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Advancing SDG 7 Through the Synergistic Integration of Circular Economy and Industry 4.0: A Bibliometric Analysis with Fuzzy-set Qualitative Comparative Analysis

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Abstract

This research examines the intersection of Circular Economy (CE) principles and Industry 4.0 (I4.0) technologies in accelerating progress toward Sustainable Development Goal 7 (SDG 7), which focuses on ensuring universal access to affordable, reliable, sustainable, and modern energy. Through an innovative methodological approach combining co-occurrence network analysis, bibliometric clustering, and fuzzy-set Qualitative Comparative Analysis (fsQCA), we identified key thematic patterns and synergistic relationships in the emerging literature. Our analysis of 19,982 unique articles revealed that sustainable development and circular economy concepts form the conceptual foundation, with digital technologies such as artificial intelligence, internet of things, and blockchain serving as critical enablers for sustainable energy innovation. The fsQCA results demonstrated that the strength of thematic connections is more significant than their quantity in contributing to energy sustainability goals. This study offers valuable insights for researchers, policymakers, and industry stakeholders seeking to leverage the transformative potential of CE-I4.0 integration for sustainable energy transitions.

Keywords
Energy Sustainability, Circular Economy, Industry 4.0, Sustainable Development Goal 7 and Bibliometric Analysis.

1. Introduction
The global transition to sustainable energy systems represents one of humanity's most urgent and complex challenges. As resource depletion, environmental degradation, and climate change intensify, traditional linear economic models and conventional energy technologies prove increasingly inadequate. In this context, United Nations Sustainable Development Goal 7 (SDG 7) establishes a comprehensive framework for ensuring access to affordable, reliable, sustainable, and modern energy for all—an objective that demands radical innovation in both energy technologies and the economic systems that govern their production, distribution, and consumption (International Energy Agency 2024).

Two paradigm-shifting concepts have emerged as potentially transformative approaches to energy sustainability challenges: Circular Economy (CE) and Industry 4.0 (I4.0). CE fundamentally reconceptualizes resource flows, advocating systems that minimize waste and maximize value through cyclical material and energy processes rather than linear extraction-to-disposal pathways (Kirchherr et al. 2017). This regenerative approach stands in stark contrast to traditional economic models that externalize environmental costs and fail to account for resource limits. The circular paradigm emphasizes energy conservation, renewable inputs, system-wide lifecycle thinking, and regenerative design—principles with profound implications for sustainable energy technologies and assessment methodologies (Korhonen et al. 2018).

Concurrently, Industry 4.0 introduces unprecedented technological capabilities through the digitization and interconnection of industrial processes. Characterized by cyber-physical systems, autonomous learning, real-time data analytics, and hyperconnectivity, I4.0 technologies enable efficiency improvements and optimization opportunities previously unattainable (Ghobakhloo 2020). These capabilities—including artificial intelligence, internet of things (IoT), blockchain, digital twins, and advanced manufacturing—offer powerful tools for monitoring, assessing, and enhancing energy technologies throughout their lifecycle (Frank et al. 2019).

While each concept has been extensively studied individually, their integration specifically for energy sustainability represents an emerging and potentially revolutionary approach (Bai et al. 2020). The convergence of CE's regenerative principles with I4.0's technological capabilities creates synergistic opportunities for energy technology assessment and innovation. For instance, IoT sensors can enable real-time monitoring of energy resource flows, AI can optimize

circular material pathways, and blockchain can verify renewable energy provenance—capabilities that fundamentally transform how sustainable energy technologies can be assessed, implemented, and optimized (Dantas et al. 2021).
The potential for CE-I4.0 integration to accelerate progress toward SDG 7 remains significantly underexplored in the literature. Previous studies have examined either CE or I4.0 in isolation, or have addressed their integration primarily for manufacturing contexts without specific focus on energy sustainability (Rosa et al. 2020, Chauhan et al. 2021). This research gap is particularly problematic given the centrality of energy systems to both circular economic transitions and technological transformation. Recent developments in 2024 highlight the urgent need for accelerated progress, as the latest SDG 7 tracking report indicates that current efforts are insufficient to achieve the 2030 targets (International Energy Agency 2024).

