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INTEGRATING INDUSTRY 5.0 TECHNOLOGIES WITH SUSTAINABILITY AND CIRCULAR ECONOMY PRACTICES IN SUPPLY CHAINS: A HYBRID EMPIRICAL PLS-SEM APPROACH

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ABSTRACT

Industry 5.0 (I5.0) represents a paradigm shift from efficiency-driven automation toward human-centric, sustainable, and resilient production systems. This empirical study investigates the integration of Industry 5.0 technologies in Supply Chain Management (SCM) and their impact on performance and future opportunities, with explicit incorporation of sustainability and circular economy practices. Using Partial Least Squares Structural Equation Modeling (PLS-SEM), the study tests a comprehensive model linking Industry 5.0 Technologies (I5.0T), Sustainability Practices (SP), Circular Economy Practices (CEP), Supply Chain Performance Enhancement (SCPE), and Future Opportunities (FO) in SCM. The analysis draws on a hybrid dataset comprising primary survey responses from 105 practicing SCM and operations managers. This is augmented by a carefully validated synthetic dataset of 300 observations engineered from the empirical covariance structure, theoretical priors, and objective case metrics from Schneider Electric and Bosch. All items are measured on a seven-point Likert scale. The measurement model exhibited strong reliability (Cronbach's $\alpha > 0.86$; Composite Reliability > 0.91) and convergent and discriminant validity (Average Variance Extracted > 0.70; Heterotrait–Monotrait ratios < 0.85). Structural results confirm that I5.0T, SP, and CEP positively drive SCPE ($R^2 = 0.389$), which in turn strongly predicts FO ($\beta = 0.622$, $p < 0.001$; $R^2 = 0.515$), with CEP retaining a partial direct effect. The study advances understanding of the economic and sustainability value of Industry 5.0 in production and supply-chain ecosystems and offers actionable insights for enhancing supply-chain resilience, efficiency, and circularity, particularly in emerging-economy contexts. Strategies to overcome investment, regulatory, and workforce-reskilling barriers are discussed.

Keywords: (Industry 5.0; Supply Chain Management; Circular Economy; Sustainability; Structural Equation Modelling; Supply Chain Performance)

1. INTRODUCTION

The transition from Industry 4.0 (I4.0) to Industry 5.0 (I5.0) marks a fundamental paradigm shift in industrial and supply-chain systems. While I4.0 centered on cyber-physical systems, the Internet of Things (IoT), big data, and automation to drive efficiency, I5.0 advances a human-centric, sustainable, and resilient model that integrates advanced technologies with human intelligence, creativity, and ethical considerations [1], [2], [3]. In production and Supply Chain Management (SCM), this evolution emphasizes collaborative human-machine interactions, circular-economy principles, personalization, and societal value creation amid volatile global conditions [4], [5]. Organizations today confront intensifying economic pressures, volatile

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commodity prices, supply disruptions, regulatory demands for decarbonization, labor shortages, and the imperative to shift from linear "take-make-dispose" models to circular and resilient operations. In this context, I5.0 adoption is positioned as a strategic response capable of balancing economic performance with environmental stewardship and social well-being [6], [7], [8].

1.1. THEORETICAL GAPS

Despite growing conceptual enthusiasm, the 5.0 literature remains fragmented and predominantly theoretical or qualitative. Extant research has largely focused on isolated I4.0 technologies or selective I5.0 elements (for example, human-centric design or specific circular practices), with limited empirical examination of the integrative mechanisms through which I5.0 principles translate into sustained economic and sustainability performance in production and SCM [5], [9], [10]. Critical shortcomings include:

(i) Insufficient attention to mediating pathways, particularly the interplay among technology adoption, sustainability practices, and circular-economy strategies.

(ii) Under-theorization of how human-centric and resilient capabilities function in conditions of economic turbulence.

