty about the impact on day-to-day operations and short-term profits. These barriers include fear of the risk of failure in transformation, temporary loss of profits, and reliance on established linear business models.

Many organizations, especially in the small and medium-sized sector, face challenges in terms of the skills and digital literacy required to adopt CE based ICT solutions. Lorek et al. (2020) emphasized that a lack of training and skills among the workforce can hinder the adoption of new technologies, including the use of big data, IoT, and blockchain. This leads to gaps in the ability of companies to utilize available technologies in an effective way. The diversity of organizational culture may also slow down the adoption of ICT for CE. Heyes et al. (2018) noted that some companies have work cultures that are not prepared to collaborate cross departmentally or with external stakeholders on circularity initiatives. This lack of a culture that supports cross-functional collaboration can hinder an organization's ability to take advantage of the opportunities offered by ICT. Most organizations experience barriers in terms of funding and limited commitment from top management to support the digital transformation required for CE. Petre et al. (2023) identified that weak leadership commitment can limit the allocation of adequate resources and long-term strategies needed to 6 effectively adopt ICT technologies that support circularity.

The implementation of ICT to support CE often requires significant initial investment, including the sourcing of hardware, software, and digital infrastructure. Heyes et al. (2018) note that small and medium-sized enterprises, in particular, may face difficulties in providing funds for new technology investments required to transition to circularity business models. These challenges may slow down the wide-scale adoption and scalability of ICT-based technologies. Adopting advanced technologies such as the Internet of Things (IoT), big data, blockchain, and artificial intelligence (AI) can require considerable initial investment. For small and medium-sized enterprises, such costs can be a barrier to implementing ICT in support of the circular economy, even though in the long run it can result in efficiency and cost savings.

One of the main concerns of companies in adopting ICT-based technologies for CE is the uncertainty surrounding return on investment (ROI). Petre et al. (2023) point out that many companies are hesitant to make large investments without a clear guarantee of return within a reasonable timeframe. In many cases, the transition to a circularity model requires substantial changes to business processes that can take a long time to generate tangible economic benefits. Kumar & Chopra (2022) highlight that blockchain technology can help overcome financial challenges in CE implementation by providing transparency and efficiency to the supply network. However, cost and infrastructure limitations are still major obstacles that restrict the application of this technology in CE. Asif et al. (2018) discuss the importance of new circular based business models, such as “product as a service”, but they face major challenges in financing and adequate ICT infrastructure to support this transition process.

IoT, big data, and blockchain have great potential to improve efficiency in resource management and waste reduction. While there are many challenges in applying ICT to support a circular economy, technology still plays an important role in creating a more sustainable economic system. With the right support in terms of policy, infrastructure, and education, these challenges can be overcome and ICT can be maximized to support circular economy principles. The need for collaborative efforts between sectors to overcome the challenges and create an ecosystem that supports sustainability, without the right support in terms of infrastructure, education, and clear policies, the application of ICT in circular economy will be difficult to be optimally realized.

1.5 Highlight specific examples of organizations that have successfully implemented ICT-enabled CE strategies

Gorenje doing a manufacturing company based in Slovenia, is one of the pioneers in adopting Circular Economy principles through transforming its business model from the traditional product sales-based approach to a “product-as-a-service” service-based model. In this model, customers not only buy products, but they get services that cover the use, maintenance and repair of the product throughout its life cycle. This creates a huge opportunity for companies to reduce waste, extend product life, and improve resource efficiency.

Gorenje's success is supported by the utilization of advanced information and communication technology (ICT) infrastructure. ICT technology enables companies to manage and share data in real-time with various stakeholders in their value chain, including suppliers, customers, and other partners. This infrastructure plays a critical role in product status monitoring, predictive maintenance needs, and more sustainable lifecycle management.

Through the utilization of real-time data, Gorenje can extend the life of their products more effectively. Data collected from sensors and connected devices allows the company to predict maintenance needs and make preventive repairs before damage occurs. In addition, products that 7 reach end-of-life can be reclaimed, refurbished or recycled, thereby reducing waste and supporting environmental sustainability. This initiative reinforces the principle of circularity by creating a closed product life cycle.