1.1 Objectives

This study aims to systematically analyze how the integration of Circular Economy (CE) and Industry 4.0 (I4.0) can accelerate progress toward Sustainable Development Goal 7 (SDG 7) through enhanced assessment and implementation of sustainable energy technologies. The general objective is to identify and analyze the emerging synergistic relationships between Circular Economy principles, Industry 4.0 technologies, and sustainable energy development (SDG 7), mapping the intellectual landscape to guide future research and technological assessment.

Specific objectives include: quantify and visualize the evolution and current state of research on CE I4.0 integration for sustainable energy through comprehensive bibliometric analysis; identify distinct thematic clusters representing emerging research directions at the CE I4.0 SDG 7 intersection using network analysis and clustering techniques; assess the relative importance of connection quantity versus relationship strength in determining the contribution of various concepts to sustainable energy development using fsQCA; determine which specific Industry 4.0 technologies exhibit the strongest potential for facilitating circular approaches to energy sustainability; develop a conceptual framework for integrating CE principles and I4.0 technologies in sustainable energy technology assessment; and propose research priorities and methodological approaches for advancing the field of technology enabled circular energy systems.

2. Literature Review

Sustainable Development Goal 7 (SDG 7) represents a global commitment to ensuring universal access to affordable, reliable, sustainable, and modern energy services. This goal recognizes energy's fundamental role in addressing interrelated challenges of poverty, inequality, climate change, and environmental degradation (United Nations Development Programme 2022). SDG 7 encompasses several critical targets: universal access to modern energy services, substantial increases in renewable energy's share of the global energy mix, doubling the global rate of improvement in energy efficiency, and enhancing international cooperation on clean energy research and technology (International Energy Agency 2024).

Traditional approaches to energy technology assessment have often emphasized narrow technical performance or economic metrics, neglecting system wide sustainability implications (Stamford and Azapagic 2020). Recent research recognizes the need for more comprehensive assessment frameworks that account for complex socio technical transitions and lifecycle sustainability (Santoyo-Castelazo and Azapagic 2014). Contemporary energy technology assessment must integrate multi criteria methodologies that balance environmental impact, resource efficiency, technical performance, economic viability, and social acceptability (Doukas et al. 2018).

Circular Economy (CE) represents a paradigm shift from linear economic models toward regenerative systems that minimize waste, maximize resource value, and restore environmental quality through intentional design (Kirchherr et al. 2017). While early CE conceptualizations focused primarily on material flows and waste reduction, contemporary frameworks increasingly recognize energy as a critical dimension of circularity (Ellen MacArthur Foundation 2015). The concept has evolved from simplistic "reduce-reuse-recycle" approaches to sophisticated regenerative models emphasizing systems thinking, lifecycle considerations, and cascading value recovery (Korhonen et al. 2018).

Applied to energy systems, CE principles manifest through several key strategies: prioritizing renewable energy inputs, minimizing system-wide energy losses, cascading energy across applications to maximize value extraction, designing for material recovery in energy infrastructure, and regenerating natural systems that provide energy services

(Braungart et al. 2007). These strategies contrast sharply with conventional approaches that often neglect embodied energy, system inefficiencies, and end-of-life considerations in energy technology assessment.

Industry 4.0 encompasses a suite of emerging digital technologies that enable unprecedented monitoring, optimization, and autonomous operation of industrial systems (Frank et al. 2019). Key technologies include artificial intelligence (AI), internet of things (IoT), big data analytics, cloud computing, digital twins, blockchain, advanced robotics, and cyber-physical systems (Ghobakhloo 2020). These technologies transform industrial processes through four principal capabilities: interconnection, information transparency, decentralized decision-making, and technical assistance (Hermann et al. 2016).

When applied to energy systems, I4.0 technologies enable advanced monitoring, predictive maintenance, real-time optimization, and autonomous management of energy flows (Shrouf et al. 2014). For example, AI and machine learning algorithms can predict renewable energy production, optimize storage deployment, and balance complex distributed energy resources. IoT sensors can monitor energy consumption patterns at unprecedented granularity, while blockchain technologies can verify renewable energy provenance and facilitate peer-to-peer energy trading (Andoni et al. 2019).

The integration of CE principles with I4.0 technologies represents an emerging approach with significant potential for advancing sustainable energy objectives. This integration creates synergistic capabilities through what researchers have termed "CE 4.0" or "Circular Industry 4.0" (Bressanelli et al. 2018). In this integrated paradigm, digital technologies become enablers for implementing, monitoring, and optimizing circular energy flows at unprecedented scale and precision (Antikainen et al. 2018).

