Internet of Things and Circular Economy: A State-of-the-Art Review

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This paper presents a comprehensive, state-of-the-art review of the confluence between the Internet of Things (IoT) and the Circular Economy (CE), two interdisciplinary areas with immense potential for promoting sustainable development. The review first delves into the fundamental technologies and methodologies driving IoT, followed by a discussion on the technological underpinnings enabling the CE. It subsequently analyses the intersection of IoT and CE, supported by relevant examples. The challenges of integrating these two domains and potential solutions are also addressed. The review concludes with prospective technical research directions and potential areas for future exploration.
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1 Introduction

The Internet of Things (IoT) and the Circular Economy (CE) are two transformative concepts that have the potential to reshape our world in a new era of technological innovation and sustainable development. These two interdisciplinary domains, while vastly different in their fundamental objectives and mechanisms, intersect in intriguing ways with a great potential to revolutionize industry, economics, and society as a whole.

The Internet of Things represents a technological revolution that allows devices, sensors, and systems to communicate and interact, enabling the collection, exchange, and analysis of vast quantities of data [1]. In essence, IoT embodies the interconnection of computing devices embedded in everyday objects, enabling these entities to send and receive data. This data-driven interconnectedness has profound implications across various sectors, including industry, healthcare, transportation, and urban development. Also, IoT enables the remote monitoring and control of physical environments, opening doors for enhanced automation, improved efficiency, and innovative services. Its overarching objective is to make systems smarter, paving the way for intelligent decision-making and efficient resource utilization [2].

Simultaneously, the concept of a Circular Economy has emerged as an influential paradigm in economics, sustainability, and environmental management [3]. The CE paradigm promotes the transition from the traditional linear economic model of “take-make-waste” to a more sustainable circular model characterized by reduced waste, optimized resource usage, and the recycling or reuse of products through the redesign of processes and systems, driving towards a closed-loop system where outputs can be reintegrated as inputs [4]. Also, the CE model requires a shift in thinking about how we produce and consume, with a focus on systems that enable the recovery and regeneration of products and materials at the end of life [3].

The intersection of IoT and CE presents a unique opportunity for both business and technical advancements [5]. Indeed, the IoT technologies can play a significant role in enabling and enhancing the Circular Economy, leading to improved resource efficiency, extended product lifespans, and closed-loop systems [6]. On the other hand, the CE, as a new economic system, has emerged as a viable solution to the environmental challenges posed by the traditional linear economy [3]. From a business standpoint, the convergence of IoT and CE can lead to innovative business models that promote sustainability and create new value propositions, while from a technical perspective, the integration of IoT and CE presents interesting challenges and opportunities in areas such as sensors, connectivity, data processing and management [6]. This synergy between IoT and CE is particularly relevant in the current context, characterized by increasing environmental concerns and the rapid advancement of digital technologies [5]. Moreover, the advent of Industry 4.0 (I4.0) and its related technologies such as Big Data analytics, Artificial Intelligence (AI), Information Technology (IT) and Operational Technology (OT) convergence, and Cyber-Physical Systems (CPS) have a profound impact on sustainability and the environment [7], [8]. However, the sustainability impact of these IoT and I4.0 technologies is still under investigation, with studies indicating both positive and negative impacts related to the basic production inputs and outputs flows of raw material, energy and information consumption, and product and waste disposal [5], [6].

In this comprehensive review, we delve into these two transformative concepts, exploring how they converge, and what implications this convergence has for the future, specifically addressing how IoT can drive the implementation of CE. Given the multi-disciplinary nature of both fields, the review is conducted from a technical perspective, focusing on technological foundations, system architectures, applications, and practical examples.

The aim of this review is to provide researchers, practitioners, and policymakers alike with a thorough understanding of the state-of-the-art in this interdisciplinary domain by synthesizing the latest research on IoT and CE, offering a solid foundation and highlighting the technical challenges and opportunities in this field, and suggesting directions for further exploration, research, and innovation.

After establishing the research framework, the current state-of-the-art regarding the technical foundations of IoT and CE will be discussed, followed by an analysis of the IoT and CE integration and a discussion on the relevant examples showcasing this confluence. At the same time, the technical challenges, and the potential solutions, as identified from the literature review, are also presented. The last chapter highlights the future technical directions for advancing the field of study. Finally, the main conclusions are presented and specific research direction for future scientific research are proposed.