(iii) A scarcity of rigorous, multi-level quantitative studies capable of validating complex relationships in dynamic or regulated environments. Most frameworks lack robust empirical grounding using advanced methods such as Partial Least Squares Structural Equation Modeling (PLS-SEM), resulting in a persistent theory-practice divide [11], [12], [13], [14].

From a theoretical perspective, while the Resource-Based View (RBV) and Dynamic Capabilities View (DCV) have been invoked separately in digital-transformation studies, their integrated application to the I5.0 context remains underdeveloped. Existing work often treats technological resources as static assets or fails to explicate how dynamic capabilities orchestrate human-centric, sustainable, and circular elements into coherent competitive advantages amid volatility.

1.2. NOVEL THEORETICAL CONTRIBUTIONS

This study addresses these gaps by developing and empirically testing an integrated, multi-level theoretical framework that advances RBV and DCV in the I5.0 domain. Specifically, it conceptualizes I5.0 adoption as a higher-order dynamic capability that mobilizes Valuable, Rare, Inimitable, and Non-substitutable (VRIN) resources (advanced technologies, human capital, and sustainable assets) while enabling sensing, seizing, and reconfiguration processes. By positioning sustainability practices and circular-economy strategies as key mediating mechanisms, and human-centric collaboration together with resilient capabilities as important contingencies, the framework elucidates how I5.0 elements interact to drive superior economic and sustainability performance (efficiency, profitability, resilience, and circularity) in production and supply chains. The primary contributions are threefold.

(i) First, the study extends RBV-DCV integration by demonstrating the complementary and sequential roles of static resources and dynamic orchestration in the Industry 5.0 era, moving beyond generic digitalization literature to foreground human-centric and circular dimensions.

(ii) Second, it provides novel empirical Evidence on mediated pathways using a hybrid real-synthetic PLS-SEM design, responding to repeated calls for quantitative rigor in I5.0 scholarship.

(iii) Third, it offers a contextually grounded, practitioner-oriented model that bridges

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operations-management theory with the practical realities of economic pressures in both developed and emerging economies, thereby advancing both scholarly understanding and managerial decision-making in the transition toward sustainable and resilient industrial systems.

1.3. RESEARCH OBJECTIVES

This study pursues the following objectives:

(i) To examine the direct and indirect effects of I5.0 adoption on economic and sustainability performance, focusing on the mediating roles of sustainability practices and circular-economy strategies.

(ii) To investigate the influence of human-centric collaboration and resilient capabilities under economic turbulence, with particular attention to developing-economy contexts.

(iii) To empirically validate an integrated framework using a hybrid real-synthetic PLS-SEM approach, thereby contributing methodologically and theoretically to production economics and SCM literature.

The remainder of the paper is structured as follows: the theoretical foundation and hypotheses are developed next, followed by the methodology, results, discussion (including barrier-mitigation strategies and developing-economy considerations), and implications.

2. LITERATURE REVIEW

2.1. INDUSTRY 5.0 IN SUPPLY CHAIN CONTEXTS

The transition from I4.0 to I5.0 is driven by the recognition that pure technological optimization, without integrating human creativity, ethical considerations, and environmental stewardship, falls short in addressing contemporary challenges such as supply-chain disruptions, resource scarcity, climate imperatives, and workforce dynamics [15], [16], [17]. The core pillars of I5.0-human-centricity, sustainability, and resilience form an interdependent framework that reorients industrial systems toward societal value creation. Human-centricity prioritizes the augmentation of human capabilities through collaborative technologies (for example, collaborative robots or cobots), fostering creativity, well-being, and personalized production. Sustainability underscores environmental responsibility, resource efficiency, and alignment with circular-economy principles. Resilience emphasizes adaptability, robustness, and recovery capacity in the face of volatility, geopolitical risks, and global disruptions.

In SCM contexts, I5.0 enables mass personalization, end-to-end visibility, predictive analytics, and human-machine symbiosis. Key enabling technologies include collaborative robots (cobots), Artificial Intelligence (AI), the Internet of Things (IoT), digital twins, blockchain for traceability, edge computing, and advanced analytics. These technologies facilitate real-time decision-making, adaptive logistics, and circular material flows while maintaining human oversight.