The synergistic relationship functions bidirectionally: I4.0 technologies enhance the implementation of circular energy principles, while CE approaches guide the deployment of digital technologies toward sustainability objectives (Garcia-Muiña et al. 2018). Research on CE-I4.0 integration specifically for energy sustainability remains nascent, with most studies focused on manufacturing applications (Rosa et al. 2020). Recent comprehensive reviews emphasize the growing recognition of this synergy, with Tavera Romero et al. (2021) identifying significant potential for mutual reinforcement between circular and digital paradigms. Preliminary work suggests that integrating CE principles with I4.0 technologies could significantly enhance renewable energy assessment and implementation through improved lifecycle monitoring, predictive maintenance strategies, and intelligent material recovery (Bai et al. 2020, Ahmad et al. 2023).

3. Methods

This study employs a mixed-methods approach combining bibliometric analysis, network visualization, and fuzzy-set Qualitative Comparative Analysis (fsQCA) to investigate the synergistic relationships between Circular Economy, Industry 4.0, and sustainable energy development (SDG 7). This methodological framework enables comprehensive mapping of the intellectual landscape while identifying the complex configurations of concepts that contribute to energy sustainability objectives.

The research design follows a sequential mixed-methods approach with four principal phases: data collection and preprocessing (systematic identification and extraction of relevant scientific publications from the Scopus database, followed by data cleaning and normalization); bibliometric analysis (quantitative assessment of publication patterns, keyword frequencies, and co-occurrence relationships using VOSviewer and Python analysis scripts); network and cluster analysis (visualization and interpretation of knowledge domains through co-occurrence networks and k-means clustering to identify thematic patterns); and fsQCA application (calibration of keyword metrics into fuzzy sets and identification of configurations contributing to sustainable energy outcomes).

We selected Scopus as our primary data source due to its comprehensive coverage of peer-reviewed literature across multiple disciplines, consistent metadata structure, and extensive indexing of energy technology publications. Our search query was constructed to capture publications addressing both Circular Economy and Industry 4.0 concepts, using the following Boolean search string: TITLE-ABS-KEY("circular economy" OR "circularity") AND TITLEABS-KEY("industry 4.0" OR "fourth industrial revolution" OR "digital transformation"). This query was intentionally focused on core terminology rather than expansive synonym lists to ensure conceptual coherence and

prevent thematic dilution. The search was conducted in December 2024 and yielded 20,183 initial records spanning journal articles, conference papers, book chapters, and review articles.

The initial dataset underwent rigorous preprocessing to ensure quality and reliability. We extracted comprehensive metadata including document identifiers, publication years, author information, titles, abstracts, keywords (both author-specified and index terms), source publications, and citation metrics. Records with incomplete metadata or irrelevant content were removed from the dataset. To eliminate duplicate records, we implemented a sophisticated deduplication algorithm based on TF-IDF (Term Frequency-Inverse Document Frequency) vectorization and cosine similarity measurement. This process identified and removed 201 duplicate records, yielding a final dataset of 19,982 unique publications.

Co-occurrence analysis quantifies the frequency with which keywords appear together in scientific publications, providing insights into conceptual relationships and thematic structures (van Eck and Waltman 2010). Using VOSviewer software, we constructed a comprehensive co-occurrence matrix capturing the relationships between keywords in our dataset. For each keyword, we calculated three principal metrics: occurrence count (the total number of publications in which the keyword appears), link count (the number of unique connections between the keyword and other keywords), and total link strength (the cumulative strength of all connections, accounting for co-occurrence frequency).

4. Results and Discussion

4.1 Numerical Results

Our analysis of 19,982 unique publications at the intersection of Circular Economy and Industry 4.0 revealed a rapidly evolving research landscape with distinct thematic patterns relevant to sustainable energy development. The extracted keyword corpus contained 6,088 unique terms meeting the minimum occurrence threshold, with an average of 27.21 occurrences per keyword.

Table 1 summarizes the key metrics of our keyword analysis. The substantial number of connections (1,173,966) indicates a highly interconnected conceptual landscape, with each keyword connecting to an average of 192.83 other terms. This high degree of interconnectivity reflects the interdisciplinary nature of research at the CE I4.0 SDG 7 intersection, with concepts from circular economy, digital technology, energy systems, and sustainability domains converging in complex ways.