2 Research Methodology

The methodology involved a Systematic Literature Review (SLR) approach. As explained in [9], the SLR process involves a structured approach to searching for relevant literature, selecting articles based on predefined criteria, and analyzing and synthesizing the findings from these articles. In this scope, peer-reviewed articles, conference papers, and technical reports were sourced from databases such as: *Google Scholar*, *IEEE Xplore*, *ScienceDirect*, *Web of Science* and *Scopus*, among others. The search terms used for the data collection included but were not limited to the following keywords: "*Internet of Things*", "*Circular Economy*", "*Sustainability*", "*Industry 4.0*", while Boolean operators ("and", "or", "not") have been applied to combine and refine the search results. The articles selected were published between 2009 and 2023, a period of intense research activity in both fields and the literature was evaluated based on relevance, technical rigor, innovation, and contribution to the field. The selection process included an initial screening of titles and abstracts to identify potentially relevant articles, followed by a full-text review to determine the final selection of articles for inclusion in the review. The data analysis process involved the extraction of relevant information from the selected articles, using a critical thinking approach, while the recurrent themes were identified and classified in the structure of this state-of-the-art review paper. A total of *60 articles* were included and used as references in this review paper. The aim was to provide a comprehensive overview of the current state of the field, highlighting the technical foundations and the synergy between the IoT and CE domains, their applications and use cases, various challenges and potential solutions, and the opportunities for future research in this area.

3 Technical Foundations of IoT

The Internet of Things (IoT) is defined by the ability of objects to sense, communicate, interact, and collaborate with each other to achieve common goals [1]. IoT represents a paradigm shift in how we interact with the physical world [10]. It involves interconnected devices and systems that collect, exchange, and process data, thereby achieving a higher level of automation and efficiency [1]. The technical foundations of IoT encompass various elements such as sensors and actuators, connectivity technologies, data processing and storage, and computing paradigms [2]. The sophistication of IoT can be attributed to these multitude of the technologies and elements, which all contributes uniquely to realize the full potential of IoT systems [11].

3.1 IoT System Architectures. The design of IoT systems revolves around specific architectures that organize the functioning of various components and their interactions. These architectures may range from simple, three-layer models comprising perception, network, and application layers, to more complex, five-layer models that additionally include processing and business layers and specific ones [11]. IoT architectures aim to facilitate the implementation of IoT applications by providing a structured framework that guides the deployment and interaction of IoT devices, data management systems, and application services [12], [13]. The Figure 1 depicts a logical view of the most used IoT system architecture, the three-layer model.

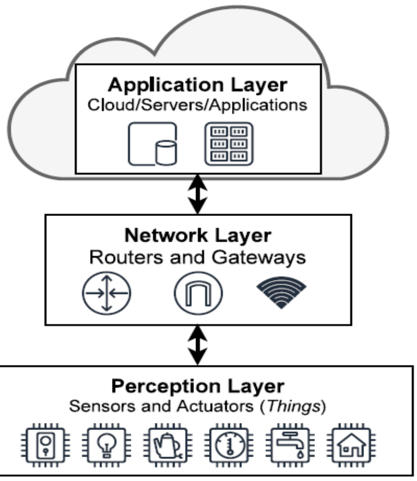

Fig. 1. IoT three-layer system architecture *(source: [11], pg.7)*

3.2 Sensors and Actuators form the fundamental building blocks of any IoT system [14]. Sensors, often embedded within everyday objects, gather information from their environment, converting physical quantities into digital signals that can be processed and analysed [13]. Sensors can measure a variety of parameters, such as temperature, pressure, light intensity, and motion, amongst others. Actuators, on the other hand, are devices that convert these digital signals into physical action. They serve as a response mechanism within the IoT architecture, acting upon the commands derived from processed sensor data. Together, sensors and actuators enable an IoT system to interact effectively with its physical environment [10], [13].

3.3 Connectivity in IoT refers to the data communication mechanisms that interlink IoT devices. It constitutes a critical factor in IoT architecture due to the necessity of transmitting sensor data to processing units and delivering processed information to actuators or end-users [13]. Standardization

plays a critical role in IoT and given the diverse range of devices and systems involved, standards and protocols ensure interoperability, compatibility, and reliability among devices and systems, facilitating smooth communication and data exchange [13].
The choice of an appropriate standard or protocol often depends on the specific requirements of the IoT application, such as power consumption, data rate, communication range and latency, and scalability, amongst other functional and non-functional requirements [13]. Numerous connectivity technologies are employed for the IoT systems [11], [13], Table 1 presents some of the most used ones.

