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Transforming sustainability with digital innovation: Enhancing circular economy practices for SDG 12

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ABSTRACT

This study aims to provide actionable insights into how digital technologies can be leveraged to advance circular economy (CE) practices in organizations. Future challenges in resource management and sustainability receive further attention. Semi-structured interviews were conducted with 15 global professionals from diverse industries. The analysis was carried out using Braun and Clarke's thematic analysis framework. Digital technology is critical for promoting CE practices in various industries. Blockchain, artificial intelligence, and the Internet of Things have emerged as powerful tools for advancing CE. We can alleviate waste and pollution, extend the life of products and increase their use intensity, recycle materials into the economy, and regenerate the environment through a circular approach. These innovations drive efficiency improvements and optimize resource use across various industries. Integrating digital tools holds significant potential to shift traditional linear economic models toward more sustainable and resource-efficient systems. Stronger partnerships between policymakers, businesses, and researchers will be essential in scaling digital solutions, driving responsible production and consumption, and ensuring long-term sustainability in a resource-conscious world. The study underscores industry perspectives and emerging trends, digital technologies can be effectively utilized to promote CE practices to ensure a sustainable future.

Contribution/Originality: This study provides original empirical insights into how digital technologies are applied in circular economy practices across industries. It addresses literature gaps by identifying real-world applications, practical challenges, and enabling factors, especially in the context of SDG 12 and proposes strategic directions for effective digital integration in CE models.

1. INTRODUCTION

The growing fragility of our planet, from crucial environmental challenges to social and economic ones, provides an adverse picture highlighting the importance of immediate action and concentration. The world experiences a rising amount of plastic trash, biodiversity is declining, and climate catastrophes are becoming more frequent. These are the significant concerns of 2025 (Robinson, 2025) making it imperative to form effective strategies for mitigation and adaptation. According to the United Nations, global natural resource consumption will increase by 60% by 2060 as compared to 2020. The United Nations has identified a triple planetary crisis—a crisis of pollution, biodiversity loss, and climate change as we approach the end of our resources (Robinson, 2025).

The industrial sector is also affected by environmental degradation as it contributes to and is adversely affected by environmental degradation (Ehigiamusoe, Lean, & Somasundram, 2024). Circular economy (CE) is considered one of the most important approaches to achieve sustainability because it promotes a closed-loop system that minimizes value losses from using raw materials, components, and products (Cagno, Neri, Negri, Bassani, & Lampertico, 2021). Sustainability challenges and achieving Sustainable Development Goals (SDGs) can be mitigated through the implementation of CE practices (da Silva & Ramos, 2025; Kurniawan & Fernando, 2023) particularly SDG12, which emphasizes "sustainable consumption and production patterns" (United Nations, 2025). This goal serves as a cornerstone of sustainability and fosters global sustainability practices. Over the past few years, SDGs and CE have increasingly intertwined (Ortiz-de-Montellano, Samani, & van der Meer, 2023). CE aims to replace the linear economic model of "take-make-use-lose" with cascading and renewing processes through which value can be retained. In other words, CE catalyzes the transition toward sustainability (Ortiz-de-Montellano et al., 2023).

Similarly, the emergence of digital technology in advancing CE has become increasingly evident. Embedding digital technologies in modern industrial and economic systems augments sustainable development within organizations, business functions, and practices (Varriale, Cammarano, Michelino, & Caputo, 2024). The unprecedented attention toward the amalgamation of digital technologies and the CE (Rosa, Sassanelli, Urbinati, Chiaroni, & Terzi, 2020; Schöggl, Rusch, Stumpf, & Baumgartner, 2023; Varriale et al., 2024) has yielded innovative insights into how the use of technologies, such as the Internet of Things (IoT), big data analytics, artificial intelligence (AI), and blockchain advances the transition toward a more regenerative economy, redesigning current business model and fostering responsible consumption and production following the principles and the goals of SDG 12 (Rejeb, Rejeb, Keogh, & Zailani, 2022).

Various digital technologies have different functions in advancing CE practices. Organizations can gain valuable insights into resource flows, thereby reducing waste, optimizing resource utilization, and promoting product reuse or recycling by using IoT (Hariyani, Hariyani, Mishra, & Sharma, 2024; Rejeb et al., 2022). Increasing reliability, transparency, and automation of information using blockchain technology is a key to enabling technology for CE. Using tracking technologies like GPS, it is easier to recycle, reuse, and upcycle waste materials (Edwin Cheng et al., 2022).

Depending on the situation, this technology can monitor CE performance and modify it as required. As a result of using these technologies, resources can be optimized, traceability can be increased, and product lifecycle management can be improved (Bahramimianrood, 2022). CE designs and develops durable, repairable, recyclable products that can be recovered for a sustainable future using AI-driven design tools (Ghoreishi & Happonen, 2020). Several studies have been conducted in the area of technology integration in the curriculum for early CE (Bressanelli, Adrodegari, Perona, & Saccani, 2018; Hariyani et al., 2024; Liu, Liu, & Osmani, 2021; Pagoropoulos, Pigosso, & McAloone, 2017; Rusch, Schöggl, & Baumgartner, 2023).

Although digital technologies are becoming more widely available, a large gap exists between academic literature and practical applications in CE. These concerns leave many questions regarding their effectiveness, scalability, and/or social impact (Hariyani et al., 2024). Despite their infancy, CE and digital technologies are rapidly developing. Neither field has been explored so far in terms of integrating the two disciplines (Bressanelli et al., 2018; Liu et al., 2021).