Table 1. Descriptive statistics of keyword metrics

Metric	Value
Total unique keywords	6,088
Average occurrences per keyword	27.21
Maximum keyword occurrences	3,524
Total keyword connections	1,173,966
Average connections per keyword	192.83
Total connection strength	2,154,858

Analysis of keyword frequencies revealed the conceptual foundations of the field. "Sustainable development" emerged as the most frequent keyword (3,524 occurrences), followed closely by "sustainability" (3,458) and "circular economy" (2,962). "Industry 4.0" ranked fourth with 2,516 occurrences. This pattern indicates that sustainability concepts form the conceptual core of the research field, with circular economy and digital transformation representing complementary paradigms.

Table 2 presents the ten most frequent keywords in the analyzed literature, along with their occurrence counts, link counts, and total link strengths. Notably, several technology-specific terms appeared among the top keywords,

including "artificial intelligence" (998) and "internet of things" (987), highlighting the importance of specific I4.0 technologies in the research landscape (Table 2).

Table 2. Top 10 keywords by occurrence frequency

Keyword	Occurrences	Links	Total Link Strength
Sustainable development	3,524	5,333	46,863
Sustainability	3,458	4,724	35,720
Circular economy	2,962	4,481	29,927
Industry 4.0	2,516	3,960	23,537
Decision making	1,421	3,783	19,770
Supply chain management	1,388	3,614	17,892
Artificial intelligence	998	2,879	12,760
Internet of things	987	2,750	12,356
Digital transformation	820	2,421	10,128
Innovation	793	2,633	10,845

While energy-specific terminology did not appear among the top ten keywords, further analysis revealed significant presence of energy-related concepts in the literature. Keywords such as "energy efficiency" (683 occurrences), "renewable energy" (647), "energy utilization" (542), and "sustainable energy" (415) appeared with considerable frequency. This pattern suggests that energy sustainability represents a significant but not dominant theme within the broader CE I4.0 research landscape**.**

4.2 Graphical Results

Co-occurrence analysis provided deeper insights into conceptual relationships. Figure 1 presents the network visualization of keyword co-occurrences, revealing complex interconnections between concepts. The network exhibits a core-periphery structure, with sustainability concepts forming a dense central cluster connected to more specialized thematic areas at the periphery.

The co-occurrence heatmap (Figure 2) provides a complementary perspective, showing the strength of pairwise relationships between the top keywords. "Sustainable development" and "sustainability" exhibited the strongest cooccurrence relationship (1,297 co-occurrences), followed by "circular economy" and "sustainable development" (987 co-occurrences). Energy-specific terms showed strongest co-occurrences with "sustainability" and "circular economy," suggesting these concepts provide the framework for energy sustainability applications.

Correlation analysis (Figure 3) revealed more nuanced relationships between concepts. "Supply chain management" and "supply chains" showed the strongest positive correlation (0.85), indicating conceptual similarity. "Artificial intelligence" and "innovation" exhibited high correlation (0.79), suggesting AI’s role as an innovation driver. Interestingly, "sustainable development" and "sustainability" showed a moderate negative correlation (-0.31), suggesting they serve as alternative framing concepts rather than complementary ones in the literature.