Table 1. IoT Common Connectivity Technologies

Network type	Examples
Personal Area Network (PAN) represents a network that covers a small area, such as a home or office. These are used for communication among devices close to a person.	***Bluetooth*** is commonly used in wearables, speakers, and headphones ***Zigbee*** and ***Z-Wave*** are commonly used in home automation systems. ***RFID*** is used for tracking and identifying objects in various contexts. ***NFC*** allows for close-proximity data exchange, often used in mobile payment systems.
Body Area Network (BAN) represents a network that is used for wearable computing devices. These networks collect data from devices worn on the body.	***Medical devices*** can monitor patient health parameters. ***Fitness trackers*** monitor person-al health metrics like heart rate and sleep patterns.
Local Area Network (LAN) represents a network that connects devices in a limited area, such as a home, school, or office. It provides high-speed connectivity but has a limited range.	***WiFi*** is used in homes and offices for connecting various de-vices to the internet. ***Ethernet*** is used for wired connections. ***HomePlug*** uses existing electrical wiring to connect devices.
Wide Area Network (WAN) represents a network that covers a large geo-graphical area and are typically used to connect devices or smaller networks that are far apart.	***Cellular (4G, 5G)*** networks are used to connect mobile devices over large distances. ***Satellite*** networks provide global coverage.
Low Power Wide Area Network (LPWAN) represents a network optimized for long-range communications at a low bit rate. These networks are power efficient and often used for IoT devices that don't need high-speed connectivity but need to send data over long distances.	***LoRaWAN*** is used in smart cities for things like parking sensors. ***Sigfox*** is used for remote monitoring. ***NB-IoT*** for applications like smart meters. ***6LoWPAN*** allows for devices to connect to the internet using IPv6.
Metropolitan Area Network (MAN) represents a network that spans a city or campus. It's larger than a LAN but smaller than a WAN.	***WiMAX*** provides broadband wireless connectivity over a city or large campus ***Citywide WiFi*** networks provide connectivity within a city.
Industrial Networks are designed for specific industrial applications where reliability and real-time control are critical. Usually wired connection are preferred.	***Modbus*** and ***Profibus*** are used in industrial automation systems. ***Industrial Ethernet*** is a version of Ethernet used for automation. ***CAN*** is used in vehicles and machinery for device communication. ***Ethernet/IP*** is used for industrial automation applications.

3.4 Data Processing and Management are central to the operation of IoT systems. IoT devices generate vast amounts of data, necessitating efficient systems for data storage, organization, and analysis [12]. Real-time processing of data often occurs, offering dynamic insights that inform immediate decision-making. The computing paradigms enabling the data processing and management for IoT includes Cloud, Ubiquitous, Fog, and Edge Computing [15].

- **Cloud Computing** has emerged as a prevalent approach for IoT data management. As a remote data storage and processing center, cloud computing affords the ability to manage large data volumes, offering scalable, flexible, and cost-effective storage solutions and robust computing processing capabilities, while ensuring the availability, integrity, and confidentiality of IoT data throughout its lifecycle [16]. While cloud computing offers considerable benefits for data management in IoT systems, its centralized nature can present challenges, including latency and connectivity interruptions. These concerns have catalysed the development of decentralized paradigms: ubiquitous, fog, and edge computing [15].
- **Ubiquitous computing**, or pervasive computing, refers to the embedding of computing capabilities into everyday objects and environments, enabling them to communicate and interact with humans and other objects seamlessly [17]. IoT is often seen as a realization of the ubiquitous computing vision, providing the infrastructure and technologies that embed intelligence into physical objects and connect them to the Internet [15]. Ubiquitous computing also questions and challenge the IoT in terms of human-computer interaction, context-aware computing, and the integration of digital and physical spaces [17].
- **Edge computing** is an architectural paradigm in computing where data processing is shifted from the centralized nodes (e.g., cloud) to the edge of the network, closer to the source of data [15]. This approach can reduce the latency of decision-making, enhance data privacy, and reduce the volume of data transferred to the cloud. In the context of IoT, edge computing can be highly beneficial, especially for time-sensitive applications such as autonomous vehicles, industrial automation systems, and emergency response systems [18]. Edge computing also enables local data storage and processing even in intermittent network connectivity scenarios, making it suitable for remote IoT deployments [18].
- **Fog computing** is often seen as an extension of edge computing [15]. While edge computing focuses on processing at or near the source of data, fog computing encompasses processing at the edge as well as within the network itself [19]. Fog nodes or gateways, positioned between the data source (IoT devices) and the cloud, can provide localized processing, storage, and networking services [12]. This can help balance the load between the edge and the cloud, provide low-latency responses, and support mobility and geo-distribution of services in IoT applications [19].

Fog computing extends the cloud closer to the data source, placing computing resources at the network edge. In contrast, edge computing pushes computational processes directly onto IoT devices. Both fog and edge computing aim to reduce the data transmission latency and enhance the real-time responsiveness of IoT systems, thereby improving overall performance and reliability of the IoT systems, as can be seen in Figure 2.

