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Digital Technologies for Real-Time Carbon Accounting in Circular Economy Frameworks

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Abstract: Carbon accounting has emerged as a key tool to drive the transition to circular economy models and achieve global climate goals. This review examines various digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, digital twins, and cloud platforms that play a critical role in accurate and real-time monitoring of greenhouse gas (GHG) emissions and facilitate transparency in life-cycle carbon accounting. These technologies can provide a major contribution to data accuracy, but they also represent barriers to the application of low-carbon innovations and floor-filling in chains with improved reliability. However, the growth of these technologies is challenged by problems such as non-independent standards, different methodologies, and limited access to digital infrastructure. It also puts an emphasis on the revolutionary potential of carbon accounting, which is helped by digital tools, to handle carbon emissions in a way that can be seen and verified at a large scale. The technologies that are introduced here enable the quick flow of information from on-the-spot monitoring to evaluation-driven decision-making, thus making the shift to a sustainable, low-carbon economy considerably quicker. This research points out various aspects regarding the technology opportunities and limitations that need to be addressed to ensure the maximum impact of technology in promoting sustainable practices across different industries. This research underscores the importance of developing standardized approaches and cross-sector collaborations to fully leverage digital tools in the carbon accounting space.

Keywords: circular economy, carbon accounting, digital technologies, climate policy

1. Introduction

As the global climate crisis worsens, cutting greenhouse gas (GHG) emissions has emerged as a key objective of sustainability science, corporate strategy, and international policy. In this regard, measuring, reporting, and verifying emissions—a process known as carbon accounting—has developed into a vital tool for facilitating transparent environmental reporting and well-informed decision-making [1]. In the context of the circular economy, which aims to reduce waste and maximize resource utilization through recycling, regeneration, and reuse, carbon accounting provides a means of coordinating environmental indicators with systemic material flows. Especially when incorporated into business operations and supply chains, carbon accounting in circular models improves climate mitigation and accountability [2].

However, there are several challenges in integrating carbon accounting into circular economy frameworks. For practitioners and policymakers, the fragmentation of measurement frameworks, inconsistent life cycle assessment (LCA) terminology, and the absence of standardized methodologies present significant difficulties [3, 4]. Different definitions of carbon accounting at the macro and micro levels lead to misunderstandings and complicate implementation, as highlighted in recent efforts to unify carbon accounting frameworks [5]. Furthermore, the credibility of corporate sustainability disclosures has been compromised, and cross-sector benchmarking has become challenging due to variations in Scope 1, 2, and particularly Scope 3 emissions accounting practices [4].

These methodological and practical limitations hinder the ability of carbon accounting systems to accurately reflect the climate benefits of circular practices, such as reuse, remanufacturing, or substitution of materials. Furthermore, conventional models often lack the responsiveness needed to track real-time greenhouse gas emissions in dynamic, multi-loop circular systems.

Recently, digital technologies have been increasingly recognized for their transformative potential to improve the accuracy of carbon accounting and allow real-time monitoring. Digital tools like smart meters, blockchain platforms, machine learning, artificial intelligence (AI), and the Internet of Things (IoT) provide an opportunity to dynamically monitor emissions across supply chains with greater granularity and more timely accuracy for carbon data [6]. These innovations further enable the efficiency of resources and operations, as well as aid in transparency in emissions reporting. In addition, digital platforms enable the linkage of environmental metrics with broader accounting systems to help organizations harmonize financial and environmental decision-making [7].

At the organizational level, real-time carbon accounting is becoming increasingly important in environmental, social, and governance (ESG) strategies. Companies that practice dynamic tracking of emissions can identify carbon hotspots and set science-based targets to align with net-zero goals [5]. Research has shown that digital innovations such as smart grids, waste-to-energy analytics, and advanced data systems help reduce emissions from energy companies by making the supply chain more efficient and eliminating operational waste [6]. These developments promote hourly emissions accounting rather than averages per year or per month, revealing previously hidden

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biases in emissions reporting and sharpening the accuracy of mitigation actions [8].

Despite these advancements, the existing literature lacks a comprehensive synthesis of how digital technologies specifically enable carbon accounting within circular economy frameworks. Most prior research treats digitalization and circularity as separate domains, overlooking their convergence in practice and policy.

With a focus on digital technologies for real-time GHG emission monitoring and low-carbon innovation, this review aims to synthesize the body of research on carbon accounting in the circular economy. It offers insights into new best practices and implementation challenges by looking at the technological, methodological, and policy aspects of this multidisciplinary field. It also suggests new lines of inquiry. The objective is to raise awareness of the ways in which digital carbon accounting can promote sustainable change and assist in locating low-carbon, scalable solutions for various industries.

2. Research Approach

This review used a thematic approach to synthesize research on digital tools for real-time carbon accounting in circular economy systems. Thematic reviews allow us to draw on a wide range of data sources, such as journals, reports, and policy papers, which are useful for new and interdisciplinary topics because they help identify common ideas and research needs. The review looked at studies from 2018 onwards to capture current advances in digital technology and circular economy methodologies. A comprehensive search of major academic databases, including Scopus, Web of Science, and Google Scholar, was conducted using search terms such as "carbon accounting," "circular economy," "digital technologies," "greenhouse gas emissions," "blockchain," "Internet of Things (IoT)," "artificial intelligence (AI)," and "real-time carbon tracking." This time frame helps the review capture up-to-date trends and technological advances relevant to the topic.

The inclusion criteria for this review consisted of peer-reviewed journal articles and conference papers published in English, with a focus on studies thematically relevant to the integration of digital technologies in carbon accounting within circular economy frameworks. Non-peer-reviewed publications were excluded to ensure the reliability and credibility of the sources included in the review. Additionally, studies that were not written in English were excluded to maintain a focused review on widely accessible literature.

The findings were organized around different themes, including emerging frameworks, standards, and metrics; digital technologies that allow for real-time carbon accounting; and carbon accounting in circular economy systems. In particular, IoT, blockchain, artificial intelligence, and digital twins were examined in the paper along with how they might enhance the precision, effectiveness, and openness of carbon emissions monitoring. The analysis also emphasized the limitations and obstacles to the adoption of these technologies, including issues with standardization and unequal access to digital infrastructure. Finally, in order to facilitate the wider adoption of these digital tools within carbon accounting systems in circular economies, the review identified governance frameworks and policy implications. In addition to examining the revolutionary possibilities of digital technologies, this thematic analysis identified limitations and obstacles to the adoption of these technologies, including issues with standardization and unequal access to digital infrastructure.

A detailed overview of the search strategy and the stages of the study selection process is provided in Table 1, ensuring transparency and reproducibility in the review methodology.