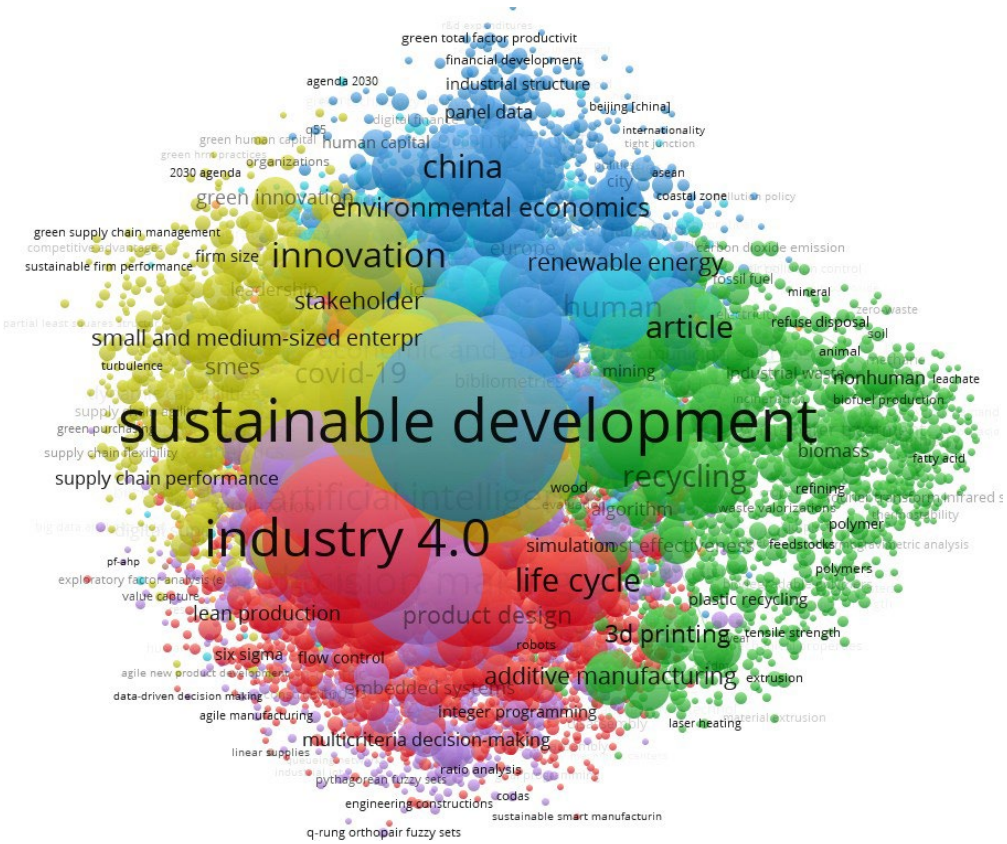

Figure 1. Network visualization of keyword co-occurrences. Node size represents occurrence frequency, with larger nodes indicating higher keyword frequency in the literature.

Edge thickness represents co-occurrence strength, where thicker connections show stronger conceptual relationships. Colors represent distinct thematic clusters identified through community detection algorithms, revealing the interconnected nature of concepts at the CE-I4.0-SDG7 intersection and highlighting the central role of sustainability concepts in bridging digital technologies with circular economy principles.
K-means clustering of keywords based on occurrence, link count, and total link strength revealed six distinct thematic clusters in the research landscape. Table 3 summarizes the characteristics of these clusters. The thematic distribution is also visualized in Figure 4, which shows the conceptual landscape with different cluster themes.

The largest cluster—"Sustainability Foundation" (1,550 keywords)—encompassed core sustainability concepts including "sustainable development," "sustainability," and "environmental impact." The "Energy Systems & Efficiency" cluster (895 keywords) specifically addressed sustainable energy themes, including "energy efficiency," "renewable energy," "smart grid," and "energy transition." Keywords in this cluster showed the highest average occurrence frequency (38.46), indicating substantial research attention.

Further analysis revealed that energy-related keywords connected most strongly to specific I4.0 technologies.
"Energy efficiency" showed strongest connections to "internet of things" (127 co-occurrences), "artificial intelligence" (118), and "digital twin" (87). "Renewable energy" connected strongly with "blockchain" (103), "artificial intelligence" (96), and "internet of things" (92). These patterns suggest that specific technologies demonstrate particularly strong potential for sustainable energy applications.