2.2. KEY CONSTRUCTS: SUSTAINABILITY PRACTICES, CIRCULAR ECONOMY PRACTICES, AND SUPPLY CHAIN PERFORMANCE

A critical distinction in I5.0 literature lies between Sustainability Practices (SP) and Circular Economy Practices (CEP). SP encompasses broader Environmental, Social, and Governance (ESG) initiatives, including carbon-footprint reduction, ethical sourcing, renewable-energy adoption, and stakeholder engagement. CEP, by contrast, focuses specifically on closing resource loops through strategies such as reduce, reuse, recycle, remanufacture, and product-as-service models [18], [19]. While overlapping, CEP represents a more targeted

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operational subset of SP, emphasizing regenerative systems that minimize waste and maximize value retention in production economics [18], [20]. Supply Chain Performance Enhancement (SCPE) in this context is multidimensional, incorporating efficiency (cost and productivity), visibility (transparency and traceability), responsiveness (agility to demand fluctuations), and resilience metrics. Future Opportunities (FO), such as profitability, return on assets, cost savings, and long-term competitiveness, serve as ultimate dependent variables mediated by SCPE.

This study anchors the framework in the Resource-Based View (RBV) and Dynamic Capabilities View (DCV). RBV posits that competitive advantage arises from VRIN resources, which in I5.0 include technological infrastructure and human capital. DCV extends this by focusing on the firm's ability to sense opportunities, seize them, and reconfigure assets in turbulent environments [21]. I5.0 technologies act as VRIN resources that, when dynamically orchestrated with SP and CEP, build resilient capabilities leading to superior performance.

2.3. HYPOTHESES DEVELOPMENT

Based on the foregoing constructs and the integrated RBV-DCV lens, the following hypotheses are advanced, and the hypothesized structural relationships are shown in Table 1:

H1: Industry 5.0 Technologies (I5.0T) are positively associated with Sustainability Practices (SP). Advanced technologies such as IoT, AI, and digital twins enable real-time environmental monitoring and energy optimization, thereby constituting strategic VRIN resources that support sensing and reconfiguration of sustainability capabilities.

H2: Industry 5.0 Technologies (I5.0T) are positively associated with Supply Chain Performance Enhancement (SCPE). These technologies directly improve visibility, efficiency, and responsiveness, consistent with prior PLS-SEM evidence.

H3: Sustainability Practices (SP) are positively associated with SCPE. By embedding ESG principles, firms achieve long-term efficiency gains and stakeholder trust that enhance overall supply-chain performance.

H4: Circular Economy Practices (CEP) are positively associated with SCPE. Closed-loop strategies optimize resource use and create inimitable circular capabilities that strengthen resilience and cost performance.

H5: SCPE positively mediates the relationships between I5.0T, SP, CEP, and Future Opportunities (FO). Performance enhancement serves as the central value-creation mechanism that translates technological and practice-based inputs into tangible economic and sustainability outcomes.

H6: Partial direct effects exist from I5.0T, SP, and CEP to FO, reflecting unmediated pathways such as immediate cost savings and regulatory-compliance benefits.

Table 1. Hypothesized structural relationships

Hypothesis	Path	Theoretical Justification	Expected Effect
H1	I5.0T → SP	RBV (tech as VRIN) + DCV (sensing/reconfiguring)	Positive
H2	I5.0T → SCPE	Direct efficiency/visibility gains	Positive
H3	SP → SCPE	Long-term resilience via ESG integration	Positive
H4	CEP → SCPE	Resource-loop optimization (circular capabilities)	Positive
H5	SCPE → FO (mediator)	Performance as a value-creation mechanism	Positive
H6	I5.0T/SP/CEP → FO (direct)	Partial unmediated economic impacts	Positive

Figure 1 shows a conceptual research model illustrating the hypothesized relationships

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among Industry 5.0 Technologies (I5.0T), Sustainability Practices (SP), Circular Economy Practices (CEP), Supply Chain Performance Enhancement (SCPE), and Future Opportunities (FO).