Table 1
Research approach and selection process

Stage	Details
Databases searched	Scopus, Web of Science, Google Scholar
Search terms used	"Carbon accounting," "Circular economy," "Digital technologies," "Blockchain," "IoT," "AI," "Real-time carbon tracking"
Inclusion criteria	Peer-reviewed journal articles, conference papers, published in English, focused on digital technologies in carbon accounting or circular economy systems
Exclusion criteria	Non-peer-reviewed publications, studies in languages other than English, studies focused on linear supply chains or financial accounting alone, and studies not related to digital technologies in carbon accounting
Screening for relevance	Studies screened based on title and abstract for relevance
Full-text review	Studies reviewed in full text to assess alignment with inclusion criteria
Final inclusion	Studies meeting the inclusion criteria selected for synthesis

3. Carbon Accounting in Circular Economy Systems: A Conceptual Overview

Carbon accounting in circular economy systems brings about a number of methodological and conceptual challenges, which extend far beyond those that apply to linear contexts. In the case of circular systems, which are more complex than linear supply chains with GHG emissions only from resource extraction to end-of-life disposal, one should account for the emissions that span multiple loops and substitutions such as reuse, recycling, remanufacturing, and material substitution. This heterogeneity makes it difficult to decide when and where GHG emissions occur or who should be liable for them if they arise in fragmented supply networks over time [9]. These challenges become even more intricate when several actors contribute to GHG emissions via shared resource cycles or joint production systems.

To ensure clarity and consistency, it is crucial to define several key terms that are central to understanding carbon accounting within circular economy systems. These include carbon accounting, LCA, material flow accounting, and circular carbon, all of which are foundational concepts in evaluating emissions and sustainability within circular models. Table 2 presents the glossary of key terms that are referenced throughout this section to aid in understanding these critical concepts.

Figure 1 presents a conceptual framework for integrating a comprehensive carbon accounting system into the circular economy model. The core of the figure depicts the circular flow of the economy through four key stages: design, production, consumption, and recycling, each of which is connected by continuous and closed loops. The model fundamentally challenges the traditional linear approach of "take, make, and dispose" by emphasizing longevity, resource efficiency, and waste reduction. At the center of this circular flow is a "carbon cloud," which is a conceptual representation of a cloud-based data management system. This central node is connected to each stage of the circular loop through real-time data streams and symbolizes the continuous tracking of carbon emissions throughout the entire life cycle of a product. The figure shows that data is not only simply collected, but also visualized, as shown by graphs and data points associated with each stage. These visualization tools make it possible to locate carbon hotspots and offer useful information about how various processes affect the environment. While consumption data can monitor the energy footprint over the course of a product's use, production stage data may highlight greenhouse gas emissions from production. The framework offers a clear and quantifiable route to establishing a genuinely sustainable and low-carbon operating model by incorporating this real-time data stream at each phase of the circular economy.

Li et al. [10] developed a complete life cycle accounting methodology specifically designed to capture the characteristics of precast construction systems—an expanding field of circular economy innovation. Their model pinpoints material production and transport activities as major contributors to the carbon footprint, while addressing the filtering accounted for by Monte Carlo simulation to verify strict carbon accounting. This emphasizes the importance of standard methods to account soundly for GHG emissions during reuse and recovery.

A more complex issue is how to deal with greenhouse gas emissions from by-products and multi-output systems. In a circular economy, waste is often converted into secondary inputs or energy, creating problems in fairly attributing greenhouse gas emissions. Marini et al. [11] examine this problem in carbon accounting for circular systems, noting that traditional attribution methods can misrepresent avoided greenhouse gas emissions and create inconsistencies when applied to circular production cycles. Their findings suggest that carbon neutrality in circular systems may not be consistent with linear models of fairness or accounting logic.

Digital technologies present a new potential for overcoming many of these conceptual challenges. Heiss et al. [12] propose a blockchain system, known as Verifiable Carbon Accounting (VCA), which facilitates secure and anonymous data sharing of emissions throughout decentralized chains. This is of specific relevance in circular settings where refurbished or remanufactured goods are brought back to market and ownership changes hands between players. The VCA enables real-time tracking of emissions at a product level, with measures to safeguard commercially sensitive information—marking an important leap forward for transparent carbon reporting within circular approaches.

Recent studies have demonstrated the critical role of green finance and advanced innovation in promoting sustainable development in various regions, especially in economic regions such as the Yangtze River Economic Belt. Zhang et al. [13] found that green finance, together with advanced innovation, plays a critical role in facilitating regional sustainability, which is directly related to advanced low-carbon solutions in circular systems. They emphasized the potential of integrating finance and technology to enhance sustainable practices and support the achievement of sustainable development goals in diverse economies.

Figure 1
Integration of circular-economy loops and real-time carbon accounting data flows

