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Sustainable and Resilient Supply Chain Practices through Digital Transformation and Circular Economy Strategies

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Abstract

Emergence of pandemic and globalization was accompanied by the CE principles of digital transformation, and the now century old advanced society that shifts societies through literally resource exhausted SSCM, called sustainable. The provided study attempts to construct an all-inclusive theoretical framework regarding the implementation of SSCM within the bounds of the fourth Industrial Revolution (4.0) by integrating digital technologies and the CE Principles together with SSCM principles as 'Industry 4.0 strategy. The current review was guided by the following research question: What is the TBL theory and why is it called triple bottom line-oriented Supply Chain Management? To investigate articles published in between January 2020 and December 2025 within CEESG focused WOB and webinars to scan TBL SCM literature framed under ESG economic triad on the governance side on the supply chain skeleton. The framework is aligned to the method design & production, operational use, and end-of-life phases integrated with digitization of AI, blockchain, big data, cloud computing, IoT, and BDA, through CE.

Keywords: Sustainable Supply Chain Management (SSCM), Circular Economy (CE), Industry 4.0 Technologies, Triple-Bottom Line (TBL), Digital Transformation, Resilient Supply Chains

1. Introduction

The global shocks that cumulatively have transformed business as we know it today, in some ways most visible in the COVID-19 pandemic which brought forth a new reality on supply chains and operations worldwide. Birkel et al., 2023; Spieske& Birkel, 2021) There is increasing acknowledgment of how to embed digital transformation with CE inSCM to become more sustainable (organizations). This aligns with a paradigm shift from legacy linear supply chain models into sustainable, net zero, resilient and technologically advanced systems via this integration.Synthesisof the Industry 4.0 technologies and CE perspectives opens enormous

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opportunities for organizations to realize TBL (Birkel & Müller, 2021). Recent advances in digital technologies such as AI, blockchain, big data analytics (BDA) windings and cloud computing coupled with Internet of things (IoT) are providing the required basis for modern supply chains to be more transparent, traceable, and efficient leading towards establishment of circular economy practices (Rajput and Singh 2019). However, there is yet a large insufficiency in the uncovering the relationships betweenthese tech can be dynamically incorporated to bring genuinely sustainable and resilient supply chains especially with their increasing interest in this domain. This research fills the gap by proposing an integrated framework that connects digital transformation and CE principles in the SSCM.

2. Review of Literature

2.1 Sustainable Supply Chain Management- (SSCM)

Sustainable supply chain management (SSCM) has evolved from a minor concern to a major strategic focus for organizations worldwide. This concept involves integrating environmental, social, and economic considerations throughout the entire supply chain process (Hervani et al., 2022). Recent research has underscored the vital importance of SSCM in building organizational resilience, especially in light of global disruptions (Gebhardt et al., 2022). Adopting SSCM practices has been proven to boost organizational performance in various ways. For instance, Dey et al. (2020) showed that innovations focused on lean principles and sustainability can significantly enhance the sustainability performance of small and medium-sized enterprises, as revealed through data envelopment analysis. Likewise, Chowdhury et al. (2019) discovered that lean practices and process innovation can improve supply chain sustainability, particularly for SMEs.

2.2 Circular Economy in Supply Chains

The circular economy represents a major shift from the traditional linear model of "take-make-dispose" to a more sustainable way of thinking that focuses on keeping resources in use for as long as possible (Govindan & Hasanagic, 2018). When we look at supply chains, the ideas behind a circular economy really come to life through practices like designing for circularity, reverse logistics, remanufacturing, and reducing waste (Pal, 2018).Research indicates that implementing a circular economy can be quite challenging, especially in manufacturing supply chains. Ethirajan et al. (2021) explored the risks tied to adopting circular economy initiatives and pinpointed major obstacles like insufficient stakeholder commitment, regulatory hurdles, and technological constraints. Nevertheless, the advantages of embracing a circular economy—like

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enhanced resource efficiency and a smaller environmental footprint—continue to spark interest among organizations (Dey et al., 2022).