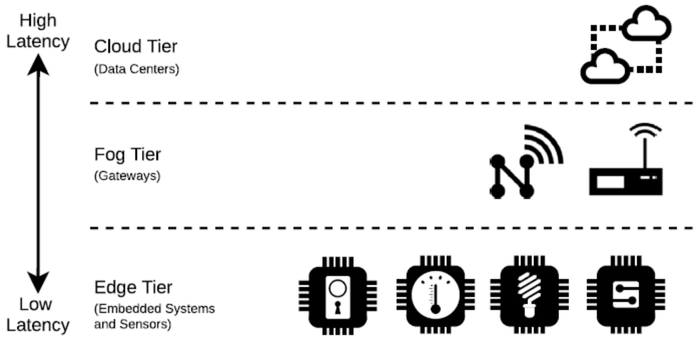

Fig. 2. IoT and Cloud/Fog/Edge architecture *(source: [11], pg.7)*

3.5 Security in IoT. As IoT systems are pervasive in their nature and frequently deal with sensitive data, they can become attractive targets for cyberattacks, including data breaches, device tampering, denial-of-service attacks, and privacy violations [13], [20]. Furthermore, with the proliferation of IoT devices and their increasing integration into critical systems and infrastructure, cybersecurity has become a paramount concern and there is a need for a strong focus on security [21]. Security in IoT encompasses securing devices, data, and networks against unauthorized access and threats [20]. Addressing cybersecurity in IoT requires a multi-layered approach, encompassing secure hardware and software design, secure communication protocols, encryption methods for data protection, secure authentication and authorization mechanisms, intrusion detection systems, privacy-preserving techniques such as data anonymization and pseudonymization, regular firmware and software updates, and continuous monitoring [21], [23].

3.6 IoT in the Industry 4.0 context. The role of IoT becomes more pivotal when discussed in the context of the Fourth Industrial Revolution, also known as Industry 4.0 (I4.0) [8]. I4.0 represents a new phase in industrial revolution that focuses heavily on interconnectivity, automation, additive manufacturing, machine learning, and real-time data [23]. IoT serves as a backbone technology in Industry 4.0, providing the connectivity and data that drives other technologies such as Cyber-Physical Systems (CPS), Big Data Analytics, Artificial Intelligence, Digital Twins (DT), and 5G networks [24]. IoT systems in industrial settings, often referred to as the Industrial Internet of Things (IIoT), provide real-time monitoring and control of industrial processes, leading to improved efficiency, safety, and productivity [25]. IIoT is often characterized by the implementation of high levels of automation, large-scale operations, and critical infrastructures and it includes industrial applications such as manufacturing, supply chain management, and predictive maintenance, among others [23], [25].

Understanding the technical foundations of IoT requires a holistic view, incorporating elements of hardware (sensors, actuators), software (data processing, security), communication (connectivity, standards), and design (architectures) as well as of emerging Industry 4.0 technologies.

4 Technical Foundations of Circular Economy

A Circular Economy (CE) represents a paradigm shift from the conventional linear economy, advocating for an economic system aimed at eliminating waste and the continual use of resources [3]. This model hinges on the principles of reduction, reuse, recycling, and recovery of materials, often referred to as the "4Rs" that resemble the core of the European Union (EU) Waste Framework Directive [39]. Furthermore, the CE model is often extended with other levels of circularity, such as: refuse, rethink, repair, refurbish, remanufacture, repurpose [39].
However, the successful execution of CE relies on various technological foundations and its integration with digital technologies, including advanced recycling technologies,

modern product lifecycle management (PLM) strategies, emerging product-as-a-service (PaaS) business models, industrial symbiosis, and eco-design principles [6], [40], [41], [42]. The CE concept moves away from the traditional linear economic model characterized by the “take-make-dispose” approach to the “cradle-to-cradle” approach, aiming to create a closed-loop or regenerative system that significantly minimizes waste production and resource consumption [55], as depicted below in Figure 3.

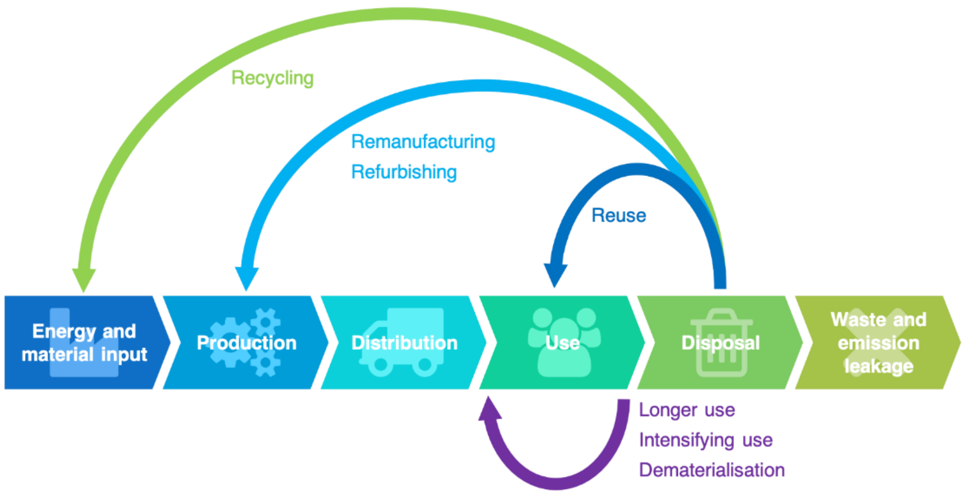

Fig. 3. Circular Economy Model (*adapted from [55], pg.4*)

The operationalization of the CE is fundamentally underpinned by a range of recycling technologies, product lifecycle management (PLM) strategies, product-as-a-service (PaaS) or product-service-systems (PSS) business models, industrial symbiosis practices, and eco-design principles [44], [45], [46], [47], [48], [51].