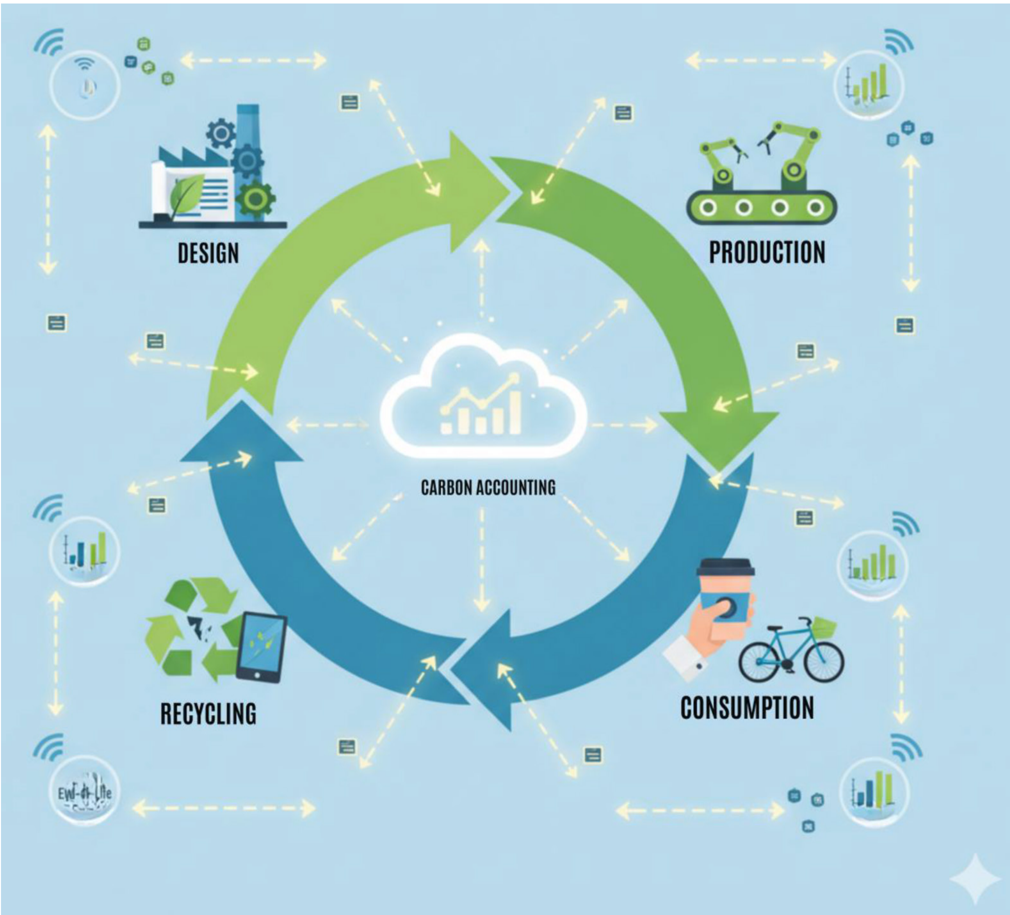


Table 2
Glossary of key terms in carbon accounting and circular economy systems

Term	Definition	References
Carbon accounting	A process of measuring, reporting, and managing GHG emissions across different system levels (national, organizational, product). It enables decision-making for climate action and tracking progress toward emissions reduction	[14]
Life cycle assessment (LCA)	A method to assess environmental impacts associated with all stages of a product's life — from resource extraction to disposal. It is used to identify carbon-intensive phases and potential improvement points.	[3]
Material flow accounting	A tool that quantifies the flow of materials in a system over time and helps evaluate efficiency and material consumption cycles by tracking inputs, inventories, and outputs.	[11]
Circular economy	An economic system aimed at eliminating waste and keeping materials in use through reuse, recycling, and recovery, thereby minimizing environmental impacts.	[15]
Circular carbon	A concept that focuses on the reuse and recycling of carbon-based materials to reduce greenhouse gas emissions and create closed-loop carbon flows. Circular carbon emphasizes the capture, storage, and use of carbon in circular systems.	[3]

Practical applications in industry are beginning to show the potential of circular design to reduce GHG emissions if properly accounted for. Zhu et al. [15] analyzed a reversible construction pavilion built with recycled materials and modular components. Their LCA demonstrated that circular design reduced embodied carbon by up to 96.5% compared to conventional concrete and steel structures. However, they also note that these carbon benefits would be invisible under traditional accounting systems that do not include avoided GHG emissions or material reuse.

Additionally, the integration of digital finance in carbon management has emerged as a significant factor in improving carbon productivity. Sun et al. [16] highlight the spatial impact of digital finance on carbon productivity, providing insights into how financial tools can be leveraged to boost sustainable practices across diverse industries. They contend that, particularly in the framework of a circular economy, digital finance can significantly increase carbon efficiency when combined with carbon management systems.

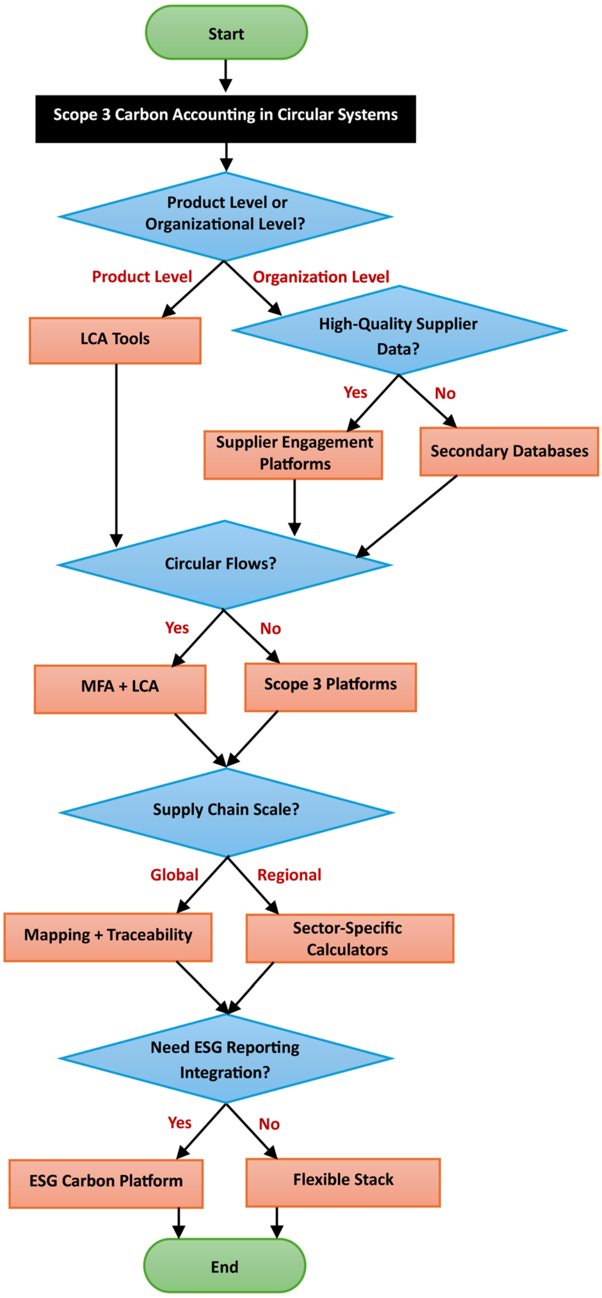
Incorporating cost accounting into carbon reporting within circular economy systems helps organizations make smarter decisions. Hu et al. [17] suggest a dual-track model that separates internal and external carbon costs across a product's entire life cycle. This approach supports circular strategies by highlighting the long-term financial benefits of cutting emissions through reuse, longer product life, and better material use. When carbon data is tied directly to financial decisions, it is easier to justify circular investments. To complement the conceptual overview above, several recent case studies have quantified the impact of digital and circular interventions on GHG emissions. These findings, summarized in Table 3, provide empirical support for the adoption of such strategies in carbon accounting frameworks.

Despite advances in methodology, practitioners often struggle to select the best digital tools for Scope 3 carbon accounting in circular systems. This problem is made worse by the lack of standard methods for managing multi-layered supply chains, circular flows, and supplier data. To fill this gap, Figure 2 presents a decision tree that captures four key factors influencing tool selection: supply chain scale, circular characteristics, data availability, and ESG integration requirements. Practitioners typically use secondary life cycle databases such as Ecoinvent or EXIOBASE, which provide sector averages but introduce uncertainty when primary supplier data is not available [18]. On the other hand, companies may engage directly with suppliers through specialized platforms and disclosure schemes when high-quality supplier data is available, strengthening their Scope 3 inventory [12]. Hybrid approaches combining material flow analysis (MFA) and life cycle assessment (LCA) are best suited for systems that use circular strategies like remanufacturing or product-as-a-service. Digital traceability solutions, in particular blockchain-enabled platforms, improve accountability and transparency among actors in global, multi-tier supply chains [19, 20]. In contrast, companies with robust analytical skills but fewer reporting requirements might use flexible, hybrid strategies that combine open LCA databases with internal analytics, while organizations with required ESG disclosures (such as CSRD and SBTi) might profit from integrated ESG–carbon platforms [21].