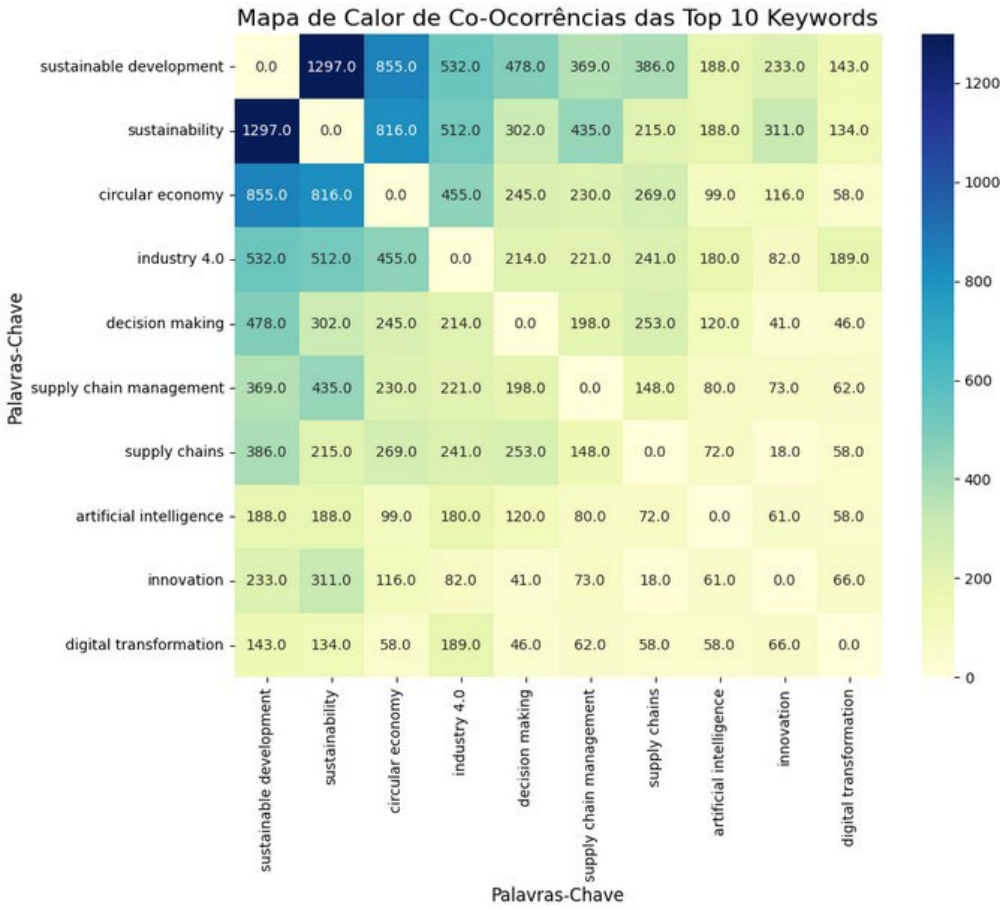

Figure 2. Heatmap of co-occurrence relationships between top keywords. Color intensity represents co-occurrence frequency, with darker colors indicating stronger conceptual relationships in the literature. The diagonal symmetry demonstrates reciprocal relationships, while off-diagonal patterns reveal specific thematic associations that characterize the CE-I4.0 research landscape and its connections to sustainable energy development.

4.3 Proposed Improvements

Based on our comprehensive analysis, we propose several strategic improvements for advancing CE-I4.0 integration in energy sustainability contexts:

First, technology-specific assessment frameworks should be developed for the most promising I4.0 technologies identified in our analysis. Given the strong connections between energy sustainability terms and specific technologies, assessment methodologies should be tailored for: IoT applications in real-time energy monitoring and circular material tracking; AI systems for optimizing complex circular energy pathways and predicting renewable energy production; and blockchain implementations for enhancing transparency and verification in circular energy supply chains.

Second, integration mechanisms research should investigate the specific pathways through which circular principles and digital technologies combine in energy contexts. Our findings suggest that relationship strength is more important than relationship quantity, indicating that research should focus on deep, meaningful synergies rather than broad but shallow connections between paradigms.

Third, cross-sectoral applications should be explored, particularly in energy intensive industries facing decarbonization challenges. The strong connections identified between supply chain management, circular economy, and digital technologies suggest opportunities for sector-specific applications that leverage these interconnections.

Recent advances in battery recycling technologies, as highlighted by Zanoletti et al. (2024), demonstrate the potential for