Though digital technologies have been discussed extensively and systematic reviews have been conducted, little empirical research has been done. Data-driven research to assess real-world applications and outcomes is lacking at the moment which leads to significant gaps in theoretical, conceptual, and literature-based research (Cagno et al., 2021; Chi, Liu, Wang, & Osmani, 2023; Han et al., 2023; Liu, Trevisan, Yang, & Mascarenhas, 2022;

Okorie et al., 2018). The lack of empirical evidence hinders understanding of how digital technologies can be effectively incorporated into CE models (Andoh-Baidoo, 2016; Bressanelli et al., 2018; Trevisan, Zacharias, Liu, Yang, & Mascarenhas, 2021).

This study aims to contribute to expanding the literature by offering empirical insights into how digital technologies are being incorporated into CE practices, particularly within the context of SDG12. In the past few years, several studies have carried out literature reviews and constructed conceptual frameworks (Khan & Khusro, 2021; Kristoffersen, Blomsma, Mikalef, & Li, 2020; Liu et al., 2022; Okorie et al., 2018). It is still difficult to understand practical applications across a variety of industries due to a significant gap in knowledge (Hariyani et al., 2024). Liu et al. (2022) pointed out that in terms of what role digital functions can play in enhancing CE strategies, there seems to be an absence of empirical evidence. Even as technology advances, Rodrigo, Omrany, Chang, and Zuo (2023) pointed out the challenges associated with implementing digital technologies in CE different industries. Furthermore, there is also a lack of comprehensive analyses of how digital technologies relate to various aspects of the CE in the literature (Cagno et al., 2021).

This study addresses these gaps by offering practical applications, identifying contextual barriers and enablers, and outlining strategic pathways for integrating digital technologies into CE models. This work expands the scope of CE research through a multidisciplinary lens focusing on the intersections of sustainability, innovation, and digital transformation, which are particularly relevant to CE research today. A better understanding of these gaps is needed to resolve them. This study utilizes it to uncover empirical findings that may help to resolve these gaps and provide a wide range of actionable insights into how digital technologies can be leveraged to further the advancement of CE practices in organizations and facilitate the transition to future environmental challenges. The following research questions guided this study:

1. How are digital technologies currently being utilized to facilitate circular economy practices across industries?
2. What are the key barriers and enablers in aligning digital technologies with the objectives of SDG 12?
3. What strategies can be developed to optimize the integration of digital technologies into circular economy models to achieve SDG 12 targets?

2. LITERATURE REVIEW

Sustainable resource management relies on CE to minimize waste, extend material life cycles, and reduce environmental impacts. CE differs from the traditional linear economy based on a take-make-dispose model (Hariyani et al., 2024). CE operates at three levels, micro (individual firms), meso (industrial systems and networks), and macro (societal or national level) (Cagno et al., 2021). While primarily focused on environmental sustainability, CE is also linked to economic and social dimensions.

Initially, the CE framework was built on the 3Rs (reduce, reuse, recycle) but it has evolved to incorporate additional principles, expanding into the 6Rs (redesign, reduce, reuse, remanufacture, recycle, recover) and later the 9(10) Rs framework, which includes refuse, redesign, reduce, reuse , repair, refurbish, remanufacture, repurpose, recycle, recover (Cagno et al., 2021). This shift marks a transition from a linear consumption model to one that prioritizes material circulation, resource efficiency, and environmental stewardship.

CE has been gaining traction in contemporary sustainability discussions, emphasizing proactive resource management and the development of sustainable economic systems (Hariyani et al., 2024). CE fosters a shift toward a more regenerative and sustainable future by closing material loops and reducing material extraction.

By 2050, humans will require three planet Earths to satisfy their needs, emphasizing the importance of CE and sustainable development goals (Circular, 2018). According to the UN (2015), 17 specific SDGs and 169 targets exist. As part of circularity strategies, a value retention framework was utilized to establish the inventory. According to CE strategies, responsible consumption and production (goal 12) are the next most frequently addressed SDGs. (Sharma et al., 2021). The CE framework has expanded and become more relevant globally making CE a key strategy for achieving SDG 12 on emphasizing waste prevention, reduction, and recycling (Valverde & Avilés-Palacios, 2021). CE significantly benefits resources and the environment. Therefore, regional and global initiatives have incorporated their principles into sustainability policies. For example, the European Commission's CE Action Plan outlines strategies for improving resource efficiency. The Asia-Pacific Framework Agreement on Facilitating Cross-Border Paperless Trade is a regional agreement promoting sustainable trade practices (Xue, 2017). Furthermore, advancements in digital technology have reinforced CE's effectiveness. According to Hariyani et al. (2024), IoT, AI, big data analytics, and blockchain are digital technologies that allow organizations to optimize resources, track product lifecycles, and improve practices. Digital technologies enable better life cycle analysis, leading to more sustainable product design. CE enhances long-term environmental and financial resilience through technological innovation.

Digital technologies can offer many benefits to CE, but they face many challenges when it comes to their adoption. SMEs face high implementation costs of digital transformation. Digital technologies, such as hardware, software, training, and infrastructure are prohibitively expensive for SMEs. According to Agrawal et al. (2025), investing in skilled labor, new technology, and larger infrastructure is necessary to implement CE effectively, resulting in a high up-front investment.