Table 3
Quantitative impacts of circular and digital interventions on GHG emissions

Case study/sector	Context/region	Intervention	GHG reduction or impact	References
Precast construction	China	LCA with Monte Carlo simulation for reuse scenarios	Up to 22.6% GHG reduction in construction phase	[10]
Hydrogen energy system	Model-based (Europe)	Circular hydrogen loop with carbon capture	36% GHG reduction compared to thermal baseline	[22]
Healthcare logistics	India	AI + drone reverse logistics	Qualitative: CO_2 reduction, energy savings	[23]
Municipal waste systems	Brazil	Circular education + waste innovation	Up to 90% GHG per capita reduction in pilot cities	[24]
Passive cooling in construction	Global	Circular, low-carbon cooling design	20–30% energy and carbon savings	[25]
Circular agriculture	India	Integrated crop-livestock system with reuse loops	2.5 tCO_2e/ha/yr avoided	[26]
PET recycling system	USA	Digitalized chemical recycling with consumer drop-off infrastructure	Significant CO_2 savings; improved material recovery	[27]
Green methanol production	Austria	Green hydrogen + methanol from biomass	Up to 80% Scope 1 & 2 GHG savings	[28]

Figure 2
Decision tree on selecting appropriate digital tools for Scope 3 carbon accounting in circular systems



In general, this methodical approach lowers the possibility of methodological inconsistency and increases transparency in Scope 3 disclosures by assisting practitioners in matching tool selection to the complexity of circular systems.

4. Digital Technologies Enabling Real-Time Carbon Accounting

Digital tools have transformed carbon accounting, moving it from slow, backward-looking reports to near real-time, high-resolution tracking. As industries adopt circular economy principles, technologies like IoT, AI, blockchain, and simulation platforms are being used to measure carbon impacts more accurately, verify emissions claims, and spot problem areas across value chains. Each tool adds distinct capabilities, making it easier to build carbon intelligence into circular operations.

4.1. Internet of Things (IoT)

In the realm of modern carbon accounting, IoT has become a core technology, especially in the context of industries seeking real-time environmental monitoring integrated with circular economy principles. IoT enables continuous measurement of emissions, energy consumption, and waste production at various levels within a company, thanks to embedded sensors, smart meters, and connected devices. These data streams empower companies to make immediate operational improvements to reduce GHG emissions and conserve resources. For example, in the maritime industry, the SmartShip project implemented a cloud-based performance system based on IoT to monitor fuel consumption for better tracking of GHG emissions across the life cycle of a ship, positively affecting energy conservation and promoting higher circularity by encouraging demand-driven remanufacturing or reuse [29].

IoT-based platforms are increasingly being used in manufacturing environments to detect carbon emission hotspots and dynamically adjust energy flows. Xiao [30] developed a tool for visualizing GHG emissions in real-time using IoT sensors, which increases transparency and supports immediate energy adjustments to reduce carbon intensity. Similarly, university-level initiatives in Italy have shown how IoT can track waste generation and emissions in near real-time, supporting low-impact behavioral changes and system optimization [31].

Beyond industrial sites, IoT technologies have also become vital in circular logistics processes. Sensors installed within transportation fleets monitor fuel consumption, route efficiency, and vehicle maintenance status in real-time. This information is essential for scheduling delivery operations to reduce Scope 3 logistics emissions. Zhou [32] emphasized that smart IoT networks in logistics hubs help to coordinate low-carbon packaging, storage, and routing structures across supply chains. IoT applications, in conjunction with carbon capture and storage (CCS) technologies, would also improve the accuracy of lifecycle carbon tracking and aid in the development of verified carbon trading systems. This synergy is also showcased by Gautam et al. [33], demonstrating how CCS systems, when integrated into circular industrial systems and supported with real-time sensor data, lead to the relocation of captured CO_2 for use in industrial inputs, transforming wastes into resources and completing carbon loops. In the shipping industry, the spread of onboard IoT-enabled CCS platforms is being trialed for capturing CO_2 on board in transit and for transporting CO_2 to port facilities where the CO_2 can be reused for fuel-making, thus putting circular principles into application [34].

To realize low-carbon innovation, IoT systems, with their ever-growing interoperability and scalability, will play a role in assisting circular carbon flows. This is achieved by enabling accurate and real-time tracking of production, use, and reuse phases.

4.2. Blockchain

Blockchain technology has played an increasing role in facilitating transparent and tamper-proof carbon accounting schemes across circular economy supply chains. With material, energy, or logistics transactions all recorded as time-stamped and verifiable blocks, its decentralized and immutable nature provides a transparent audit trail for greenhouse gas emissions, which in addition supports real-time tracking of the embedded carbon footprint from production to end-of-life. Applying this approach in practice, Ojadi et al. [35] demonstrated how blockchain can be used in conjunction with IoT sensors to facilitate authentic carbon reduction claims and traceable carbon credit issuance across distributed supply chains.

Smart contracts extend these capabilities by automating emissions verification and carbon offset transactions. For example, Wang et al. [36] proposed a blockchain-based carbon settlement framework that automates carbon credit exchanges in real time using validated emissions data. This system reduces costs and accelerates settlement compared to traditional carbon markets. Gerasimova et al. [37] highlighted the use of smart contracts and Non-Fungible Token (NFT) solutions in circular product lifecycle management, particularly in the automotive sector, where digital certificates on blockchain platforms were used to track resource reuse and extend product life spans.

Moreover, Sharma and Rohilla [38] integrated a blockchain demonstrator in Hyperledger Fabric to track the carbon footprint within a medicine supply chain and demonstrated that decentralized infrastructure can be used for GHG emissions accounting at the product level. Corsini et al. [39] combined this with other technologies, such as Radio-frequency Identification (RFID) or 3D printing, to provide real-time emissions metrics, therefore supporting circular smart city initiatives.

In construction, tracking reusable components or hazardous materials has become easier with blockchain solutions. Elghaish et al. [40] proposed a BIM-blockchain system that enables sharing of building component data among stakeholders in secure and immutable networks, helping to achieve greater transparency and support a circular economy in urban infrastructure. In a similar vein, Mukherjee et al. [41] showed that blockchain-based supply chains enhance traceability and smart contracts along with resilience in multiechelon networks, thereby achieving sustainability goals.

All things considered, blockchain not only protects the integrity of carbon data but also makes dynamic circular transactions possible, allowing for automated trading, better stakeholder trust in carbon markets, and smarter management.

4.3. Artificial intelligence (AI) and machine learning

Real-time emissions forecasting, anomaly detection, and intelligent optimization across circular supply chains are all made possible by AI and machine learning, which are revolutionizing carbon accounting. These technologies can pinpoint processes that produce a lot of emissions, forecast carbon trends across a range of operational scenarios, and suggest the best course of action to lessen their negative effects on the environment. For example, in a comprehensive review, Daios et al. [42] described how AI algorithms like natural language processing and machine learning improve demand sensing and emissions data harmonization across global value chains. Furthermore, Ojadi et al. [43] applied predictive analytics to dynamically optimize distribution routes, reducing fuel consumption and improving carbon efficiency in logistics networks.