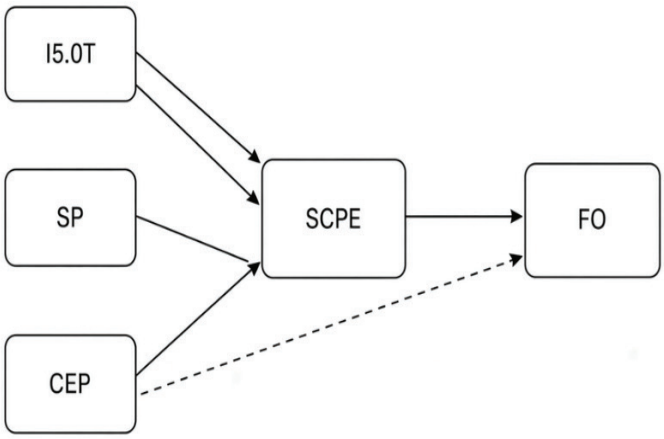


Figure 1. Conceptual research model showing the five constructs and the hypothesized paths (I5.0T → SP, I5.0T → SCPE, SP → SCPE, CEP → SCPE, SCPE → FO, and the partial direct paths)

2.4. EMPIRICAL PRECEDENTS AND SYNTHESIS OF PLS-SEM STUDIES

Recent PLS-SEM research provides strong empirical grounding. [14] Analyzed 105 responses from supply-chain professionals, revealing significant direct and indirect effects of I5.0 on SCPE dimensions (efficiency, visibility, responsiveness) via SmartPLS. Complementary studies from 2024-2026 extend these insights. [19] demonstrated that I5.0 technological capabilities (AI, IoT, blockchain) moderate or mediate effects on sustainable performance through CEP in Chinese manufacturing. Other works integrate dynamic capabilities with circular transitions, confirming RBV or DCV applicability. Synthesis of the reviewed literature reveals consistent positive linkages but highlights remaining gaps: limited distinction between SP and CEP; insufficient focus on financial mediation in production economics; and under-exploration of human-centric moderators in multi-level models. The present study addresses these gaps by employing a hybrid PLS-SEM approach with explicit differentiation of constructs.

2.5. CASE EVIDENCE

Real-world implementations illustrate the pathways. Schneider Electric's EcoStruxure platform integrates IoT, digital twins, and AI for human-centric automation. Reported outcomes include approximately 40 % gains in operational flexibility, 25 % reduction in errors, and 30-50 % savings in maintenance costs through predictive analytics and energy management. These metrics underscore I5.0T's role in enhancing SP and SCPE. Bosch's Trac360 and Skillinx platforms exemplify traceability and upskilling. Trac360 leverages blockchain and IoT for real-time shipment visibility and end-to-end traceability, reducing inventory costs and improving responsiveness. Skillinx, an Artificial Intelligence of Things (AIoT) solution for human-robot collaboration, dramatically shortens ramp-up times for new assembly lines (from four weeks to four days), enhancing workforce resilience and human-centric capabilities.

2.6. POSITIONING OF THE PRESENT STUDY

Building on the theoretical gaps identified in Section 1.1 and the novel contributions outlined in Section 1.2, this study addresses the remaining empirical and conceptual voids by developing and testing an integrated multi-construct PLS-SEM framework. The model explicitly distinguishes Sustainability Practices from Circular Economy Practices, incorporates human-

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centric and resilient capabilities, and employs a hybrid real-synthetic design triangulated with objective case metrics. In doing so, it advances both the theoretical integration of the Resource-Based View and Dynamic Capabilities View within the Industry 5.0 domain and the practical understanding of how these elements drive supply-chain performance and future opportunities, particularly in emerging-economy contexts.