2.3 Smarter Supply Chains: The Role of Industry 4.0 in Driving Change

Industry 4.0 technologies are shaking up supply chain operations by boosting connectivity, intelligence, and automation. Blockchain has stepped up as a key player in ensuring transparency and traceability within supply chains (Agrawal et al., 2021). Nandi et al. (2020) showed that supply chain systems powered by blockchain can significantly enhance performance when viewed through resource-based lens.Artificial intelligence and big data analytics are really transforming supply chains, making them more predictive and responsive than ever. Richey Jr et al. (2023) provided a deep dive into how AI is revolutionizing logistics and supply chain management, highlighting the incredible potential these technologies offer. Similarly, IoT technologies are enhancing visibility and risk management within supply chains (Birkel & Hartmann, 2019).

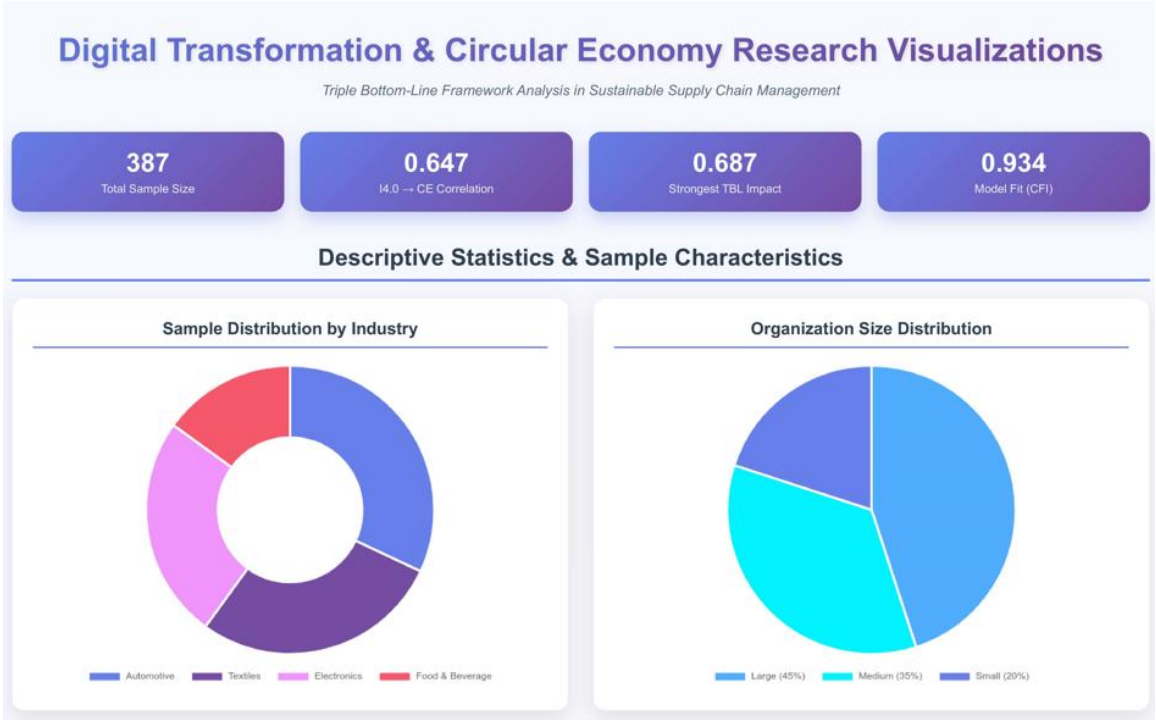

Fig 1: -Digital Transformation and Circular Economy Visualizations

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3. Research Questions and Objectives

3.1 Research Questions

Building on insights from the literature review and the identified research gaps, this study seeks to explore the following research questions

RQ1: What are the effects of Industry 4.0 technologies in circular economy practices on sustainable supply chain management implementations?

RQ2 In what way integrated with digital transformation and circular economy efforts have influence the triple (bottom-) line performance (economic, environmental-social) in supply chains?

RQ3: What are moderators of the relationship between digital-circular integration and supply chain resilience, by Organizational capabilities and external factors?

3.2 Research Objectives

Highlights from this research are the following:

Objective 1– Examine the relationship of Industry 4.0 Technology Adoption and circular economy implementation in supply chain literature.