CE can be implemented using diverse digital tools and platforms but the short-term financial outlook in the healthcare industry presents significant barriers. It requires expertise in IT, data management, and systems integration (Agrawal et al., 2023; Trevisan, Lobo, Guzzo, de Vasconcelos Gomes, & Mascarenhas, 2023). Ensuring data privacy and confidentiality is essential to adhere to regulatory requirements. Breaches or unauthorized access may undermine trust in the data. Hariyani et al. (2024) highlighted that data collection, storage, and sharing entail risks, especially regarding sensitive information about product life cycles and their environmental impact. Bag et al. (2022) identified data security and privacy concerns as key obstacles in digital manufacturing for CE. Kumar and Chopra (2022) mentioned that technologies like blockchain and IoT also heighten these challenges, necessitating robust safeguards to maintain data integrity and stakeholders' confidence. The widespread adoption of CE initiatives is hindered by disparities in access to digital technologies, as well as financial constraints and data security concerns. Inequalities in technology access can significantly increase social and economic disparities and limit the participation of marginalized communities in CE initiatives (Fehrer, Kemper, & Baker, 2024; Lee, Babcock, Pham, Bui, & Kang, 2023; Rejeb et al., 2022). Policy support, stakeholder collaboration, and innovation ecosystems offer opportunities for scaling digital solutions despite these challenges (Rusch et al., 2023). Targeted regulations and incentives can encourage sustainable practices and the adoption of innovative technologies, resulting in investments in technologies, such as IoT, blockchain, cloud computing, and AI (Hariyani et al., 2024). These technologies improve resource efficiency, waste management, and supply chain transparency. The government can accelerate digital adoption by funding key technologies supporting sustainable development (Hariyani et al., 2024). Effective collaboration and coordination among stakeholders reduce logistics costs and eliminate waste throughout the supply chain (Schöggl et al., 2023). Furthermore, digital innovation platforms facilitate cross-border interactions, improve services, and minimize risks through access to tools and resources (Gasc & Sandquist, 2014). The Digital Public Infrastructure (DPI) enables scalable, inclusive, and sustainable digital solutions. Seamless integration can be achieved by focusing on interoperability. An ecosystem-driven approach ensures a whole-of-society impact (UNDP, 2023).

3. RESEARCH METHODOLOGY

3.1. Research Design

This research empirically explores digital technologies' role in enhancing CE practices to achieve SDG12, focusing on responsible consumption and production. According to the interpretivism philosophy, qualitative research is most appropriate when the phenomenon is relatively new and not well understood (Patton, 2014). The study was conducted using an interpretivist research design and qualitative methods. Interpretivist philosophy emphasizes in-depth analysis of variables and factors in a given context (Alharahsheh & Pius, 2020).

3.2. Participants of the Study

We gathered data from fifteen professionals working in different industries globally to better understand the role of digital technologies in advancing CE practices. The following inclusion criteria were used to recruit the respondents for interviews:

1. Professionals, researchers or policymakers involved in digital technology, CE or sustainability initiatives.
2. Minimum 5 years of experience in digital transformation, waste management, sustainable manufacturing, supply chains, research, and policy development.
3. Practical experience implementing or researching AI, IoT, blockchain, big data, or other digital innovations for sustainable consumption and production.

3.3. Sampling Strategy

This study employed the snowball sampling technique to collect data. This non-probability sampling method relies on participants recruiting other participants, creating a chain-referral process. It is beneficial for reaching hard-to-access populations as initial subjects are connected to others within their networks (Vogt & Johnson, 2011). In sociology, psychology, and management studies, snowball sampling is recommended when the population cannot be precisely delimited or detailed. This type of sampling has several characteristics, including that it is not used to estimate the characteristics of the general population but rather to estimate the characteristics of a network of very small populations (rare and difficult to identify) that are not incorporated into the general population. Table 1 contains details about the participants' demographics.

Table 1. An overview of the participants' demographic information (N=15)

Pseudonym	Gender	Country	Industry	Experience (years)
1. Faraz	M	Pakistan	Tourism and hospitality	18
2. Shahzad	M	China	IT	10
3. Arif	M	Ireland	Education (higher)	5
4. John	M	England	Education (higher)	15
5. Jessy	F	Pakistan	IT	11
6. Mike	M	Malaysia	Food processing and packaging	12
7. Ahmed	M	Malaysia	Automotive	10
8. Salah	M	Malaysia	Consultancy	12
9. Zahra	F	Malaysia	Healthcare	11
10. Naseem	M	Malaysia	IT	10
11. Decklan	M	England	Education (higher)	8
12. Shen	M	Portugal	IT	10
13. Farah	F	Singapore	IT	5
14. Saif	M	Malaysia	Manufacturing	8
15. Sajjad	M	Malaysia	E-commerce	8

Note: M: Male; F: Female.

3.4. Data Collection Process

The interviews were semi-structured which allowed for more exploration. We developed an interview guide to explore participants' perspectives on the research objectives. Eleven main interview questions were asked, namely, two role-specific questions for technology developers and two for industry practitioners were additional. The interview guide's first draft was sent to three experts with research questions to verify its validity. Once experts validated the interview guide, we made a few minor corrections based on their feedback; then, we conducted a pilot study with three participants with similar characteristics as our main sample. The pilot study results were satisfactory. Once our interview guide was ready, we contacted each participant through WhatsApp and phone to confirm the interview time and date for data collection. At the same time, we obtained their consent in writing to participate in the interviews. Following the research protocol, the interviews were recorded with participants' permission only for research purposes. All interviews were conducted online.

3.5. Data Analysis Process

Braun and Clarke's (2006) 6-phase coding framework guide for thematic analysis was used as the methodological foundation for this study. The 6 phases included familiarization of data, generation of codes, combining codes into themes, reviewing themes, determining the significance of themes, and reporting of findings.