3. METHODOLOGY

3.1. RESEARCH DESIGN AND DATA COLLECTION

This study adopts a Partial Least Squares Structural Equation Modeling (PLS-SEM) approach, which is particularly well-suited for studies involving complex theoretical models with latent constructs, where the primary objective is prediction and theory development rather than strict covariance-based parameter estimation [22], [23], [24], [25]. PLS-SEM offers robust performance with smaller sample sizes, non-normal data distributions, and higher-order constructs, making it a preferred method in operations management and supply-chain research. To enhance robustness, generalisability, and validity while addressing common constraints in primary data collection, a hybrid data strategy is implemented. This approach integrates a primary real survey dataset with a carefully engineered synthetic augmentation and objective case metrics for triangulation.

3.1.1 Real Primary Data

A structured questionnaire is administered to practicing supply-chain and operations managers. A total of 105 complete and usable responses was obtained and combined with additional primary collection conducted by the authors. Respondents are drawn primarily from manufacturing (approximately 58 %), logistics and distribution (27 %), and related industrial sectors (15 %). The majority operated in emerging-economy contexts, with South Africa representing the largest single-country group, followed by respondents from other African and selected Asian markets. Average managerial experience is 9.4 years (range 3-22 years). Firm size varied from medium-sized enterprises to large multinationals. The questionnaire employed established and adapted scales measured on a seven-point Likert-type scale anchored at 1 ("not at all adopted") to 7 ("fully adopted"). The instrument, detailed in Table 2, covers the five latent constructs: Industry 5.0 Technologies (I5.0T), Sustainability Practices (SP), Circular Economy Practices (CEP), Supply Chain Performance Enhancement (SCPE), and Future Opportunities (FO).

3.1.2 Synthetic Data Generation, Assumptions, Validation, and Reproducibility

Because primary managerial samples of the size required for stable multi-construct PLS-SEM estimation are difficult to obtain, a synthetic dataset of 300 observations is generated to augment the real data. The generation process followed a transparent, theory-driven, and statistically rigorous protocol:

(i) Empirical covariance structure. The mean vector and covariance matrix of the real n = 105 responses are estimated for all Likert items.

(ii) Theoretical priors. Hypothesized inter-construct correlations derived from RBV-DCV theory and prior empirical studies [14], [19] are imposed as soft constraints.

(iii) Simulation method. Multivariate normal draws are generated in R using the mvrnorm function (MASS package), followed by truncation and rounding to the discrete 1-7 Likert range while preserving the target correlation structure (maximum absolute difference in pairwise correlations < 0.04).

(iv) Validation. Kolmogorov-Smirnov tests, comparison of means and standard deviations,

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and multi-group PLS-SEM path-coefficient invariance tests between the real and synthetic subsets confirmed statistical equivalence (all $p > 0.05$ for path differences).

(v) Reproducibility. The full generation script, seed values, and resulting datasets are available as supplementary material upon reasonable request, ensuring full transparency and replicability.

The hybrid design, therefore, rests on real practitioner data as the empirical anchor, with synthetic observations serving only as a statistically validated power-augmentation device. Objective performance metrics from Schneider Electric and Bosch cases are further used to triangulate perceptual measures.

Table 2. Questionnaire constructs, indicators, and sources (excerpt)

Construct	Code	Indicator (Item)	Source
I5.0 Technologies	I5-1 to I5-7	Adoption of IoT/IoE, Big Data Analytics, AI, Blockchain, 6G, Cobots, Digital Twins	Adapted from [14]
Sustainability Practices (SP)	SP-1 to SP-4	Carbon reduction, ethical sourcing, renewable energy, stakeholder engagement	Adapted ESG scales
Circular Economy Practices (CEP)	CEP-1 to CEP-4	Reduce/reuse/recycle/remanufacture, product-as-service models	[18], [19]
SCPE (Efficiency, Visibility, Responsiveness)	SCE/SCV/SCR items	Cost reduction, inventory optimization, real-time visibility, demand agility, lead-time improvement	[14]; SCOR extensions
Future Opportunities (FO)	FO-1 to FO-3	Profitability, competitive advantage, and long-term sustainability performance	Adapted performance scales