2. Methods

The manuscripts collected in this study consisted of 275 papers classified into several study topics. The most researched main topic is circular economy with 46 papers (16%). Next is the topic of development economics with 34 papers (12%). Then there were 27 papers on economic growth (9%), and 25 papers related to urban and rural areas (9%). Finance came in fifth with a total of 24 papers (8%), and there were 13 papers on industrialization (4%) and others.

This research applied a systematic literature review (SLR) approach, which is the best method to synthesize various research findings (Creswell, 1998). This approach provides evidence at the meta-level, while pointing out areas that require further research, particularly in the context of the circular economy. This process serves as an important component in building theoretical frameworks and conceptual models, as well as illustrating the diverse and interdisciplinary nature of the field.

This research used several journals as references with some adjustments. Article searches were conducted through several journal aggregators such as Sciencedirect, Emerald, Consensus, and MDPI with the keyword "circular economy". The collected articles were then manually organized based on the suitable themes. The stages in retrieving articles follow the following steps as journal database identification. Databases used in article selection include Science Direct, Emerald Insight, MDPI.

Then, for the keyword Selection, the keyword "ICT" and "circular economy" was used to ensure the articles found were relevant to the research focus. Article type selectio, the type of article selected is Research Article to ensure that this research only focuses on articles from empirical research results. After undergoing all these stages, the selected articles are then screened further through several steps. First, it was ensured that the articles were indexed in Scopus by checking them directly on scopus.com. Secondly, only articles that dealt predominantly with circular economy were selected from the databases used.

3. Results and Discussion

3.1 Research data

This research was conducted by reviewing 23 papers related to ICT and circular economy that have been published in scopus indexed international journals in 2017 - 2024. Based on Table 1 below, the most published source is Procedia CIRP with the number of Journals on Circular Economy. The journals on circular economy have 6 research papers, followed by MDPI Open Access Journal with 3 research papers.

Table 1. Research publication with ICT and circular economy theme

Publication	Total	Percentage
Procedia CIRP	6	26.09%
MDPI Open Access Journal	3	13.04%
Others	14	60.87%
Total	23	100.0%

The classification of papers based on the methodological approach used by the authors is shown in Table 2. After filtering the articles, we founfd Based on the results of the review of 275 papers, there are three categories: Qualitative Approach, Quantitative Approach, and Mixed Approach. A total of 15 papers use a Qualitative approach or 65.22%, 4 papers use a Quantitative approach or 17.39%, and finally 4 papers use a Mixed approach or 17.39%.

Table 2. Classification based on methodology

Research Methodology	Total	Percentage
Qualitative Approach	15	65.22%
Quantitative Approach	4	17.39%
Mixed Approach	4	27.39%
Total	23	100.00%

This research was also conducted based on the main topic of the research paper. Classification by topic can be observed that from several studies reviewed, the most researched main topic is ICT and Circular Economy with a total of 14 papers. Then in second place is 6 papers with the theme of Business Model, then in third place is Supply Chain Management paper with a total of 3 paper.

Table 3. Classification based on Topics

Topic	Total	Percentage
ICT and Circular Economy	14	60.87%
Suplly Chain Management	3	13.04%
Business Model	6	29.09%
Total	23	100.0%

Furthermore, from this total of 23 papers, the papers were examined using 3 Quartile ranking categories. This quartile grouping is based on the calculation of the number of cite scores from journals contained in the Scopus database. Journals that have the highest cite score will be included in quartile 1 (Q1). Meanwhile, journals that have the least cite score will be included in quartile 4 (Q4). So, Q1 journals are the highest level of journals, because they have the highest cite score. While Q4 journals are the lowest level of journals because they have the least cite score.

Table 4. Classification based on quartile

Quartile	Total	Percentage
Quartile 1	17	73.91%
Quartile 2	6	26.09%
Total	23	100.0%

3.2 Role of information and communication technology (ICT) in supporting the implementation of a circular economy

The role of ICT in supporting the circular economy is very important, as there are currently many technologies that help facilitate the implementation of the circular economy. According to Demestichas et al (2020), cuttingedge technologies such as big data, cloud computing, cyber-physical systems, internet of things, virtual reality and augmentation, along with blockchain can play an integral role in the application of CE concepts and the implementation of CE programs by governments, organizations, and society as a whole. This is in line with technologies such as the Internet of Things, Big Data, and Analytics are able to face the challenges of implementing a circular economy in companies when adopting business models. Chauhan et al (2020) found that the Internet of Things and AI play an instrumental role in the transition to a circular economy. That technologies help ICT play a role in the circular economy such as IoT sensors for monitoring, AI for automation, Big Data for analytics, and Blockchain for security and transactions.