4.1 Recycling Technologies play a critical role in promoting the CE model by using innovative recycling technologies capable of effectively extracting valuable materials from waste products for further use. Advanced recycling technologies such as chemical recycling, mechanical recycling, and organic recycling are capable of processing diverse waste streams, including plastic, metal, glass, and organic waste [47].

4.2 Product Lifecycle Management (PLM) plays a pivotal role in the CE by overseeing the entire lifespan of a product from conception, design, and manufacturing, through to service and disposal [46], [48]. Modern PLM systems, enabled by digital technologies such as IoT, data analytics, and cloud computing, facilitate real-time tracking, analysis, and sharing of product-related information, fostering informed decision-making and enhanced efficiency [49].

4.3 Product-as-a-Service (PaaS) and Product-Service-Systems (PSS) represents a transformative business model that aligns with the principles of CE by transitioning from the traditional product ownership to service-based consumption [39]. This model incentivizes sustainable usage and longevity of products, as the responsibility for product maintenance and end-of-life management shifts to service providers [41]. In the PaaS model, IoT plays a key role in providing the necessary data for monitoring and maintaining product performance and reliability [48].

4.4 Industrial Symbiosis promotes the sharing and exchange of resources such as materials, energy, water, and waste by-products among diverse industries. This collaboration transforms wastes or by-products from one process into valuable resources for another, optimizing resource consumption and reducing waste output, aligning with the CE's sustainability objectives [50].

4.5 Eco-design Principles integrates environmental considerations at the early stages of product design and development, seeking to minimize the environmental footprint throughout a product's lifecycle. Strategies such as design for disassembly, design for repair, and design for recyclability can be applied, promoting the recovery, reuse, and recycling of product components and materials [6], [50].

The adoption of these technologies and strategies can significantly contribute to the circular economy's operationalization with the potential to enhance its efficiency, scalability, and impact [55]. However, their implementation involves technical challenges, including those related to technology development, system integration, process optimization, and data management [51]

5 Integration of Internet of Things and Circular Economy

The integration of Internet of Things (IoT) technology with Circular Economy (CE) principles presents a compelling opportunity to drive transformational change in our approach to resource use, waste management, and sustainable development [40]. In practice, IoT technologies enable the assets to actually act as intelligent assets and promote the circular business models and “Rs” circular strategies (i.e. refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover [39]) towards a smart circular economy [41], [52], as depicted below in Figure 4.

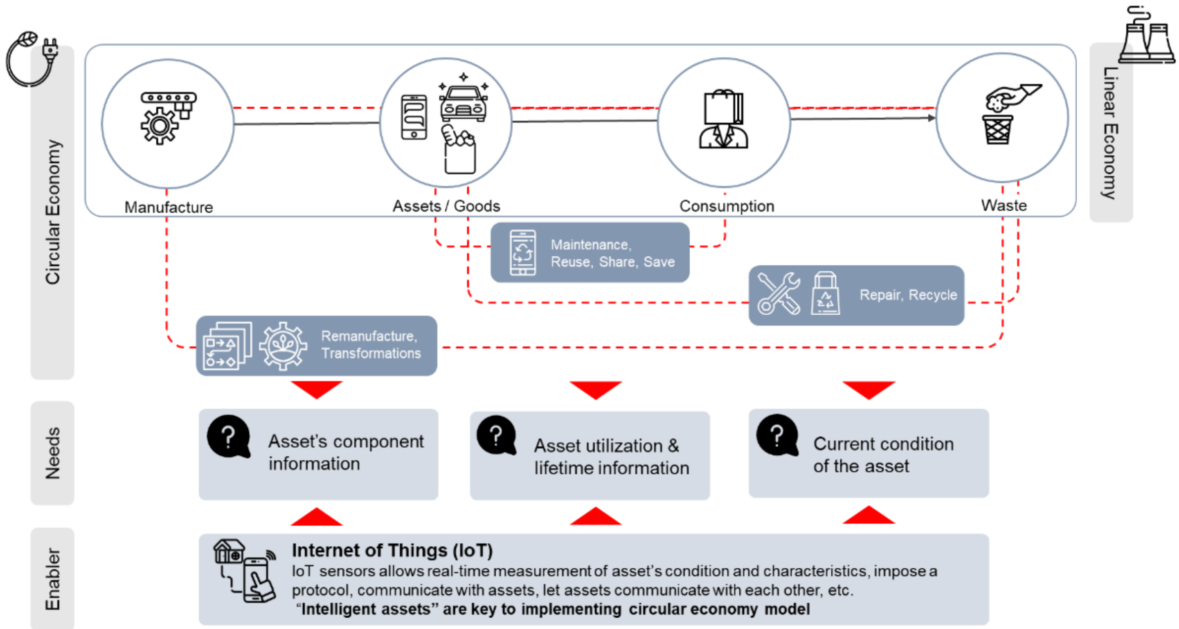

Fig. 4. Internet of Things integration with Circular Economy (*source: [52], pg.20*)

By leveraging the inherent capabilities of IoT, such as real-time sensing, monitoring and locate services, vast device connectivity and data communication, and data processing and analytics, the CE model can be significantly enhanced in terms of efficiency, visibility, and impact [52].