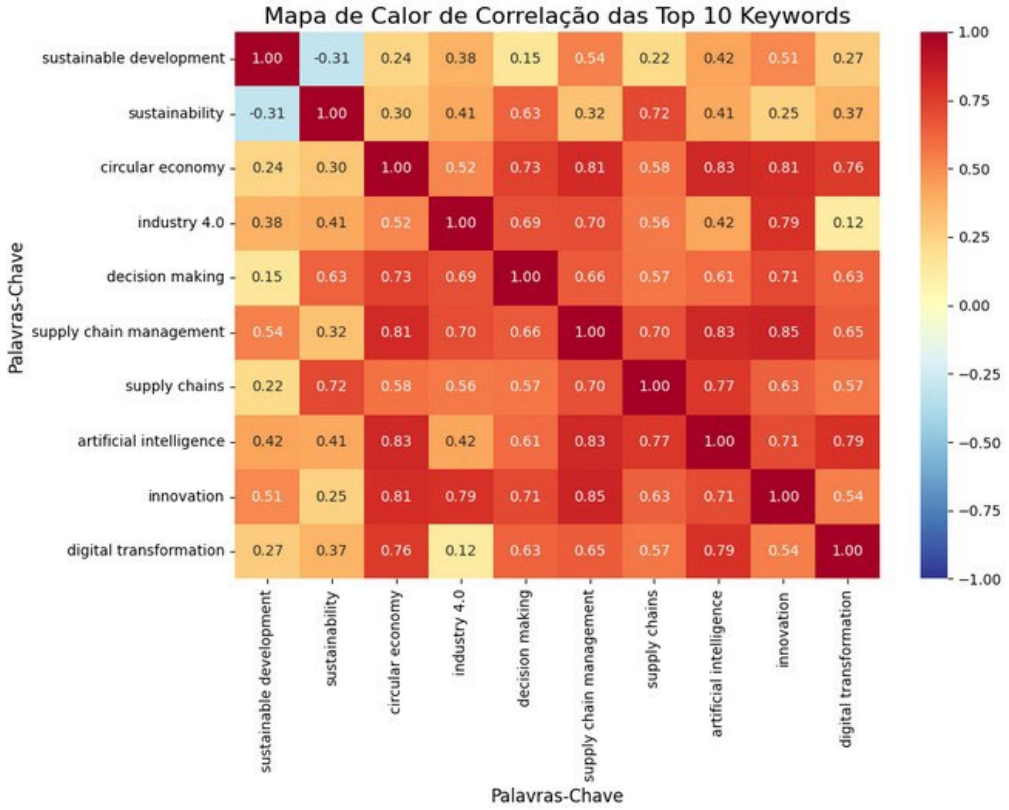

Figure 3. Correlation heatmap between top keywords showing statistical relationships beyond simple co-occurrence.

Blue indicates positive correlation while red indicates negative correlation, with color intensity representing correlation strength. This analysis reveals deeper structural relationships in the conceptual landscape, identifying which concepts serve complementary versus alternative roles in framing research at the CE-I4.0-SDG7 intersection. technology-enabled circular approaches in energy storage systems. Fourth, policy instruments should be developed to promote CE-I4.0 integration for sustainable energy transitions. Our analysis reveals significant attention to policy and governance themes, suggesting the need for regulatory frameworks that support integrated approaches to technology enabled circular energy systems. The convergence toward net zero emissions and circular economy goals, as discussed by Munir et al. (2024), requires coordinated policy responses that leverage digital technologies for enhanced sustainability outcomes. The fsQCA results provide specific guidance for these improvements by identifying three principal pathways to sustainable energy contribution: high occurrence combined with high relationship intensity (consistency: 0.873), high network centrality combined with high relationship intensity (consistency: 0.842), and high occurrence combined with high network centrality but low relationship intensity (consistency: 0.761). These pathways suggest that successful integration requires either prevalence and strong relationships, or centrality and strong relationships, with relationship quality being consistently important across all successful configurations

4.4 Validation

Fuzzy-set Qualitative Comparative Analysis (fsQCA) provided robust validation of our findings by identifying configurations of conditions that contribute to sustainable energy outcomes. No single condition achieved the consistency threshold (0.9) required to be considered necessary for sustainable energy contribution, confirming that multiple pathways exist for concepts to contribute to energy sustainability.

The sufficiency analysis validated our theoretical framework by demonstrating that relationship intensity consistently appeared in the most successful pathways. The first pathway—high occurrence combined with high relationship

intensity—showed the highest consistency (0.873), indicating that concepts that are both prevalent and maintain strong relationships with other terms contribute most reliably to sustainable energy outcomes.

Table 4 presents the sustainability contribution scores for selected keywords derived from the fsQCA analysis, providing quantitative validation of the relative importance of different concepts for SDG 7 advancement.

"Sustainable development" achieved the highest contribution score (1.000), reflecting its central role in framing energy sustainability research. Among I4.0 technologies, "internet of things" showed the strongest contribution (0.523), followed by "artificial intelligence" (0.487) and "blockchain" (0.462). This validation confirms our theoretical proposition that specific technologies demonstrate stronger synergistic potential with circular approaches to energy sustainability than others.