AI frameworks now enable smart energy balancing, emissions-aware routing, and predictive maintenance in manufacturing and energy systems. In order to lower emissions and improve supply chain agility, Onukwulu et al. [44] developed a hybrid AI model that combines predictive algorithms with real-time logistics data. Additionally, AI enables real-time carbon hotspot detection, enabling prompt remedial measures and ongoing improvement cycles [45]. Because of these features, AI is essential for tracking GHG emissions and for broader circular economy applications where resource recycling and real-time carbon constraints need to be balanced.

Recent innovations demonstrate how AI can optimize GHG emissions at both the micro and macro levels. Huang and Mao [46] introduced a real-time GHG emission prediction model based on AI-enhanced supply chain data that identifies upstream and downstream carbon debts. Similarly, Jahagirdar [47] showed that AI-based logistics can reduce fuel consumption and carbon intensity in fleet operations through continuous re-optimization based on weather, load, and traffic inputs.

AI is also becoming central in applications related to the circular economy. Ali [48], for instance, suggested a machine learning-based framework for making decisions about predictive end-of-life material recovery and circular product design. By dynamically connecting GHG emissions to material flows, this method makes closed-loop systems possible. Soo et al. [49] created an AI model for carbon optimization in wastewater reuse systems that concurrently supports nutrient recovery and GHG emission reduction at the water-energy-waste nexus.

Beyond environmental sensing, advanced techniques like quantum AI are emerging for next-generation sustainability intelligence. Vudugula and Chebrolu [50] described how AI-enhanced dashboards could guide carbon-aware decision-making in industrial management. Meanwhile, Ebert and Uddin [45] discussed enterprise-level tools that integrate carbon forecasting into financial planning, linking decarbonization with competitive strategy.

Altogether, AI is becoming an essential infrastructure layer in carbon accounting. From real-time emissions detection and automated logistics optimization to circular design and predictive analytics, its applications are reshaping how carbon performance is measured, improved, and scaled.

4.4. Digital twins and simulation tools

Digital twin technology provides a robust set of tools to model physical entities, such as buildings, factories, or cars, in a dynamic digital environment to model their full life cycle and forecast the effects of GHG emissions. In circular economy models, these simulations are particularly valuable because they consider different life stages, including reuse, refurbishment, and recycling, where feedback loops complicate traditional linear emission models. For example, the integration of digital twins with building information modeling (BIM) enables operational and visual carbon assessments of building projects in various life cycle scenarios, including demolition for material recovery or retrofitting [51].

A digital twin framework was used by Li et al. [52] to simulate ship operations and track emissions every 15 min in the maritime transportation industry. Fuel optimization and regulatory compliance were aided by the model's ability to dynamically modify shipping routes based on profiles of emissions. Digital twins at the city level can also be used to model emissions from buildings and transport systems and to inform policy changes. In order to evaluate mobility-related greenhouse gas emissions, a study by A.Faiad et al. [53] proposed a city-scale digital twin and showed how beneficial it is for low-carbon planning and urban fleet optimization.

Beyond construction and transportation, digital twins are increasingly applied in manufacturing for carbon-conscious operations. A framework for incorporating environmental performance into digital twins based on manufacturing was put forth by Popescu et al. [54]. According to their analysis, environmental modeling is not being used enough in current industrial applications, and they advocated for a more robust integration of carbon accounting tools. Similarly, by modeling logistics and inventory systems, digital twins and predictive analytics can actively lower emissions in global supply chains, as noted by Onma Enyejo et al. [55].

Digital twins also improve real-time decision-making for controlling greenhouse gas emissions in manufacturing by enabling adaptive simulations. For example, a recent study by Li et al. [56] used digital twins to dynamically monitor and optimize the emissions of machine tools in manufacturing. Their prototype used real-time data feedback loops to predict greenhouse gas emissions and modify operating parameters, resulting in significant energy and emissions savings. Similarly, Zhang et al. [57] showed how digital twins can be combined with remote sensing and BIM to estimate the potential for greenhouse gas emission reduction in residential areas during the operational phase.

Importantly, digital twins play a strategic role that goes beyond operational advantages. Digital building ledgers connected to digital twins can help promote circularity in construction by monitoring recyclability, GHG emissions, and materials over the course of a building's life cycle, as noted by Chumbiray Alonso et al. [58]. This degree of transparency improves compliance with changing carbon disclosure requirements while also maximizing circular performance.

The use of digital twins is expanding into new sectors with a broader range of functions, pushing them from being operationally supportive to strategically enabling low-carbon and circular transformation. Given their executable integration in BIM systems, urban planning platforms, and predictive analytics environments, they provide a strong tool to simulate emissions for any kind of industry, optimize resource loops, and align operations with carbon reduction goals.

4.5. Big data and cloud platforms

GHG emissions data are now central to modern carbon accounting, and cloud and big data platforms provide the connectivity required across dispersed, complex systems. To provide a comprehensive picture of the carbon footprint in real time, these platforms combine data from enterprise systems, logistic networks, and IoT sensors. For example, Ganesan et al. [59] combined IoT and machine learning approaches to develop an energy-aware cloud platform that processes GHG emissions data, empowering sustainability-related decision-making.

In urban contexts, smart dashboards based on big data support emissions planning and low-carbon transport design. Fiore et al. [60] showed how cloud-based mobility dashboards can help city governments monitor real-time trends in emissions and traffic flows, supporting adaptive transport strategies and public policy interventions. These tools are particularly valuable in circular economy frameworks where feedback loops require continuous recalibration of resource and emissions data.

Cloud-based sustainability dashboards are also becoming more popular in commercial and industrial settings. De Silva et al. [61] analyzed how digital knowledge systems, including cloud dashboards, support ESG disclosures and help firms track carbon performance more accurately. These tools enable transparency and help meet corporate environmental disclosures better aligned with carbon regulations and ESG targets.

Emerging research also looks at how small and medium-sized enterprises (SMEs) can utilize big data platforms to adopt the circular economy. For example, Natrajan et al. [62] presented a framework for small businesses to leverage scalable digital infrastructure driven by cloud computing and circular business models with the potential of achieving sustainability. Similarly, Afwande et al. [63] emphasized the role of cloud and big data as accelerators for carbon-aware urban infrastructure and behavioral change.

From a broader perspective, Khedkar [64] conducted a systematic analysis that showed how cloud computing can reduce the carbon footprint, despite having environmental costs, when optimized through virtual infrastructure, renewable energy, and effective cooling systems. Similar conclusions were reached by Javaid et al. [65], who examined how Industry 4.0 integrates AI and big data to improve resource recycling and minimize waste in circular healthcare systems.