5.1 Resource Management. At the heart of CE lies the efficient utilization and conservation of resources [53]. IoT, with its pervasive sensing and connectivity, can contribute significantly to this goal. For instance, IoT can enable smart grids for efficient energy management, real-time monitoring of water usage, and intelligent manufacturing systems that optimize the use of raw materials [52]. Detailed data provided by IoT sensors allow businesses to pinpoint inefficiencies, wastage, and potential opportunities for smart resource optimization [40].

5.2 Waste Reduction and Management. IoT technologies are increasingly playing a vital role in smart waste management systems [53]. IoT-enabled waste bins and recycling stations can provide real-time data on waste levels and composition, which can aid in efficient waste collection and recycling schedules as well as optimize routes for waste collection vehicles and reducing carbon emissions [40]. Automated waste sorting and processing, guided by IoT technologies, can enhance recycling rates and minimize waste directed to landfills [47].

5.3 Asset Lifecycle Management. By tracking the entire lifecycle of a product, IoT technologies can support CE principles like product-as-a-service, repair, refurbishment, and recycling [53]. IoT devices, embedded within products, creates a new type of intelligent assets that can provide valuable information on product usage patterns, condition, and potential maintenance needs and end-of-life status [54], thereby extending product lifetimes, implementing timely repairs, and planning for efficient end-of-life disposal or recycling, effectively minimizing waste, and maximizing resource recovery.

5.4 Supply Chain Management. IoT technologies can provide unprecedented visibility into supply chains, enabling tracking and tracing of materials and products throughout their lifecycle. This transparency can help identify inefficiencies, reduce waste, and ensure the ethical and sustainable sourcing of materials. Such visibility is crucial for the establishment of circular supply chains, given their intricate stakeholder interactions and the need for resource flow coordination in identifying bottlenecks, inefficiencies, and waste generation points, thereby enabling their mitigation [55].

5.5 Circular Business Models. By facilitating the continuous collection and analysis of product performance and usage data, IoT paves the way for circular business models such as product-as-a-service or product-service-systems [48]. In addition, IoT capabilities for tracking, monitoring, and optimization promotes sustainable business models oriented towards as sharing economy, regenerative, and platform models [56]. IoT sensors embedded in products provide data on product usage and performance, enabling businesses to shift from selling products to offering services based on usage [53]. These models, underpinned by the 'use rather than own' philosophy, inherently promote sustainability, resource efficiency and waste reduction [52].

Despite the promising potential of integrating IoT and CE, a series of challenges exist, including those related to data privacy and security, technology interoperability, the design of sustainable business models, and the establishment of supportive regulatory frameworks [40].

7 Technical Challenges and Solutions

Integrating IoT and the Circular Economy (CE) offers numerous benefits, as evidenced by the examples presented. However, realizing these benefits is not without technical challenges. This section outlines the primary technical obstacles to integrating IoT and CE and presents potential solutions based on existing literature.

7.1 Data Security and Privacy. The exponential increase in data generation and collection due to the proliferation of IoT devices presents substantial data security and privacy challenges [20]. The distributed nature of IoT networks exacerbates these issues, as data breaches can occur at any point in the network [21]. One proposed solution is the application of advanced cryptographic methods, such as blockchain technology, to secure IoT data. Blockchain can provide decentralized, transparent, and tamper-proof data storage, enhancing data security in IoT applications [34]. Additionally, the implementation of stringent data privacy regulations and the application of privacy-by-design principles in IoT system development can contribute to addressing privacy concerns

[22].

7.2 Interoperability Issues, caused by the lack of standardization in IoT device manufacturing and software development, hinder the seamless integration of IoT devices [13]. Overcoming this challenge is crucial for the effective utilization of IoT in CE applications. The development and adoption of universal IoT standards, protocols, and architectures can enhance interoperability [13]. Efforts by international standardization bodies, such as the IEEE and the Internet Engineering Task Force (IETF), are making significant strides in this regard [57]. Additionally, the use of middleware platforms that provide interoperability solutions can bridge the gap between different IoT devices and systems [12].