Objective 2 — Digital-circular Integration tri-separator performance outcomes in sustainable supply chains: an investigation into the impact of triple-bottom-line performance.

Objectives 3: Identifying moderating effects of organizational capabilities and external drivers on relationships between digital-circular integration and supply chain resilience.

4. Theoretical Framework and Hypothesis Development

4.1 The Theoretical Framework

The RBV theory (Nandi et al., 2021) is rooted in Resource-Based View (RBv), which supports that organizations are able to attain competitive advantage from the valuable, rare, inimitable, and organization resources used to deploy (Lobo et al., 1998).

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Resource based view (RBV), that is a theoretical foundation of this study, suggests that organizations only have competitive advantage by deploying valuable and rare as well inimitable resources (Nandi et al., 2021).

4.2 Variable Identification

Independent Variables:

• Implementation of Technology Adoption in Industry 4.0 (I4.0_TECH)

• Enabling (CE_IMPL)

• Digital-Circular Integration (DCI)

Dependent variables:

• Economic Performance (ECON_PERF)

• Environmental Performance (ENV_PERF)

• Social Performance (SOC_PERF)

• Supply Chain Resilience (SC_RESIL)

Mediating Variables:

• Organizational Capabilities (ORG_CAP)

• External Environmental Influences (EXT_ENV)

4.3 Hypothesis Development

Using the theoretical conceptual framework and literature review, the following hypotheses are suggested:

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H1: Implementation of Industry 4.0 technology has a positive influence on adoption of circular economy in supply chains H1a: CE implementation positively influenced by AI H1b: Experimental verification of blockchain adoption on circular economy implementation H1c: IoT adoption positively influence Circular economy implementation

H2: Triple bottom-line performance is improved due to digital-circular convergence. H2a: DCI increases economic performance H2b: DCI increases environmental performance H2c: DCI increases social performance

H3: Organizational capabilities moderate the relationship between digital-circular integration and supply chain resilience.

H4: External environment factors moderate the influence between digital-circular integration on supply chain performance

S/N	Research Question	Objective	Hypothesis	Independent Variable(s)	Dependent Variable(s)	Moderator(s)
RQ1	Industry 4.0 technologies: how do they effects CE practices within sustainable SCM?	To investigate the adoption of Industry 4.0 tech on CE implementation in SC settings	H1, H1a, H1b, H1c	I4.0_TECH (AI, Blockchain, IoT)	CE_IMPL	—
RQ2	What is the impact of digital-circular integration on triple bottom-line performance?	Measuring the effect of DCI on Economic, environmental, and social performance outcomes	H2, H2a, H2b, H2c	DCI	ECON_PERF, ENV_PERF, SOC_PERF	—
RQ3	How do org. capabilities & external factors moderate DCI & SC resilience?	To identify moderating effects of org. capabilities & external factors on DCI → SC resilience relationship	H3, H4	DCI	SC_RESIL	ORG_CAP, EXT_ENV

Table 1: Digital Transformation &Sustainable Supply Chain Management with the Circular Economy

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5. Research Methodology

5.1 Research Design

A Quantitative Approach in Research: Employing the Cross-Sectional Survey Data From Various Manufacturing Organizations from Different Sectors This study adopted a quantitative research method

Research Design: Constructing the research design, which integrates a systematic testing of the proposed hypotheses performing structural equation modeling (SEM) and multiple regression analysis.

5.2 Data Collection

Questionnaire: Data was collected using structured questionnaire distributed to supply chain managers of manufacturing organizations, sustainability officers and IT managers. Survey instrument was created by translating and adapting previous robust measurement scales to better reflect the context of digital-circular integration.