Lingdi & Yang (2023), examined the role of industry 4.0 technologies such as cloud services, artificial intelligence (AI), big data analytics (BDA), blockchain technology (BT), and internet of things (IoT) in the implementation of circular economy. They developed a framework based on these advanced technologies to support sustainable supply chain management more effectively and efficiently. Through this approach, they show how each technology can play a role in reducing material consumption, increasing transparency, aiding decision-making, and optimizing the product lifecycle from design to recycling. This framework is expected to help companies face environmental and sustainability challenges while maintaining economic advantage in the digital age. Uluturk et al. (2020) researched Philips CityTouch, which uses ICT especially IoT technology to remotely manage smart lights through a cloud-based platform. The system enables communication between the lights, the municipality, and Philips, supports energy efficiency, and the circular economy by remanufacturing used lights.

3.3 The role of internet of things (IoT) in CE

IoT is a key element that supports the implementation of circular economy (CE) by increasing the circularity of a product's usage stage. IoT enables a product to be equipped with sensors that can be used to monitor its condition, usage, and lifetime in real time. The data obtained from the monitoring results is used by companies for predictive maintenance efforts and determining when the product needs to be repaired or replaced, so that the product life can be extended.

This supports CE sustainability principles by reducing waste and the need to overproduce new products. IoT technology also facilitates better record keeping throughout the product life cycle that helps companies understand usage patterns and effective product design needs for longer-lasting products. With the data available, companies can make better strategies and decisions regarding product design, product durability, and help minimize environmental impact (Chauhan et al., 2022). In addition, IoT enables the Product Service System (PSS) model, which is a service-focused business model that encourages repeated use of products in a pay-per-use or rental technique, thereby reducing the use of excess resources and making it more sustainable.

3.4 Big data and blockchain technology for CE support

Digital technologies such as big data and blockchain also contribute to supporting CE. Big data in enterprises is used to collect, store, and analyze large amounts of data related to the product life cycle and supply chain (Grady et al., 2019). The analytical data obtained can help companies identify product usage patterns, market demand trends, and optimization of recycling strategies or reuse of products. By understanding the resulting data trends, companies can design more ecologically friendly products and build more sustainable business strategies. On the other hand, blockchain in this case plays a role in ensuring data security and transparency at every stage of the supply chain. This digital technology allows for asset tracking from the early stages to the end of the product life cycle which facilitates verification of information and minimizes risk. By using digital blockchain technology, the entire supply chain can be monitored and documented securely.

There are several findings from the paper titled “Unleashing the circular economy in the EV battery supply chain”: A case study on data sharing and the potential of blockchain”. Data sharing supports a shift from a linear to a circular supply chain model in the electric vehicle battery industry. Blockchain technology can help remove barriers to circularity in the electric vehicle battery supply chain by improving transparency and traceability, especially for second-life battery applications.

3.5 ICT and supply chain management (SCM) in the circular economy

Information and communication technology (ICT) plays an important role in optimizing Supply Chain Management (SCM) in the Circular Economy (CE) model. In this case, ICT facilitates the integration of digital technologies that support sustainability in CE, such as reusing, recycling, and remanufacturing material products. ICT enables companies to be able to collect and retrieve large amounts of data across the supply chain to optimize resource use and enhance better decision-making processes. The adoption of Industry 4.0 technologies in CE including cloud services, artificial intelligence (AI), blockchain and Internet of Things (IoT) promotes more efficient management of supply chain activities. By utilizing digital technology, the results of product analysis throughout the cycle from the initial design stage, production stage, to the distribution and end-of-life stages of the product are better assessed and obtained in real time. This helps reduce the potential for waste and supports recycling or remanufacturing, thereby promoting circular development.

The integration of green supply chain management (GSCM) with ICT can also lead to enhanced environmental performance by reducing carbon footprint and improving sustainability across the supply chain (Okorie et al, 2018). In addition, the application of digital technology can have a significant impact on the circular economy capabilities of an enterprise by enhancing supply chain collaboration and minimizing risks while addressing the challenges posed by supply chain integration (Yuan et al., 2023). In summary, ICT can enhance SCM by fostering collaboration and improving risk management to achieve circular economy goals.