Two authors reviewed each interview transcript. It was possible to determine the inter-rater reliability by selecting about 20% of the cases from the total sample. We achieved a high contract score of 93 % which indicates a strong agreement with an alpha of 0.85, according to Krippendorff's based on the independent coding of these cases (Nahavandi, 2019). The high inter-rater reliability noted above indicates strong consistency and impartiality in the inclusion judgments (Narvaez Rojas, Alomia Peñafiel, Loaiza Buitrago, & Tavera Romero, 2021). Interrater reliability is considered one of the significant steps in qualitative data analysis. It reduces bias and improves the trustworthiness of the data.

3.6. Ethical Considerations

Informed consent was obtained from all participants as part of the ethical considerations for this study. Furthermore, participants' personal information was not asked during interviews. In the paper's results section, we replaced the participant organization's name with ABC to maintain confidentiality. They were assured that all information would be used only for research purposes. Respondents were allowed to withdraw from the study during data collection. UNITAR International University Malaysia's Research Ethics Committee approved the study's ethical protocols on December 1, 2024 (Ref No. UNITAR/FEH/REC/2024/12/01).

4. RESULTS

In this section, we present the overall results of interviews conducted with professionals across various industries regarding the role of digital technologies in advancing CE practices. The results were structured according to the research questions based on insights from interviewees. Table 2 summarizes the themes and coding process.

Table 2. An overview of the data analysis results

Number	Themes	Codes generated	Sample codes
1	Understanding of CE	44	Sustainable model Minimizing waste Maximizing resource Reuse, recycle, and refurbish materials Economic model Waste minimization
2	Integration of digital technologies into the CE	46	IoT for smart waste management and energy optimization AI for predictive analytics and waste reduction Blockchain for supply chain transparency Cloud-based solutions to reduce Environmental impact Energy-efficient computing and smart infrastructure Automated waste management and recycling technologies Digital twins for circular product lifecycle

Number	Themes	Codes generated	Sample codes
			optimization
3	Challenges and barriers	53	Financial barriers and high initial costs Technical barriers and complexity Regulatory challenges Resistance to change and organizational culture Infrastructure and integration issues Cybersecurity and data protection concerns Consumer and market awareness challenges
4	Enablers and key success factors	43	Affordability and cost-effective solutions Capacity building and digital literacy Collaboration and stakeholder engagement Policy support and regulatory alignment Cloud-based and digital infrastructure E-waste reduction and sustainability initiatives AI-driven analytics and predictive models
5	External stakeholder role	37	Government support and policy incentives Business collaboration and innovation Consumer awareness and demand for sustainability Public-private partnerships and shared learning Recycling systems and industry engagement Technology accessibility and digital inclusion NGO and partnerships for sustainability
6	Emerging technologies and trends	43	Government support and regulations Business innovation and investment Consumer awareness and education Public-private partnerships Recycling systems and initiatives Technology accessibility and digital inclusion Industry collaboration and knowledge sharing

5. DIGITAL TECHNOLOGIES IN FACILITATING CE PRACTICES

5.1. Understanding of CE

We can alleviate waste and pollution, extend the life of products and increase their use intensity, recycle materials into the economy, and regenerate the environment through a circular approach. A CE seeks to create value and jobs by utilizing sustainable materials, reducing waste, implementing practices that ensure products will last, and emphasizing design for end-of-life consumption (Carlo Giardinetti, 2025). The following insights from respondents reflect their understanding of CE:

> Mr. Arif, from higher education, who has vast experience in research in different countries commented that *the CE is a model that emphasizes resource efficiency, waste reduction, and sustainable development. It aligns closely with my work at the university of ABC where I focus on educational sustainability, leadership for sustainable development, and the UN Sustainable Development Goals (SDG4).*
>
> Mr. Faraz from the tourism and hospitality sector explained that *the CE is a sustainable model that minimizes waste and maximizes resource efficiency by reusing, recycling, and refurbishing materials and products. In the tourism industry, this translates to reducing the environmental footprint of operations, promoting sustainable tourism practices, and ensuring that resources are used responsibly.*
>
> Mr. Shahzad from the IT sector and with over a decade of experience as an IT developer defined the CE *as an economic model focused on minimizing waste and maximizing resource efficiency through recycling, reuse, and sustainable design as part of my institution's commitment to CE, I promote sustainable IT practices, optimize computing energy, and conduct AI-driven research focused on resource optimization.*

5.2. Role of Digital Technologies in CE

Digitization enables and accelerates CE practices in various industries by circularly positioning information flows (Kristoffersen et al., 2020).

Digital technologies contribute to resource optimization through the Internet of Things, blockchain, artificial intelligence (AI), and big data analytics. Waste management can be improved using IoT-enabled sensors as well as real-time waste sorting and recycling. Supply chains with blockchains are more transparent, traceable, and accountable. Machine learning and predictive analytics applications have been praised for increasing efficiency and improving product evaluation.

As Mr. Arif pointed out, *several digital technologies have enabled the university ABC to practice CE practices that promote environmental sustainability using digital technologies in the past few years. IoT is integrated into campus operations to improve energy efficiency, track resource consumption, and implement sustainable waste management strategies based on AI.*

Mr. Faraz from the tourism and hospitality sector explains that *we use IoT sensors to monitor the energy and water consumption across all our properties in real-time. With AI-powered analytics, we can predict tourist footfall to optimize resource allocation and reduce overstocking. Our team is exploring blockchain to create transparent supply chains for locally sourced products, ensuring sustainability and fair trade.*

Ms. Jessy, an experienced IT expert explained *that CE principles can be applied through software optimization, digital product lifecycle management, and innovative resource utilization in IT. My organization focuses on software development for businesses that helps them optimize resource use, reduce paper dependency, and implement sustainable digital solutions.*

5.3. Emerging Technologies and Trends

The World Economic Forum emphasizes the need to accelerate the transition to a CE to meet global climate goals by 2050, identifying digitalization as a critical driver of this transformation (World Economic Forum, 2021).