7.3 Energy Efficiency. The energy consumption of IoT devices, particularly those powered by batteries, is a significant challenge for their deployment in CE applications. The need for frequent battery replacements not only increases the environmental impact of IoT devices but also contradicts the waste reduction principles of the CE [37]. Energy harvesting technologies, which convert ambient energy (e.g., solar, thermal, mechanical) into electricity, are potential solutions for powering IoT devices. These technologies can enhance the sustainability of IoT applications and align them with the CE principles [36]. Also, the development of low-power IoT devices and protocols can further improve the energy efficiency of IoT applications [35].

7.4 Data Overload and Management. The large volumes of data generated by IoT devices pose significant data management challenges, including storage, analysis, and the extraction of useful information [16]. These challenges, if not addressed, could hinder the effective use of IoT in CE. Technologies like cloud computing, fog computing, and edge computing can provide scalable and flexible data storage and processing solutions [15]. Also, the application of advanced data analytics [27], [28], machine learning and artificial intelligence [32], [33] can facilitate the efficient analysis of IoT data and the extraction of valuable insights, aiding in the realization of CE principles.

7.5 Data Ownership and Governance. The intricate web of stakeholders in IoT deployments (device manufacturers, service providers, end-users, etc.) raises complex questions about data ownership and governance [27], [58]. Deciding who holds ownership over the data generated by IoT devices and how this data is accessed, used, and shared represents a significant challenge [40]. The development of comprehensive data governance models and policies can address this challenge [52], [59]. Clear stipulations regarding data ownership, usage rights, and responsibilities can help establish transparency and accountability in IoT data management, aligning with the accountability principle of the CE [40], [59].

7.6 End-of-Life Device Management. The handling of end-of-life IoT devices poses a significant challenge, particularly concerning data privacy and electronic waste [60]. The disposal of IoT devices containing sensitive data can lead to privacy breaches, while the improper disposal of electronic waste contradicts the CE principles [3], [60]. End-of-life device management strategies, such as secure data deletion methods and recycling or repurposing schemes for electronic waste, can mitigate these issues [5], [35]. Adhering to the waste hierarchy of reduce, reuse, recycle can align the end-of-life device management with CE principles [43].

7.7 Scalability. As IoT deployments continue to grow, the ability to scale systems becomes increasingly critical. Given the massive number of IoT devices expected in the future, managing and processing data on this scale is a considerable challenge [6]. Scalability can be addressed through the use of technologies such as edge computing, which moves data processing closer to the data source, reducing the load on central servers [18]. Moreover, the use of scalable data processing technologies, like big data frameworks, can also help manage the large volumes of data generated by IoT devices [35].

7.8 Real-Time Processing. Many IoT applications, especially those in the context of CE, require real-time or near-real-time data processing to provide timely insights and responses [26]. The challenge lies in the ability to process vast amounts of data within the required time constraints [25]. Real-time data processing can be facilitated through the use of stream processing technologies, which process data on-the-fly as it is generated, as opposed to batch processing technologies which process data in large groups [28], [30]. In addition, Edge and Fog computing can also play a role in this, reducing latency by moving processing closer to the data source [15].

7.9 Lifecycle Tracking of Products. In a CE, the ability to track products throughout their lifecycle - from production to disposal - is of utmost importance [43]. IoT devices can provide this capability but enabling reliable, energy-efficient, and secure tracking for a myriad of different products and materials can be challenging [53]. Adoption of standardized communication protocols and energy-efficient tracking technologies (like RFID and NFC) can help overcome these challenges [13]. Secure data handling protocols can ensure privacy and security of the data generated during tracking [22].

7.10 Integration of Multiple IoT Systems. For the implementation of a CE, multiple IoT systems need to work in harmony - like manufacturing, logistics, and waste management systems [31]. Integrating these systems seamlessly can be a substantial challenge due to differences in data formats, communication protocols, and system architectures [30]. Data interoperability standards and use of middleware can enable seamless integration of different IoT systems. Middleware can abstract the differences between systems, allowing them to communicate effectively [12].

7.11 Enabling Behaviour Change. A significant aspect of achieving a CE lies in encouraging and enabling sustainable behaviour among consumers [4]. IoT can facilitate this by providing consumers with real-time feedback on their consumption habits [5]. However, making this information understandable, actionable, and engaging for consumers is a significant challenge [11]. Consumer-centric design and use of persuasive technologies can make sustainability information more engaging and effective in driving behaviour change [14], [17]. Gamification and social comparison features can also increase consumer engagement [49].

7.12 Integration with Existing Infrastructures. The integration of IoT technologies into existing industrial and societal infrastructures, such as manufacturing plants or urban environments, to promote a CE represents a substantial challenge. This is due to compatibility issues, as well as financial and operational constraints [23]. Adopting a gradual, modular approach to IoT integration can help manage these issues [52]. Retrofitting existing infrastructures with IoT devices can also be a cost-effective solution. Public-private partnerships can support the financial viability of such integrations [60].