Currently the most widely used ICT methods in Estonian companies to manage orders and deliveries are conventional email, web-based portals and conventional surface mail/phone/fax communication. Although the use of fax as a communication tool has begun to be replaced after 2012. In this case, the supply chain in Estonia is becoming increasingly digitized, supported by ICT. In addition, manufacturing companies in Jordan prove that the integration of supply processes through the internet is very profitable (Jum'a et al., 2024). ICT facilitates online communication with key channel partners on various aspects. Digitalization in supply chain management integrates sustainability into business operations which is one of the drivers to achieve economic sustainability.

3.6 ICT and circular business models in the circular economy

Based on case studies, digital technologies are identified as two main roles, enabler and trigger (Uluturk et al., 2020). As an enabler, ICT or digital technologies (DTs) facilitate and enable various elements of the circular economy business model canvas whilst as a trigger, ICT can initiate or lead to innovation in the circular business model, such as offering use-oriented productservice systems (PSS), creating intelligent products, and enabling pay-per-use revenue models. That ICT or DTs are used to overcome the challenges that companies face when adopting a circular economy business model through a product-service system (PSS) approach. However, DTs still can't help overcome challenges related to financial risks and market cannibalization. Another study conducted that DTs can enable a circular business model, such as product-service systems, to support the transition to a circular economy.

DTs supports the three key circular economy performance objectives of increasing resource efficiency, extending product life span, and closing the loop. This study focuses on a conceptual framework that identifies the eight functionalities enabled by DTs, such as improving product design, attracting target customers, monitoring and tracking product activity, providing technical support, providing preventive and predictive maintenance, optimizing the product usage, upgrading the product, enhancing renovation, and end-of-life activities. Ranta et al. (2018), paper provides an empirical synthesis on how DTs improve resource flows with narrowing, slowing, and closing techniques. Tamura et. al. (2023) proposes the idea of the importance of integrating the design of ICT systems with the design of other components of a circular economy business, such as the product, service, and business model, in order to effectively realize the value proposition, environmental consciousness, and economic profitability of the circular economy business.

4. Conclusions

Information and Communication Technology (ICT) significantly advances the circular economy through its diverse applications and contributions. IoT equips products with sensors to monitor usage, condition, and lifecycle in real-time, enabling predictive maintenance, prolonging product lifespan, and adhering to sustainable practices such as waste reduction. IoT also facilitates the Product-Service System (PSS) model, promoting resource-efficient practices like rental or pay-per-use systems. Big data provides insights into product lifecycle trends, optimizing product design, recycling strategies, and fostering sustainable business models, while blockchain ensures transparency and security in supply chain management, enabling reliable data tracking from production to recycling. ICT integrates advanced technologies, such as AI, cloud computing, and IoT, enhancing supply chain management (SCM) by enabling better decision-making, real-time data analysis, and fostering collaboration across the supply chain. Additionally, ICT aids in green supply chain management (GSCM), reducing environmental impact and improving sustainability. As both an enabler and a trigger for circular business model innovation, ICT supports key circular economy goals—extending product lifespans, improving resource efficiency, and closing material loops—by facilitating intelligent product design, predictive maintenance, and innovative frameworks like PSS. Digital technologies play a pivotal role in achieving circular economy principles, optimizing resource utilization, enhancing transparency, and supporting innovative business models, although challenges like financial risks and market acceptance still need to be addressed to maximize their potential.

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Biographies of Authors

Nicky Arnezti, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: nickyarnezti42@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Putri Maziya Ikhsanti, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: maziyaputri26@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Denisya Ziva Alika, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: denisyaziva1@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Faridatul Ummah, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: faridatulummah99@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Muhammad Akbar Saputra, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: akbarrsaputraa69@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Muhammad Faisal, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: mhmmdfaisal1711@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

R. Candra Ahmad Syaukani, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: rcandraahmads@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Muhammad Addif Rayza, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: rayzaddif@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Zamsyah Dwi Hushaini Ramadhan, Department of Economics, Faculty of Economics and Business, Brawijaya Unversity, Malang, 65141, Indonesia.

- Email: zamsyahdwihr@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A