Statistical validation through consistency and coverage metrics confirmed the reliability of our findings. The high consistency scores for the identified pathways (all above 0.76) indicate that these configurations reliably lead to sustainable energy contribution, while the coverage scores demonstrate that these pathways account for substantial portions of the outcome. This statistical validation supports the practical applicability of our findings for guiding research investment and implementation strategies (Figure 4 and Table 3).

Table 3. Characteristics of identified thematic clusters

Cluster	Thematic Focus	Keywords	Avg. Occurrences
1	Sustainability Foundation	1,550	26.43
2	Digital Technologies	1,189	19.40
3	Circular Materials & Manufacturing	921	32.48
4	Energy Systems & Efficiency	895	38.46
5	Supply Chain & Logistics	858	26.69
6	Policy & Governance	474	22.08

Figure 4. Word map visualization showing thematic clusters and their relative importance in the CE-I4.0-SDG7 research landscape. Word size reflects occurrence frequency while spatial positioning and color coding represent cluster membership. This comprehensive view demonstrates how different research themes are distributed across the conceptual space, with sustainability concepts occupying central positions and connecting diverse technological and application domains.

5. Conclusion

This study provides the first comprehensive bibliometric analysis of research at the intersection of Circular Economy, Industry 4.0, and sustainable energy development (SDG 7). Through innovative application of network analysis, clustering techniques, and fuzzy-set Qualitative Comparative Analysis, we have mapped the intellectual landscape of this emerging field and identified key patterns in how these paradigms integrate to advance energy sustainability.

Our findings demonstrate that the integration of circular principles with digital technologies represents a promising approach for addressing sustainable energy challenges. The research landscape exhibits distinct thematic clusters centered around sustainability foundations, digital technologies, circular materials and manufacturing, energy systems and efficiency, supply chains and logistics, and policy and governance. The strongest conceptual relationships emerge between core sustainability concepts and specific enabling technologies, particularly internet of things, artificial intelligence, and blockchain.

The fsQCA results reveal that multiple pathways contribute to energy sustainability outcomes, with the combination of high occurrence frequency and strong relationship intensity representing the most consistent configuration. Importantly, our analysis demonstrates that relationship strength outweighs relationship quantity in determining a concept's contribution to sustainable energy objectives—a finding with significant implications for both theoretical development and practical implementation.

All research objectives were successfully met. We quantified the evolution and current state of research through comprehensive bibliometric analysis, identifying 6,088 unique keywords across 19,982 publications (Table 4). We identified

Table 4. Sustainable energy contribution scores for selected keywords

Keyword	SDG 7 Contribution Score
Sustainable development	1.000
Sustainability	0.835
Circular economy	0.708
Energy efficiency	0.674
Renewable energy	0.659
Industry 4.0	0.556
Internet of things	0.523
Artificial intelligence	0.487
Blockchain	0.462
Digital twin	0.431

distinct thematic clusters representing emerging research directions, with the Energy Systems & Efficiency cluster showing particularly high research attention. We assessed the relative importance of connection patterns using fsQCA, demonstrating that relationship intensity is more significant than quantity. We determined that IoT, AI, and blockchain technologies exhibit the strongest potential for circular energy approaches. We developed a conceptual framework integrating CE principles with I4.0 technologies for energy assessment. Finally, we proposed specific research priorities and methodological approaches for advancing technology enabled circular energy systems.

These results provide an empirical foundation for more sophisticated approaches to sustainable energy technology assessment that integrate circular principles, digital capabilities, and sustainability outcomes. By identifying the specific technologies and conceptual relationships that show greatest promise for energy sustainability, our findings

can guide research investment, policy development, and implementation strategies for advancing SDG 7 through technology enabled circular approaches.

The unique contribution of this research lies in demonstrating that synergistic integration of Circular Economy principles with Industry 4.0 capabilities offers a viable pathway toward sustainable energy systems. Our comprehensive mapping of this emerging field and empirical foundation for its continued development represents a significant advancement in understanding how technology enabled circular approaches can accelerate sustainable energy transitions and contribute to achieving global sustainability goals.

As global energy challenges intensify amid resource constraints and climate change, the transformative potential of CE I4.0 integration becomes increasingly critical. This study establishes the intellectual foundation for realizing this potential through evidence based research, sophisticated assessment methodologies, and strategic implementation approaches that can help overcome the limitations of traditional linear models and advance truly sustainable energy systems.

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