7.13 Ensuring Circular Design of IoT Devices. While IoT devices can facilitate a CE, it's important to ensure that the devices themselves are designed following CE principles [60]. This includes the design for longevity, modularity, and recyclability. However, current market tendencies lean towards rapid obsolescence, which is at odds with the principles of a CE. Regulations and policies encouraging the design of sustainable IoT devices, along with market incentives for companies practicing such designs, can promote the circular design of IoT devices [44], [48].

7.14 Standardization. The lack of standardized protocols and interfaces in IoT is a major challenge in integrating IoT and CE [6]. Interoperability issues can arise due to the use of diverse hardware, software, and communication protocols in IoT devices [13]. Standardization bodies like IEEE and IETF can play a crucial role in the development and adoption of universal standards for IoT. This can enhance interoperability and ease the integration of IoT technologies in various sectors of a CE [57].

8 Future Technical Directions

As we continue to deepen our understanding of the intersection between IoT and CE, various promising research directions are emerging. Future research can aim to address the challenges we have discussed in this review and capitalize on the potential of IoT to drive CE.

8.1 Interdisciplinary Research on IoT and CE. A promising direction for future research is to explore the integration of IoT and CE from an interdisciplinary perspective, involving fields such as computer science, environmental science, economics, and social sciences. This would ensure the technological solutions developed are not only technically sound but also environmentally sustainable, economically viable, and socially accepted [49].

8.2 Advanced Data Analysis Techniques. Another important area of future research is the development of advanced data analysis techniques for processing and extracting insights from the vast amounts of data generated by IoT devices in a CE context. These techniques can include AI, machine learning, and predictive analytics, which can help in proactive decision-making and forecasting in CE [29].

8.3 Green IoT Technologies. Research should also focus on the development of Green IoT that are energy-efficient and have minimal environmental impact. This includes designing IoT devices that are modular, upgradable, and recyclable, thereby reducing e-waste [35].

8.4 Privacy and Security in IoT-CE. Given the pervasive nature of IoT and the sensitive nature of some of the data it generates, future research should address the challenges related to privacy and security in IoT-CE applications. This includes developing robust security protocols and privacy-preserving data handling mechanisms as well as post-quantum internet [38].

8.5 IoT-Enabled Life-Cycle Assessment (LCA) in CE. Developing IoT-enabled LCA methods can be another promising direction. This can involve using IoT devices to collect real-time data about products' environmental impact throughout their life cycle and leveraging this data to optimize product design and production processes [46].

8.7 IoT for CE in Industry 4.0. Future research can also focus on integrating IoT for CE in the context of Industry 4.0. This involves deploying IoT devices to facilitate resource optimization, predictive maintenance, and efficient waste management in smart factories, thereby promoting a more sustainable industrial sector [7], [24], [51], [73].

8.8 Circular Business Models Leveraging IoT. From a business perspective, investigating how IoT can enable new circular business models is an interesting research direction [43]. This includes developing business models that leverage IoT to provide product-as-a-service offerings, thereby extending the product lifecycle and reducing resource consumption [46].

8.9 Social Aspects of IoT-CE. The social aspects of implementing IoT in CE should not be neglected. Research can be conducted to understand users' perceptions, acceptance, and use of IoT technologies and to develop strategies to enhance user engagement and adoption [49].

8.10 IoT for Policy and Regulation in CE. The potential role of IoT in shaping policy and regulatory frameworks for the CE is another important future research direction. This might involve leveraging IoT data to inform policy decisions and regulatory strategies, thereby supporting the wider adoption and implementation of CE principles [3].

9 Conclusion

This comprehensive review article has systematically surveyed and synthesized the landscape of research at the intersection of the Internet of Things (IoT) and Circular Economy (CE) with an emphasis on understanding the technological foundations. The effort to intertwine these two revolutionary concepts is relatively novel yet holds remarkable potential for fostering sustainable systems that balance economic prosperity with ecological responsibility. We acknowledged that the capabilities offered by IoT - such as real-time data collection and analysis, ubiquitous connectivity, and intelligent decision-making - can serve as the digital backbone infrastructure that propels the operationalization of a CE domain towards the use of intelligent assets within smart and digital circular economy framework. However, our investigation also brought to light the inherent challenges and possible solutions in this convergence, including data privacy, security, and governance, interoperability among diverse IoT devices, energy efficiency, and managing the lifecycle of these very devices. In addition, we ventured into the realms of possibility, proposing areas of future research that could hold the key to further integrating IoT and CE. These areas included a call for interdisciplinary investigations, a focus on development of energy efficient and green IoT solutions, addressing the ever-present concerns around data privacy and security, and understanding the role and environmental impact of novel technologies implementation. In conclusion, while the integration of IoT and CE is still in its early stages, the emerging body of literature underscores the pressing need for the integration of IoT and CE could pave the way for innovative, intelligent, and sustainable systems and promoting the digital transformation of the circular economy and, at the same time, the circular transformation of the digital economy.

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