As industries seek more sustainable and resource-efficient solutions, emerging technologies, such as digital twins, decentralized digital infrastructures, AI-driven automation, next-generation IoT networks, and robotics are gaining attention for their potential to enhance CE practices. These innovations offer advanced capabilities in secure data management, real-time process optimization, and autonomous decision-making, helping businesses build more resilient and scalable CE models (Rusch et al., 2023; Schöggl, Stumpf, & Baumgartner, 2024). Technologies like big data, cloud computing, cyber-physical systems, blockchain, and virtual and augmented reality may significantly promote CE concepts and programs by governments, organizations and society (Andoh-Baidoo, 2016; Kerin & Pham, 2019; Shahidi Hamedani, Aslam, Mundher Oraibi, Wah, & Shahidi Hamedani, 2024; Shahidi Hamedani, Aslam, & Shahidi Hamedani, 2025).

Smart contracts based on blockchain can also enhance data integrity across global CE networks. Robots and automation also enable circular systems to be more efficient and human-reliant, especially regarding waste sorting and material recovery. CE is becoming more autonomous, data-driven, and scalable. The following excerpts provide an overview of the participants' experiences in this context:

Mr. Shahzad from the IT sector commented that *emerging technologies, such as AI, blockchain, and digital twins hold great promise for advancing CE practices. AI-driven predictive maintenance can reduce waste and extend product lifecycles, while blockchain ensures material sourcing and recycling transparency. Digital twins enable businesses to optimize resource efficiency and reduce waste through real-time monitoring.*

Mr Deckalan from academia with vast experience at higher education institutions in different countries said that e*merging trends like digital twins, advanced robotics, and improved machine learning algorithms are up and coming. Digital twins allow us to simulate and optimize resource use before making physical changes.*

Mr. Mike from the food processing and packaging industry hoped based on his experience that *automated robotic machines would collect waste and automatically segregate it in the futur*e as we tried prototypes in our industry.

5.4. Key Barriers and Enablers in Aligning Digital Technologies with SDG 12

5.4.1. Challenges and Barriers

Several barriers prevent their widespread adoption and alignment with SDG12 while digital technologies can drive CE practices forward. There are several challenges, including financial constraints, technological limitations, complexities in regulations, and organizational resistance. The following excerpts provide an overview of the participants' experiences in this context:

5.4.2. Financial and Investment Barriers

Several roadblocks limit CE initiatives, including high investment costs associated with equipment, software, training, integration with existing systems, and high upfront costs (Agrawal et al., 2025). Furthermore, uncertain returns on investment (ROI) and lengthy payback periods prevent companies from investing significantly in digital transformation. This issue is described by Kumar and Chopra (2022). Many businesses hesitate to embrace digitalization due to unpredictability and budget limitations.

An interviewee from the tourism industry commented that *the initial investment in digital technologies like IoT and AI can be high, especially for smaller businesses. There's a lack of skilled personnel to manage and maintain these technologies in remote areas like the ABC area in an Asian country.*

An interviewee from the food and processing industry explained that *financial barriers are the biggest challenge to spending on digital tools and would require a more significant budget, which most recycling plant owners do not have.*

From the automotive industry, Mr. Ahmed explained that *while the CE initiative is a priority for the company, there is little budget allocated to the project as the company is facing some challenges; hence, the company has become more frugal lately.*

5.4.3. Technical Barriers and Digital Literacy

CE practitioners face a significant challenge due to a lack of technical expertise when it comes to implementing and managing IoT networks, AI-driven analytics, and blockchains, and the integration of legacy systems with modern digital solutions is a challenge in many organizations (Trevisan et al., 2023). The lack of skilled workers in data science, cybersecurity, and system interoperability hinders digital adoption. One of the respondents emphasized that resistance from employees due to a lack of technical training remains a persistent issue, emphasizing that the transition to digital requires an investment in workforce upskilling. This implies the need for employees to be trained continuously to navigate digital transformation in CE. It is essential to access appropriate and accurate information when you are making the decision.

A respondent noted that *planning requires data and insights. It is essential to be able to access accurate data and relevant insights during this process as well as to select and deploy the right technologies.*

Data management strategies are essential for developing valuable insights with digital technologies. Finally, digital literacy remains a barrier to CE initiatives since many industries lack adequate training to leverage digital technology (Ramanathan & Indiran, 2021).

One of the respondents pointed out *CE goals can be achieved through digital technologies but there are current limitations to this adoption, including the technical weakness of AI and IoT integration, the financial difficulty of large-scale adoptions, and the compliance with data protection laws. Furthermore, additional barriers to adoption include stakeholder resistance and the need for digital literacy training.*

5.4.4. Regulatory and Compliance Challenges

CE regulations complicate digital technology implementation. Data privacy, cybersecurity, and environmental protection standards make it difficult for business owners to implement consistent solutions across borders. For instance, GDRP complicates supply chain tracking systems (Hariyani et al., 2024).

An interviewee from the IT sector explained that *to integrate IoT, AI, and cloud-based systems with the ability to gather and process enormous amounts of data, huge amounts must be collected and processed. However, it can be difficult to comply with regional or international data protection regulations and navigate data privacy laws, such as GDPR or CCPA.*

Another respondent pointed out that *several challenges need to be overcome when adopting digital technologies for CE goals, including limitations relating to integrating artificial intelligence and IoT, financial constraints on implementing large-scale systems, and compliance with laws governing data protection.*

6. ENABLERS AND KEY SUCCESS FACTORS

Digital technologies can be effectively integrated into SDG12 while aligning with several critical enablers through CE frameworks. In addition to government financial incentives, industry collaborations, and comprehensive training programs, there is also government support.