The robust capabilities of big data and cloud platforms enable the tracking of emissions, forecasting, policy assessment, and the transition to a circular economy by effectively combining, evaluating, and visualizing carbon data on a large scale.

Figure 3 illustrates key digital technologies and their applications in real-time carbon accounting within circular economy systems.

5. Carbon Metrics, Standards, and Frameworks: What Is Evolving?

Carbon accounting standards are undergoing a major transformation. It is a natural evolution as the demand for more accurate, transparent, and extensive emissions data has become clearer in its requirements, informing both policymaking and investment decisions. Legacy metrics developed around the assumptions of linear production are quickly becoming inadequate as organizations move towards net-zero and more circular models [66].

One area of change is the integration of carbon metrics into core financial disclosures. Climate-related risks are now seen as essential to business performance rather than external factors. The International Sustainability Standards Board (ISSB) and regulators in the EU and UK are implementing mandatory disclosure requirements aligned with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations, covering all relevant climate impacts such as GHG emissions. These changes shift carbon accounting responsibilities from corporate sustainability teams to chief financial officers (CFOs), auditors, and financial decision-makers [2].

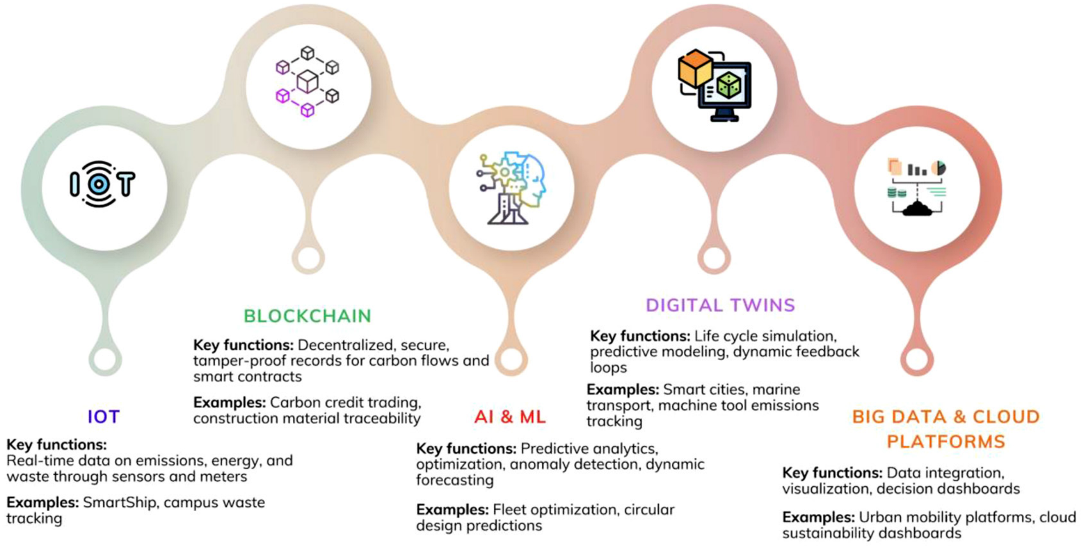
At the same time, industry-specific practices are being refined. The Malaysian energy giant PETRONAS has developed a hybrid recording system combining both International Organization for Standardization (ISO) 14064-1:2018 and International Petroleum Industry Environmental Conservation Association (IPIECA) standards to create a more nuanced emissions profile. Their tactics entail operational control and equity mechanisms for correct carbon accounting across joint ventures and outsourcing networks [67]. It is part of a gradual shift to hybrid models in carbon reporting that take into account varying organizational structures and complexities of value chains.

Still, conventional protocols such as the GHG Protocol have problems with circularity. They often fail to reward reuse, remanufacturing, or recycled content appropriately. For example, allocating Scope 3 emissions to companies that use recycled materials, rather than rewarding them, can unintentionally discourage low-carbon circularity schemes. This issue stems from the strict boundary rules and the lack of dynamic allocation mechanisms [66], which have led to increased interest in new forms of emission crediting.

Terminology poses another obstacle to tackle. Inconsistent usage of terms such as "avoided emissions," "negative carbon," and "circular carbon" in LCA documentation and carbon disclosure leads to misunderstandings and hinders verification processes. Zeilerbauer et al. [3] have attempted to establish a unified taxonomy for carbon terms related to the carbon cycle to enhance clarity in carbon credit schemes, procurement policies, and product declarations.

Emerging frameworks also focus on inclusion. Many SMEs are excluded from high-integration carbon accounting due to high costs and technical and reporting difficulties. Ogunyemi and Ishola [68] call for more scalable and low-cost tools and regulatory support mechanisms to help SMEs participate in formal carbon disclosure, especially in supply-heavy industries where indirect emissions are dominant.

Figure 3
Core digital technologies for real-time carbon accounting in circular systems



Furthermore, empirical models such as the e-responsibility framework offer an alternative to static inventories. In this model, carbon is tracked and allocated like financial liabilities and flows through supply chains in real time. Ameh [69] argued that this method better reflects how greenhouse gases are produced and transported in modern global production systems, especially when paired with digital infrastructures for carbon tracking. This approach offers a glimpse into the future of carbon accounting as an active and integrated business practice.

In short, carbon accounting standards are evolving and adapting to the challenges of cyclicality, finance, and supply chains. New taxonomies, real-time asset-liability models, and accessible frameworks for SMEs to include in the measurement of emissions are examples of these emerging changes that will have a significant impact on making measurements more meaningful, accurate, and fair in the coming decades.

6. Barriers and Limitations

Numerous obstacles hinder the full potential of carbon accounting to reduce climate change within circular economy frameworks (see Table 4).

The disparity between circular concepts and widely accepted norms, like the GHG Protocol, is one major problem that may deter businesses from implementing greener practices [66].

Another challenge lies in the fragmentation and inconsistency of carbon accounting across sectors and jurisdictions. Most often, companies do not have a unified reporting standard that covers all Scope 3 emissions—even those that can be crucial in closed-loop systems. Indeed, the GHG emissions created upstream and downstream can be particularly problematic to monitor and validate when they occur across multiple entities or geographies [2]. Moreover, national carbon inventories are generally organized along territorial boundaries and do not include GHG emissions embodied in imports/exports, which is another mismatch with the globalized and loop-oriented nature of circular systems [70].

Real-time carbon accounting is also constrained by technological and data-related challenges. While an increasing number of tools, such as IoT, blockchain, and AI, are being explored for their potential to fight the crisis, the foundation that allows these technologies to be implemented on a large scale is uneven. Smaller firms and developing countries, which are responsible for a large portion of GHG emissions, often lack the resources to adopt these innovations, leading to a global digital divide in monitoring GHG emissions [71]. Furthermore, the application of circular approaches is increasing dramatically, particularly in the construction and real estate sectors. At the same time, data gaps on embodied carbon in building materials and life cycle emissions remain a challenge due to insufficient post-occupancy evaluations [15].