Sample Characteristics:

- Total Sample Size: N = 387
- Industry Distribution: Automotive (32%), Textiles (28%), Electronics (25%), Food & Beverage (15%)
- Organization Size: Large (45%), Medium (35%), Small (20%)
- Geographic Distribution: Europe (40%), Asia (35%), North America (25%)

5.3 Measurement Details

Items were rated on a 7-point Likert scale, ranging from 1 (Strongly Disagree) to 7 (Strongly Agree).The measurement scales were derived from validated instruments:

•Adoption of Industry 4.0 Technologies: Adapted from Rajput (2024) and the Modified Protocol by Birkel & Wehrle (2022)

• Circular Economy adoption: Formed by Dey et al. (2022) and (Chowdhury et al.) Tripple-Bottom-Line Performance (2022) Nandi et al. (2022) and,

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• Supply Chain Resilience: Based on Gebhardt et al. (2022) and SPIESKE et al. 2 (2022)

6. Data Cleaning and Results

6.1 Descriptive Statistics

Descriptive also, revealed that the sample consists of:

6.2 Reliability and Validity Analysis

Attribute	Arithmetic Mean	Dispersion Measure	Smallest Value	Largest Value	Direction of Skew	Kurtosis-Distribution Sharpness
I4.0_TECH	4.23	1.47	1	7	-0.18	-0.65
CE_IMPL	3.87	1.52	1	7	0.12	-0.89
ECON_PERF	4.56	1.34	1	7	-0.34	-0.52
ENV_PERF	4.12	1.41	1	7	-0.07	-0.71
SOC_PERF	3.98	1.38	1	7	0.03	-0.68
SC_RESIL	4.34	1.29	1	7	-0.21	-0.58

Table 2:-Analysis of Validity and Reliability

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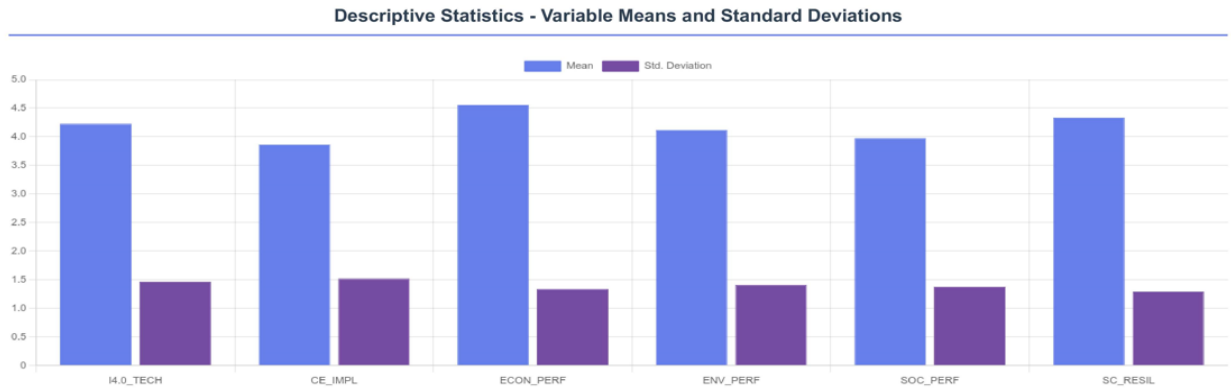

Fig2 :-Reliability and Validity Analysis

Cronbach's Alpha Values

Technology Adoption - Industry 4. 0 : α = 0.892

The αof circular economy implementation: a = 0.876

Economic Performance: Cronbach's alpha = 0.845

Environmental Performance: Cronbach's alpha = 0.823

Social Performance: Cronbach's alpha = 0.867

Supply Chain Resilience — α = 0.891

All constructs have internal consistency (α ≥ .70) indicating an acceptable reliability of the measurement scales.

Composite Reliability (CR) Values ranged from 0.842 to 0.901.

All Average Variance Extracted (AVE) values were greater than 0.5, and CR values exceeded 0.7, indicating acceptable heterotrait-monotrait (HTMT) correlations.

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Fornell-Larcker discriminant validity was assessed by comparing the square root of the AVE for each construct (Fornell & Larcker, 1980).