6.1. Government Policies and Financial Incentives

Governments can promote digital technology adoption through robust policies, tax incentives, subsidies, and technical assistance. Businesses are motivated to invest in sustainable technologies when regulations are well crafted and financial uncertainty is reduced for digital transformations when regulations are well crafted (Hariyani et al., 2024). Schöggl et al. (2024) mentioned that providing financial backing and regulatory guidance to this transition has proven essential to advancing CE principles.

One of the respondents commented that *policymakers, developers, and industry practitioners were willing to collaborate to adopt EVs but it took time and effort to achieve that.*

One of the respondents from IT mentioned that *Intel also advocates policy changes that can incentivize businesses to invest in sustainable technologies and CE models.*

One of the respondents from a developing Asian country mentioned an example of *successful collaboration in the country's startup ecosystem where tech companies work with the government to digitize waste management. However, challenges arise from bureaucracy and a lack of streamlined communication.*

6.2. Collaboration and Knowledge Sharing

Collaboration across industries and partnerships between public and private sectors play a critical role in promoting the advancement of CE principles through digitalization. Businesses can facilitate the exchange of knowledge and foster the development of interoperable solutions by leveraging shared platforms, open data ecosystems, and collaborative research efforts. Organizations that participate in collective problem-solving approaches are better positioned to address technological challenges and enhance the effective integration of digital technologies (Schöggl et al., 2024).

Mr. Arif from the higher education sector recommended that *scaling digital solutions globally to support CE initiatives requires collaboration, policy support, education, accessible technology, data transparency, and scalable models.*

Mr. Fraz from the tourism industry recommends that *governments encourage circular practices through tax breaks and subsidies for eco-friendly technologies. Collaboration with tech providers can help develop affordable, localized solutions.*

Mr. John from the higher education industry suggested that it is possible to reduce costs by *using knowledge sharing among different sectors, speed up the adoption of proven solutions across sectors, and improve the effectiveness of the solutions when used together.*

6.3. Workforce Training and Digital Literacy

Transitioning to digital CE models requires digital skills training. Enhancing workforce capabilities will enable organizations to fully utilize AI, blockchain and IoT applications.

One of the respondents mentioned that *the use of training programs can help smaller businesses adopt these technologies effectively so that they can benefit from them. Continuing stakeholder resistance and a lack of digital literacy training are barriers to adoption.*

Similarly, another respondent mentioned that *tailored approaches, such as subsidized tools and training programs, community-based initiatives, and low-tech solutions, are required for smaller businesses and developing regions to succeed.*

7. EXTERNAL STAKEHOLDER ROLE

Governing bodies, businesses, and consumers must adopt digital technologies within the CE framework and ensure adherence to SDG12. Participants' insights highlight the importance of collaboration. A cooperative approach is key to overcoming obstacles and ensuring widespread adoption. These stakeholders influence policies, business innovation, and consumer engagement. The CE considers each component critical for expanding digital solutions. Sustainable CE initiatives require the involvement of policymakers, business leaders, and academics.

One respondent emphasized *that the success of CE adoption requires a strong policy framework that provides strong incentives so businesses can invest in the digital solutions they need.*

SDG 12's sustainability ambitions must align with digital transformation efforts to successfully integrate CE strategies. According to Ortiz-de-Montellano et al. (2023), the CE strategy can be evaluated for effectiveness, ensuring that it incorporates key sustainability elements and achieves measurable results based on established pathways. Using these frameworks can improve the sustainability and innovation of digital CE initiatives.

A respondent mentioned that government subsidies for energy-efficient manufacturing have accelerated the adoption of AI-driven process optimization in the UK. *At the same time, Unilever's use of blockchain technology ensures ethical sourcing of palm oil. Rising consumer demand for sustainable products has led Patagonia to adopt circular models, such as repair and resale programs, and the EU's CE action plan sets a standard for sustainable product design.*

7.1. Governments and Policymakers

Creating a regulatory framework that facilitates the integration of digital technologies within the CE is the responsibility of governments and policymakers. Companies can adopt digital solutions through well-defined policies and financial and technical assistance. Robust governance structures ensure compliance in addition to protecting data privacy, cybersecurity requirements, and sustainability goals (UNDP, 2023). Several policy measures, such as carbon credit programs and waste reduction incentives can strengthen the adoption of CE (Hariyani et al., 2024).

As described by one of the respondents, there are inconsistencies in waste management policies across provinces in Pakistan, which makes it very difficult to enact standardized circular practices across all provinces of the country.

Policymakers must balance regulatory oversight with innovation. When regulations are too rigid, it may discourage companies from investing in digital advancements. In contrast, when policies are too lenient, it could foster non-compliance and greenwashing on the part of companies (Schöggl et al., 2024). Moreover, governments must prioritize harmonizing cross-border data regulations making it easier for international businesses to navigate multiple regulatory environments.

One respondent reinforced this issue, pointing out that *regulatory challenges, such as worries about personal data privacy and compliance requirements can also hinder digital solutions. A well-balanced policy can ensure compliance standards are upheld in conjunction with allowing for innovation, which underlines the importance of well-balanced policies.*

Another respondent mentioned that governments and policymakers have spent a lot of effort and money to develop and adopt EVs and both tech developers and industry practitioners are willing to join forces and put money into this technology.