Institutional, managerial, and behavioral barriers further impede progress. Research from developing nations has demonstrated that the main obstacles to adapting current carbon accounting frameworks to circular models are a lack of awareness among managers, limited institutional incentives, and inadequate capacity-building [72].

Additionally, many sectors are still influenced by a mentality that prioritizes short-term cost-efficiency over long-term sustainability investments, making it difficult to implement carbon accounting practices that need upfront costs.

Inertia in regulations and policy uncertainty are also major issues. Although regional frameworks such as the EU Green Deal and taxonomy regulations offer guidance, there isn't a universally recognized standard

Table 4
Challenges of carbon accounting in circular economy frameworks

Challenge category	Description	Reference(s)
Methodological gaps	Incompatibility between traditional GHG protocols and circular flows	[3, 66]
Scope 3 complexity	Tracking GHG emissions across distributed, multi-actor supply chains	[2, 4, 70]
Technological divide	Limited digital infrastructure in SMEs and developing economies	[71, 72]
Behavioral/incentive barriers	Managerial inertia, short-term financial thinking, lack of awareness	[72]
Policy and regulatory gaps	Absence of unified, circularity-integrated carbon reporting standards	[73, 74]

that incorporates circular principles into carbon reporting. Businesses are left in a voluntary or semi-regulated environment due to the absence of an enforceable policy architecture, which lessens the incentives for them to practice strict carbon accounting [73]. Sankaran [74] points out that the scalability and profitability of carbon capture and utilization strategies within circular frameworks are also impacted by policy misalignment across jurisdictions.

In summary, despite the fact that carbon accounting is crucial for achieving the objectives of the circular economy, methodological misfits, fragmented data systems, behavioral stagnation, and policy gaps hinder its application. For circular carbon strategies to reach their full potential, cross-sectoral cooperation, capacity building, technology investment, and improved regulatory coordination are needed to address these issues.

7. Policy Implications and Governance Frameworks

As carbon accounting systems evolve within the circular economy, policymakers must create rules that are flexible and inclusive. The policy environment needs to understand that circular carbon flows complicate traditional emissions tracking. These flows extend product lifecycles, decentralize production, and introduce feedback loops that confuse responsibility and measurement. Carbon in reused, recycled, or remanufactured materials often falls outside current reporting frameworks. This situation calls for updated policies that accurately reflect these dynamics.

Policymakers have begun to address these gaps by advancing new regulatory architectures that take into account the carbon embedded in product life cycles. On the regional scale, the European Union has spearheaded initiatives including the Circular Economy Action Plan and Sustainable Product Regulation, with the former measuring emissions from the entire lifecycle perspective vis-à-vis product passports, eco-design standards, and end-of-life traceability mechanisms [75]. Meanwhile, the Circular Carbon Economy (CCE) model of Saudi Arabia presents a diametrically opposite perspective by creating a circular fossil-based economy in the earnest hope that the carbon can be captured and reused or offset [76].

Urban management initiatives are increasingly becoming a gateway for testing circular carbon policies. In several cities, including The Hague and Rössler, circular carbon metrics have been mandated in zoning regulations and infrastructure planning, as well as public procurement programs. These efforts include measuring life cycle emissions in public infrastructure and buildings, along with encouraging low-carbon design [77]. Likewise, more sophisticated mechanisms for carbon accounting are being introduced by regional governments in China, where green procurement and construction codes incorporate a responsible accounting system for material reuse and embodied greenhouse gas emissions [78].

The emergence of digital policy infrastructure is an important trend in promoting circular carbon governance. Tools like the EU's Digital Product Passport, along with APIs for carbon data exchange, are building a technical base for real-time emissions verification across borders and supply chains. By controlling how carbon data is created, shared, and certified, policymakers can address existing accountability gaps and enhance the detail of sustainability reporting [79].

Institutional regulators and standard-setting organizations have also started to connect cyclical principles with carbon disclosure. For instance, there is mounting pressure on carbon accounting firms to abandon linear scope-based frameworks. By recycling, reusing, and remanufacturing, they must acknowledge the downstream carbon savings and avoided emissions. Initiatives for sustainability reporting, such as those run by the International Sustainability Standards Board (ISSB), clearly reflect this change. Life cycle perspectives are becoming more incorporated into ESG guidelines by these initiatives [2].

The path ahead will require cross-sector and cross-jurisdictional coordination. Investments in cross-sector capacity-building, digital infrastructure, and inclusive frameworks that guarantee fair access to carbon data tools are all necessary to support policy innovation. In order to enable cities and businesses to measure and cut emissions in a circular logic, urban, regional, and international governance bodies must work together to develop standards. In addition to improving the accuracy of emissions reductions, a future-ready carbon governance regime will establish regulatory frameworks that encourage and reward circular practices.

Table 5 lists key policy initiatives in selected countries and regions to provide a comparative overview of how digital carbon accounting is integrated into climate and circular economy frameworks in different jurisdictions. The table highlights digital measurement, reporting, and

Table 5
Comparative overview of digital carbon accounting integration in policy frameworks

Jurisdiction	Policy framework	Digital carbon accounting integration	Scope	Status	Digital requirements	References
European Union	Circular Economy Action Plan; EU Taxonomy; EU ETS	MRV systems standardized under EU ETS; interoperable digital reporting tools (E-PRTR, EEA)	Multisector	Mandatory	Digital data portals, annual verified reporting	[2]
Saudi Arabia	Circular Carbon Economy (CCE) under Vision 2030	Emerging MRV integration; proposed blockchain and digital twins	Energy, industry	Voluntary	Targeted pilot systems	[76]
Saudi Arabia	Circular Carbon Economy (CCE) Model	High-level promotion of digital MRV for oil, hydrogen, and CCUS; not fully institutionalized	Energy, industry, CCS	Voluntary	Blockchain pilots, national carbon registry in development	[80]
China	Green Procurement & Dual Carbon Goals	National digital MRV for emissions trading & LCA platforms (CERC)	Industry, public sector	Mandatory (key sectors)	Real-time emissions monitoring	[17]
Australia	Full Carbon Accounting Model (FullCAM)	National model uses NDVI from remote sensing; key for emissions reporting	Land-use, agriculture, forestry	Mandatory (UNFCCC & local reporting)	Satellite NDVI layers, GIS tools	[81]

verification (MRV) platforms, blockchain registries, satellite-based monitoring, and other tools and systems, along with the scope of each framework and whether digital reporting is mandatory or voluntary. The table has multiple entries, given the ongoing development and implementation of Saudi Arabia's CCE strategy through various initiatives. The table also distinguishes between established systems such as the European Union's Emissions Trading System (ETS) and China's dual carbon targets and emerging approaches in countries such as Saudi Arabia and Australia.