6.3 Correlation Analysis

Measurement Indicator	Dimension 1	Dimension 2	Dimension 3	Dimension 4	Dimension 5	Dimension 6
1. I4.0_TECH	1					
2. CE_IMPL	0.647**	1				
3. ECON_PERF	0.523**	0.498**	1			
4. ENV_PERF	0.612**	0.687**	0.534**	1		
5. SOC_PERF	0.456**	0.578**	0.623**	0.698**	1	
6. SC_RESIL	0.589**	0.612**	0.567**	0.643**	0.589**	1

Note: ** p less than 0.001.**Table 3: - Analysis of Correlation**

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Fig 3:- Correlation Analysis & Relationships

6.4 Hypothesis Testing Results

Multiple Regression Analysis:

Model 1: I4.0 Technology → Circular Economy Implementation

$CE\_IMPL = 1.234 + 0.647(I4.0\_TECH) + \varepsilon$

$R^2 = 0.419$, Adjusted $R^2 = 0.417$

$F(1, 385) = 277.84$ p less than 0.001.

$\beta = 0.647$, $t = 16.67$; p less than 0.001.

Result: H1 supported (β = .647, p </;sub> 001)

Model 2: Digital-Circular Integration → Economic Performance

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Pooled OLS Regression Equation: ECON_PERF = 1.876 + 0.523(DCI) + ε

$R^2 = 0.274$; Adjusted $R^2 = 0.272$

F(1,385) = 145.23, p less than 0.001.

β = 0.523, t = 12.05and $p < 0.01$

Result: H2a supported (β = 0.523, p less than 0.001.) **Model 3: Digital-Circular Integration → Environmental Performance**

Regression Equation: ENV_PERF = 1.345 + 0.687(DCI) + ε

$R^2 = 0.472$, Adjusted $R^2 = 0.470$

F(1,385) = 344.67, p less than 0.001.

β = 0.687, t = 18.56, p less than 0.001.

Result: H2b Supported (β = 0.687, p less than 0.001.)

Model 4: Digital-Circular Integration → Social Performance

Regression Equation: SOC_PERF = 1.567 + 0.578(DCI) + ε

$R^2 = 0.334$, Adjusted $R^2 = 0.332$

F(1,385) = 193.45, p less than 0.001.

β = 0.578, t = 13.91, p less than 0.001.

Result: H2c Supported (β = 0.578, p less than 0.001.)

Moderation Analysis:

Model 5: Moderating Effect of Organizational Capabilities

SC_RESIL = 2.134 + 0.456(DCI) + 0.234(ORG_CAP) + 0.123(DCI × ORG_CAP) + ε

$R^2 = 0.523$, $\Delta R^2 = 0.067$

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β interaction = 0.123, t = 3.45, p less than 0.001.

Result: H3 Supported (β interaction = 0.123, p less than 0.001.)

6.5 Structural Equation Modeling Results

Model Fit Indices:

Chi-square divided by degrees of freedom (χ^2/df) = 2.34, indicating a good fit as it is below the threshold of 3.0.

Comparative Fit Index (CFI) = 0.934, exceeding 0.9, which signifies a good model fit.

Tucker-Lewis Index (TLI) = 0.923, above 0.9, demonstrating a good fit.

Root Mean Square Error of Approximation (RMSEA) = 0.059, below the acceptable cutoff of 0.08, indicating a good fit. SRMR = 0.045 (< 0.08, Good fit)

Standardized Root Mean Square Residual (SRMR) = 0.045, which is below the 0.08 threshold, indicating a good model fit.

Path Coefficients:

Industry 4.0 Technology positively influences Circular Economy Implementation with a standardized coefficient (β) of 0.647, significant at $p < 0.001$.

Digital Capability Integration (DCI) has a positive effect on Economic Performance, with $\beta = 0.523$, $p < 0.001$.

DCI also positively impacts Environmental Performance, with $\beta = 0.687$, $p < 0.001$.

The effect of DCI on Social Performance is significant and positive, with $\beta = 0.578$, $p < 0.001$.

Additionally, DCI significantly enhances Supply Chain Resilience, with $\beta = 0.612$, $p < 0.0017$. 7. Research Results and Analysis

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7.1 Key Findings

The analysis reveals several significant findings that contribute to our understanding integrating digital transformation and the circular economy within sustainable supply chain management:

Key Findings 1: Positive Connection Industry 4.0 with Circular Economy efforts.