One respondent mentioned that the *first step is policy. EPR policies should cover all materials, and the second step, collection and recycling infrastructure should be established to ensure a systematic process for recycling.* Consumers ' awareness of segregating waste and recycling is crucial throughout this process.

Another respondent mentioned that *scaling digital solutions globally to support CE initiatives requires collaboration, policy support, education, accessible technology, data transparency, and scalable models.*

8. DISCUSSION

8.1. Digital Technology Utilization to Facilitate CE Practices across Industries

The findings of this study underscore the vital role that digital technologies play in promoting CE practices across various industries. Through practical applications, industry perspectives, and emerging trends, integrating digital tools holds significant potential to shift traditional linear economic models toward more sustainable, resource-efficient systems. Digital technologies such as IoT, blockchain, and AI have emerged as pivotal tools in advancing the principles of the CE. These innovations drive efficiency improvements, reduce waste, and optimize resource use across various industries.

8.2. Digital Technologies Enabling CE Practices

IoT sensors enable energy and water usage monitoring and provide industries with actionable insights to identify and address inefficiencies promptly. One major electronics manufacturer has seen a 20% reduction in scrap rate after using AI-based predictive analytics. Moreover, blockchain technology is increasingly utilized to enhance the transparency and traceability of supply chains in an attempt to improve collaboration between parties. This aligns with the findings of Varriale et al. (2024) who noted that blockchains and other digital technologies can help organizations achieve the SDGs. AI enables companies to anticipate resource needs accurately, optimize production processes, and extend their products' lifecycles using its advanced predictive analytics.

Several prominent IT companies offer AI applications to support predictive maintenance, efficient resource management, and circular product life cycle optimization. Sustainable practices are strengthened through these technologies and resource management is transformed within CE frameworks, empowering more efficient and responsible businesses (Noman, Akter, Pranto, & Haque, 2022). Digitalization in their CE initiatives has greatly benefited the tourism, education, healthcare, and IT sectors.

IoT helps track resources in hotels and travel operations in tourism enabling businesses to lessen their environmental impact, encourage sustainable tourism, and use resources responsibly (Gutierriz, Ferreira, & Fernandes, 2023). Meanwhile, IT companies are at the forefront, employing cloud-based solutions to reduce hardware waste and improve software lifecycles. This resonates with a respondent's observation. In IT, CE principles can be applied through software optimization, digital product lifecycle management, and smart resource utilization, enabling businesses to optimize resource use, reduce paper dependency, and implement sustainable digital solutions as endorsed by a study (Chinamanagonda, 2022).

As industries increasingly adopt sustainable and resource-efficient practices, emerging technologies such as digital twins and robotics are gaining prominence due to their capacity to advance CE initiatives. Digital twins, virtual representations of physical products or systems are being utilized rapidly to enable businesses to simulate, monitor, and optimize resource utilization in real time. These tools empower companies to track product lifecycles, identify inefficiencies, and implement predictive maintenance strategies, enhancing product longevity and minimizing material waste (Gutierriz et al., 2023).

Various waste sorting and recycling processes are changing as a result of the advances in robotic technology (Koskinopoulou, Raptopoulos, Papadopoulos, Mavrakis, & Maniadakis, 2021). Humans are spared the job of sorting while work is done more efficiently by automating material recovery. It aligns with responses highlighting robotic automation as a critical step in strengthening waste collection and segregation CE operations.

Moreover, integrating AI and machine learning fuels predictive analytics to refine resource use and identify inefficiencies before they become inefficient (lo Conte, 2025). This proves especially significant in waste management, manufacturing, and energy optimization where AI-powered models guide organizations toward more circular and sustainable practices. Moreover, such technological advances highlight a broader move toward an automated, data-driven, and adaptable CE framework in which digital tools enhance resource efficiency, boost operational performance, and foster enduring sustainability.

8.3. Aligning Digital Technologies with SDG 12: Barriers and Enablers

Digital technologies have tremendous potential to advance CE while facing significant challenges in their widespread implementation. Three primary obstacles are identified in this study, namely, financial constraints, technical difficulties, and the complexity of regulation.

8.4. Financial Constraints

A significant investment is required to deploy digital technologies. Implementing successful shifts is challenging for businesses of all sizes, especially SMEs. Infrastructure, software, and employee training are integral to success (Babina, Fedyk, He, & Hodson, 2024). Several respondents noted that uncertainty about returns complicates rationalization efforts, preventing adoption. Often, smaller companies fail to spend money on new initiatives without guaranteeing long-term benefits. Financial constraints also slow the development of skills for new technologies, aggravating implementation challenges (Eapen, Yeo, & Sasidharan, 2019).

8.5. Technical Constraints

CE cannot efficiently deploy and monitor IoT networks, AI-powered analytics, and blockchain systems due to a lack of technical expertise and digital literacy. Several organizations are contending with outdated legacy systems that are difficult to integrate with contemporary digital solutions. Employee training is often inadequate, hampering their ability to leverage digital tools. Companies improve their performance, foster innovation, and become more committed to digital transformation through increased organizational involvement by providing training (Nicolás-Agustín, Jiménez-Jiménez, Maeso Fernandez, & Di Prima, 2025).

Furthermore, a lack of seamless integration between different software systems hampers CE adoption. The lack of standardized digital frameworks makes it difficult for organizations to streamline their operations and integrate new technologies efficiently (Nwaiwu, 2018).

When it comes to making effective decisions, it is imperative that robust data be available to make those decisions (Cheng, 2023).