8. Positioning Within Existing Literature

This review confirms the growing recognition in the literature that digital technologies such as blockchain, AI, IoT, and digital twins are essential for improving carbon accounting practices, particularly in the context of a circular economy. For example, Williams et al. [82] show that digital tools can significantly increase resource efficiency and reduce waste by enabling closed-loop systems aligned with circular economy principles. Our review builds on this and combines how such tools can be deployed not only to track materials but also to monitor GHG emissions in real time, thus linking technological and environmental goals in a more comprehensive way than previous studies.

Our review places more emphasis on the integration of digital technologies within circular business models, which adds complexity due to feedback loops, reuse, and shared ownership, compared to previous studies that mainly focused on linear supply chains or generic digitalization trends. For example, Rao et al. [83] describe how digital twins and IoT are being used in manufacturing to track resource flows and prolong product life cycles—two essential components of circular systems. To provide real-time, detailed emissions data at every stage of the life cycle, our review goes one step further and examines how these tools are being matched with carbon accounting metrics.

Furthermore, although recent studies have emphasized the growing use of digital technologies to facilitate ESG reporting [61], this review adds something special by combining their use in circular systems. Our analysis demonstrates how blockchain and AI are being used to close these gaps by enabling traceable, auditable emissions data across distributed networks and product life extensions. Standard ESG frameworks frequently have trouble with Scope 3 emissions and circularity metrics.

Egbumokei et al. [84] also examine how digital transformation can lower emissions and improve transparency in oil and gas operations. Our review improves the transferability and scalability of digital carbon accounting practices by generalizing these insights across various industries undergoing circular transitions, including manufacturing, logistics, and construction, whereas their study concentrates on sector-specific applications.

By incorporating new research on carbon accounting frameworks designed for circular systems, further differentiation is achieved. Ionescu [2], for example, emphasizes how professional and institutional norms surrounding carbon disclosures are evolving and their connection to sustainability goals. By showcasing how digital tools are actively implementing these standards in dynamic, real-time formats, surpassing traditional static reporting, our review both supports and advances this trend.

Lastly, our review adds to the body of literature by pointing out solutions such as smart contracts, interoperability protocols, and digital traceability platforms while also highlighting real-world obstacles like lack of standardization and integration difficulties. This supports and supplements the findings of Boz and Martin-Ryals [85], who emphasize that in order to successfully execute changes in the circular economy, comprehensive frameworks integrating social, digital, and policy components are required.

In sum, this review offers a comprehensive synthesis of the ways in which digital technologies are being used to enable carbon accounting, particularly within circular systems. It not only complements but also greatly advances the body of existing literature. This review identifies novel use cases, draws attention to understudied intersections, and provides a roadmap for implementing digital sustainability tools across industries.

9. Opportunities and Future Directions

As carbon and circular economy objectives align, carbon accounting serves as a key tool for fostering innovation, generating value, and changing systems. Combining carbon metrics with material flow tracking opens up new chances to improve circular strategies such as reuse and remanufacturing with data-driven insights. This shift enables businesses and policymakers to link carbon reduction efforts with broader sustainability goals [86].

The function of carbon markets and trading systems in encouraging circular behavior is one prominent area of research. Redesigned cap-and-trade programs, like the EU ETS, can incentivize circular practices that lower embedded carbon, such as recycling and extending the life of products. There is evidence that when carbon pricing mechanisms, particularly ETS, are designed to incentivize resource efficiency and recovery, they can catalyze circular behavior and lead to significant GHG reductions. A global study across 30 jurisdictions found that ETSs were associated with a 12.06% average reduction in carbon emissions, outperforming carbon tax regimes in many contexts [87].

Digital innovation is one of the most important drivers for advancing carbon accounting. Everything from digital twins to big data platforms and AI-powered analytics simulates, monitors, and optimizes carbon emissions in complex systems. In industries such as agriculture and food systems, this is increasingly being implemented to become circular and carbon negative. For example, precision agriculture is being implemented alongside soil restoration operations, with the aim of further reducing and potentially reversing GHG emissions [88]. This gives rise to the concept of holistic approaches where GHG emissions are not just minimized but potentially reversed.

The development of circular business models supported by innovation frameworks presents another emerging frontier. Experimental methods and toolkits are being used to design, test, and scale circular products and services while measuring their carbon performance throughout the life cycle [89]. These methods offer replicable pathways for companies to assess feasibility and environmental performance before full-scale implementation.

The importance of strategic planning and foresight is growing. Because of shifts in consumer demand, policy, and climate risks, circular SMEs are actively engaged in future scenario modelling. Businesses can proactively modify carbon accounting systems to support flexible, circularly focused growth by foreseeing these changes [90].

Moreover, integrating financial and carbon accounting has become a top priority. The distributed value of circular practices is not taken into consideration by conventional linear accounting. Scholars of accounting now propose redefining risk and value to take social and environmental externalities into account. This modification would assist in bringing financial reports into line with circular-carbon results [91]. Verifiable, auditable carbon data from circular operations is essential, as evidenced by the growth of sustainable finance and ESG-related tools.

Innovation ecosystems and policy ecosystems are becoming more interconnected. A bibliometric review discovered that research on eco-innovation and the circular economy is focused on five main trends, such as AI-driven circularity and the transition to renewable energy. These trends necessitate a corresponding advancement in GHG emissions accounting protocols [92].

On the policy side, the European Union and other governing bodies are recognizing the need for carbon accounting systems that reflect circularity. The call is growing for new policy tools like "carbon contracts for difference" and carbon budgets for circular projects to promote investment in sustainable practices. Such mechanisms would reward companies not only for emissions reductions but also for designing out emissions in the first place [92].

Finally, building capacity and educating people are crucial for achieving these future goals. As the lines between digital, environmental, and economic fields blur, we need new training programs to provide professionals with a mix of skills. This includes not only technical knowledge of carbon metrics but also systems thinking and ethical foresight [93].

10. Conclusion

Carbon accounting in circular economy systems is both a wicked problem and a key opportunity to improve climate goals in circular economy systems. More often than not, the carbon benefits of circular solutions like reuse, remanufacturing, and resource recovery are not properly reflected within traditional accounting methods. Opportunities for increased transparency, automated emissions accounting, and lifecycle insights driven by IoT and other digital technologies, including blockchain, AI, and cloud-based platforms, are emerging. Meanwhile, carbon governance models and standards are maturing to better reflect circular flows and decentralized production systems. However, executing circular carbon accounting is struggling due to a lack of standardization in methodology, gaps in technology, and regulatory alignment. Closing these gaps will require integrated policy development, investments in data infrastructure, and aligned metrics that capture total material life cycles and emissions. Carbon governance must embrace this long-term perspective to deliver sustainability reporting that addresses today's challenges and mirrors the circular properties we now seek in our broader economy.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Seyedeh Azadeh Alavi-Borazjani: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Shahzada Adeel:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing.

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