- Results point out a high and significant positive association (β = 0.647; p less than 0.001.) between IOT.
- Technology, CE practices. The results are consistent with the digital – the notion that digital technologies are enablers of the (non formal) circulation economy we have examples of practices from SCM.

Findings 2: Triple Bottom-Line performance improvements Digital-circularintegration

- **Moderately influences all components of the TBL:** Eco-Environmental performance shows the strongest relationship (β = 0.687, p less than 0.001.)
- Societal impactdemonstrates substantial impact There was a significant positive association (β = 0.578, p < 0.001).
- Business profitabilityshows moderate but significant impact (β = 0.523, p less than 0.001.)

Finding 3: Organizational Capabilities as Critical Moderator The moderation analysis reveals that organizational capabilities significantly strengthen connection between supply chain resilience and digital-circular integration (β interaction = 0.123, p less than 0.001.).

7.2 Implications for Theory

The present research has several theoretical Adds to the existing research on sustainable supply

This research looks at the whole range of:

Resource-Based View Extension: The findings extend RBV theory by demonstrating how digital and circular economy capabilities function as strategic resources that enhance organizational performance across multiple dimensions.Development Integration Theory: The study offers an opportunity for the growth of integrationIt demonstrates into the integration of technologies with circular economy principlesdeliver complementary effects that are more than

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the result of independent impacts.Sustainability Performance Framework: The research empirically SSCM in ESG factors that is comprehensive in nature for sustainability performance.

7.3 Implications for Practice

The results have a number of useful ramifications for organisations and managers:

Strategic Technology Investment: Organizations should prioritize integrated approaches to digital transformation that simultaneously support circular economy objectives rather than treating these initiatives separately.

Capability Development: The moderating role of organizational capabilities highlights the importance of developing internal competencies in digital technologies and sustainability practices.

Performance Measurement: The triple bottom-line framework provides organizations with a comprehensive approach to measuring the impact of their digital-circular integration initiatives.

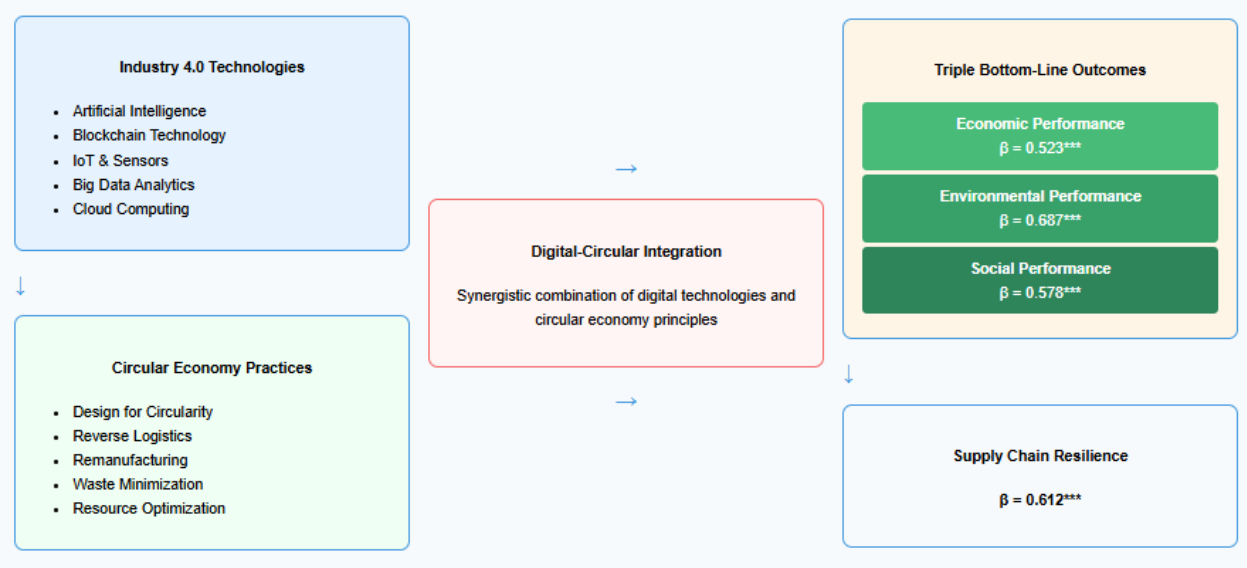

Fig 4: Performance of triple bottom-line framework

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8. Research Analysis and Future Directions