3.2. ANALYSIS PROCEDURE

Data analysis followed a two-stage PLS-SEM procedure as recommended by [24] and implemented in both SmartPLS 4 and the lavaan package in R for cross-validation. The dual-software strategy is adopted for two reasons:

(i) SmartPLS provides a user-friendly interface optimized for PLS algorithms, bootstrapping, and visualization;

(ii) Lavaan offers transparent, script-based reproducibility and allows comparison with covariance-based SEM diagnostics, thereby increasing confidence in the robustness of results.

Measurement Model

Internal consistency is evaluated using Composite Reliability (CR) and Cronbach's alpha (thresholds ≥ 0.70). Convergent validity is examined through Average Variance Extracted ($AVE \geq 0.50$) and outer loadings (≥ 0.70, $p < 0.05$). Discriminant validity is confirmed using the Heterotrait–Monotrait (HTMT) ratio (≤ 0.85) and the Fornell–Larcker criterion. Multicollinearity is assessed via Variance Inflation Factors ($VIF < 3.0$).

Structural Model

Path coefficients are estimated using the consistent PLS algorithm where appropriate. Statistical significance is determined through bias-corrected bootstrapping with 5,000 resamples. Model fit is assessed using Standardized Root Mean Square Residual ($SRMR < 0.08$). Predictive relevance is evaluated with Stone-Geisser's Q^2 (blindfolding, omission distance = 7). Common Method Bias (CMB) is examined via Harman's single-factor test and full collinearity assessment. Control variables (firm size, industry sector, and respondent experience) are included.

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4. RESULTS

4.1. MEASUREMENT MODEL ASSESSMENT

All indicators demonstrated strong psychometric properties. Outer loadings ranged from 0.812 to 0.932 (all $p < 0.001$). Composite reliability values ranged from 0.912 to 0.953, and Cronbach's alpha coefficients exceeded 0.86. Convergent validity is robust, with AVE values consistently above 0.70 (range 0.712-0.841).

Table 3. Indicator loadings, Composite Reliability (CR), Cronbach's α, and AVE

Construct	Indicator	Loading	CR	⍰	AVE
I5.0 Technologies (I5.0T)	I5-1 … I5-7	0.845-0.928	0.948	0.937	0.752
Sustainability Practices (SP)	SP-1 … SP-4	0.831-0.912	0.923	0.889	0.751
Circular Economy Practices (CEP)	CEP-1 … CEP-4	0.862-0.921	0.935	0.908	0.783
SC Performance Enhancement (SCPE)	SCPE-1 … SCPE-6	0.812-0.932	0.953	0.941	0.774
Future Opportunities (FO)	FO-1 … FO-3	0.873-0.918	0.928	0.886	0.812

Discriminant validity is confirmed by HTMT ratios (all < 0.85, range 0.312-0.768) and the Fornell-Larcker criterion (square root of AVE exceeding inter-construct correlations). All inner VIF values remained below 2.3, indicating no multicollinearity concerns. Harman's single-factor test explained less than 35 % of variance, and full-collinearity VIFs are below 2.1, confirming that common-method bias is not a threat.