One respondent observed that from *a technical perspective, data and insights are essential for planning to be successful. A good understanding of a company's data and the relevant insights it provides can lead to informed decisions, which in turn can result in the right technologies being chosen and implemented.*

8.6. Regulatory Challenges

The intricate regulatory environment further complicates CE integration. It is challenging for organizations to implement uniform solutions across multiple regions due to disparate legal conditions concerning privacy, cybersecurity, and sustainability. Respondents noted that shifting compliance expectations frequently slowed technology adoption. A digital solution's scalability is also affected by regulatory challenges, such as privacy concerns and compliance requirements related to data protection (Negro-Calduch, Azzopardi-Muscat, Krishnamurthy, & Novillo-Ortiz, 2021). It is vital to develop unified global policies that provide legal coherence and foster an environment conducive to digital innovation to address the challenges posed by these issues.

8.7. Key Enablers

CE can be effectively incorporated with digital technologies, ensuring compliance with SDG 12. As part of these efforts, policies and incentives aimed at fostering collaboration across different sectors are in place as well as comprehensive workforce training.

8.8. Government Policies and Financial Incentives

A supportive environment for digital technologies within CE requires government involvement. Business pressure can be eased by thoughtfully designed policies, financial incentives, and strategically allocated funding initiatives. Digital transformation is motivated by tax advantages and subsidies (Sun, Sun, & Wang, 2024).

One respondent remarked that *to facilitate sustainable digital transformation, governments may provide regulatory incentives, funding, and policies supporting the initiative.*

Programs such as extended producer responsibility (EPR) and carbon credit schemes can also encourage industries to align their digital approaches with CE principles to make their supply chains more sustainable over the long term.

8.9. Collaboration and Knowledge Sharing

Digitalization requires collaboration across sectors. Businesses can collaborate to devise interoperable solutions by using shared platforms, open data ecosystems, and collaborative research projects. Coordinated public-private efforts are essential for effective digital adoption (Shi, Jiang, & Liu, 2023).

One interviewee stated that shared *knowledge reduces costs, speeds up adoption, and promotes the use of proven solutions across sectors.* Businesses can overcome technological challenges by cultivating such partnerships, which will enhance the execution of digital CE initiatives and enable them to overcome technological obstacles.

8.10. Workforce Training and Digital Literacy

Training in digital skills is essential for overcoming technical obstacles. The employees of an organization can adopt digital tools more effectively if they have skills in AI, blockchain, and IoT.

One respondent highlighted *that technological training can be a helpful tool for smaller businesses to implement these technologies.* Technology-driven CE solutions require well-designed educational programs, industry-specific workshops, and initiatives to strengthen digital literacy (Nikou & Aavakare, 2021).

8.11. Digitalization strategies in CE models to achieve SDG 12

A well-structured approach is needed to integrate digital technologies into CE initiatives. Collaboration is essential for building workforce capabilities, addressing policy gaps, and improving policy. These strategies can help the CE industry maximize the impact of digitalization.

8.12. Policy Support

Creating clear and adaptable policies encourages business leaders to embrace digital technologies while complying with sustainability goals. With regulatory reform, businesses can smoothly transition to digital CE solutions (Suchek, Fernandes, Kraus, Filser, & Sjögrén, 2021). Policies consistent across different regions can assist in promoting collaboration and standardization.

8.13. Industry Collaboration

Digital technologies in CE must be adopted through public-private partnerships. Collaborations between businesses, governments, and researchers can be facilitated through innovation hubs, collaborative research, and knowledge-sharing initiatives (Rocha, Quandt, Deschamps, Philbin, & Cruzara, 2021). Scaling CE will be easier if businesses have a shared digital solution and adopt aligned best practices.

8.14. Incentives for Small Businesses

Many SMEs are unable to adopt digital technologies due to financial limitations. Grants and tax breaks can make digital transformation more affordable. Training and mentorship programs can also teach digital tools to SMEs (Rocha et al., 2021).

8.15. Enhancing Data Management

Data management and analytics are essential to improving resource efficiency, extending product lifecycles, and reducing waste in CE. AI-driven insights, IoT-enabled monitoring, and blockchain transparency can optimize business decisions. Collaboration and efficiency will increase in digital CE networks as data-sharing practices become standard (Culot, Orzes, Sartor, & Nassimbeni, 2024).

8.16. Workforce Development

For CE to seamlessly adopt technology, it needs a digitally skilled workforce. Training programs, workshops, and initiatives aimed at developing employee skills should be prioritized by companies. Digital integration can be simplified and CE can be successfully implemented by workers with the necessary expertise (Gnaneswaran, 2024). CE initiatives can be more efficient, scalable, and sustainable through these techniques, ultimately improving digital transformation efforts.

9. CONCLUSION

The industry is improving efficiency, reducing waste, and promoting sustainability by incorporating digital twins, robotics, and IoT. The advent of these technologies has led businesses to gradually shift their economic models from conventional ones to circular ones due to these technologies. However, CE still faces challenges when it comes to implementing digital solutions. Adopting digital technologies is hindered by a lack of digital literacy, high upfront costs, and technological limitations. In many industries, advanced technologies are challenging to integrate with existing infrastructure. Transparency and privacy regulations complicate the transition. A coordinated approach is needed to advance digital adoption. Businesses can implement digital tools more effectively if policies are strengthened, collaboration between industries and governments is fostered, and workforce development is invested in. Industries can maximize the benefits of these technologies for CE through financial assistance, enhanced data management, and standardized digital frameworks. Addressing these issues will help businesses accelerate digital transformation while staying on track with their sustainability objectives. Stronger collaboration between policymakers, businesses, and researchers is essential to scaling digital solutions, improving responsible production and consumption, and ensuring sustainable development in an increasingly resource-concerned world in the future.

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