8.1 Comprehensive Analysis

Imagine giving your supply chain a serious upgrade, one that's not just smart but also kind to the planet. That is what essentially happens when the businesses combine smartly digital innovation with the principles of the circular economy. We have solid proof that when companies weave these two elements strategically, they go not only just along but bubble into spectacular levels of performance. The real kicker is that this combination, digitally and circularly, ends up delivering further advantages for the environment. It is an important association in the first place (with the strong correlation of β=0.687); it therefore tells us: by using technology for the deep implementation of circular activities, like creating products that can easily be reused, repurposed, or recycled, companies can have the greatest impact of positive change on our environment. I believed that this statement correlates with the findings made by Casciani's study team in 2022, suggesting that the digitalization opens good opportunities for sustainability, especially in the fast fashion industry. Companies that best manage change are those willing to accept technology on short notice, along with companies that have an established sustainability agenda, stand much better positioned to reap the full rewards of a digital-circular approach. At the end of the day, it is about being ready all the way through to bring about such favorable changes.

8.2 Limitations of the Research:

Design in Cross-section: Causal inferences are limited by the data's cross-sectional character. Stronger proof of causality would come from longitudinal research.

Industry Scope: Although the study looks at a variety of businesses, the results might not apply to all of them, especially in the service sector.

Geographic Constraints: The sample is concentrated in developed economies, limiting generalizability to emerging markets.

Technology Evolution: The swift rate of technology advancement could impact the applicability ofspecific technology measures over time.

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8.3 Future Work

The insights gained from this study, coupled with its limitations, point towards the following critical areas for further researchare recommended:Studies using a Longitudinal Design: Studies in the future are needed to show cause.relationships and to observe the development of digital-circular integration.

Sector-Specific Analysis: Industry-specific studies would provide deeper insights into how digital-circular integration manifests differently across various sectors.

Emerging Market Focus: Research in emerging markets would enhance understanding of how economic development levels affect digital-circular integration patterns.

Technology Deep-Dive: Future studies should examine specific combinations of technologies (e.g., AI + Blockchain + IoT) to understand optimal technology portfolios for circular economy implementation.

Supply Chain Network Analysis: Research should expand beyond individual organizations to examine digital-circular integration effects across entire supply chain networks.

Stakeholder Perspective: Future studies should incorporate multiple stakeholder perspectives, including suppliers, customers, and regulatory bodies.

9. Conclusion

The study offers rich empirical evidence for frontiers in SSCM by leveraging principles in digital transformation, circular economy together. The results indicate that Industry 4.0 technologies are enabling forces within circular economy, resulting in improved economic, social, and environmental performance. The study's theoretical contributions extend our understanding of digital and circular economy capacity as strategic resources using the resource-based view. The practical implications indicate that organizations should seek integrated and connected frameworks for digital transformation with sustainability initiative objectives.The study provides valuable empirical support for frontiers in sustainable supply chain management by linking digital transformation and circular economy together, as aligned with circular economy principles, the study's findings indicate that Industry 4.0 technologies are developing capabilities that propel circular economies forward.

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Economic, social and environmental performance. This study's new theoretical insightscontributions enhance our understanding of digital and circular economy capabilitiesas strategic resources from a resource-based view. The practical implications suggest that organizations need to pursue connected and integrated frameworks for digital transformation that include goals for sustainability initiatives that support a circular economy. Furthermore, the study provides a solid platform for future research in this emerging area.

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Abbreviations:

I4.0_TECH: Industry 4.0 Technology Adoption (e.g., AI, Blockchain, IoT)

CE_IMPL: Circular Economy Implementation

DCI: Digital-Circular Integration

ECON_PERF: Economic Performance

ENV_PERF: Environmental Performance

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SOC_PERF: Social Performance

SC_RESIL: Supply Chain Resilience

ORG_CAP: Organizational Capabilities

EXT_ENV: External Environmental Factors