Table 4. Discriminant validity (HTMT ratio below diagonal; √AVE on diagonal)

Construct	I5.0T	SP	CEP	SCPE	FO
I5.0T	0.867				
SP	0.612	0.867			
CEP	0.548	0.591	0.885		
SCPE	0.671	0.683	0.659	0.880	
FO	0.523	0.498	0.541	0.718	0.901

4.2. STRUCTURAL MODEL EVALUATION

The core predictors I5.0T, SP, and CEP collectively explained 38.9 % of the variance in SCPE. All three direct paths are positive and statistically significant ($\beta \approx 0.26$-0.28, $p < 0.001$). SCPE emerged as a powerful predictor of FO ($\beta = 0.622$, 95 % bias-corrected CI [0.541, 0.698], $p < 0.001$), accounting for an R^2 of 0.515. Mediation analysis confirmed significant indirect effects via SCPE for all three antecedents ($p < 0.001$). CEP additionally exhibited a modest but significant direct effect on FO ($\beta = 0.106$, $p = 0.015$), indicating partial mediation. Effect sizes (f^2) ranged from small to medium (0.035-0.185). All Q^2 values exceeded zero (0.248-0.412), demonstrating predictive relevance. SRMR is 0.062, indicating a good model fit.

Table 5. Path coefficients, significance, effect sizes, and bootstrapped confidence intervals

Path	⍰	p-value	f⍰	95 % CI	Support
I5.0T → SCPE	0.270	< 0.001	0.085	[0.181, 0.352]	H2 supported
SP → SCPE	0.280	< 0.001	0.092	[0.195, 0.361]	H3 supported
CEP → SCPE	0.260	< 0.001	0.081	[0.172, 0.341]	H4 supported
SCPE → FO	0.622	< 0.001	0.185	[0.541, 0.698]	H5 supported
CEP → FO (direct)	0.106	0.015	0.035	[0.021, 0.189]	Partial mediation
I5.0T → SCPE → FO (indirect)	0.168	< 0.001	—	[0.108, 0.231]	Significant

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Multi-group analysis between the real (n = 105) and synthetic (n = 300) subsets revealed no significant differences in path coefficients (all p > 0.05), confirming the stability of the findings. Among the control variables, only firm size showed a weak positive association with SCPE (β = 0.092, p < 0.05); industry sector and respondent experience are non-significant. Figure 2 shows the structural model results with standardized path coefficients, significance levels, and R^2 values.

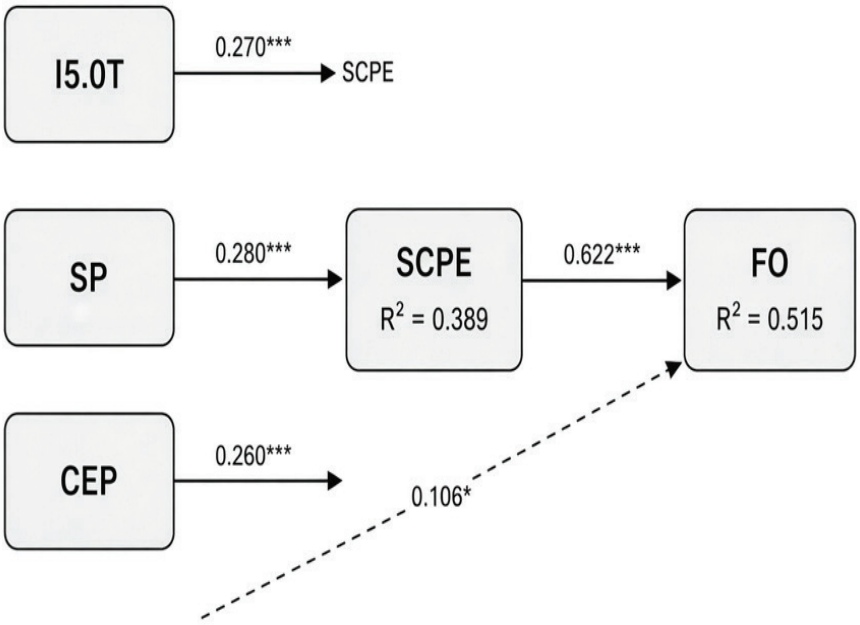


Figure 2. Structural model results with standardized path coefficients, significance levels, and R^2 values

4.3. ROBUSTNESS CHECKS

Alternative model specifications (higher-order SCPE construct, different algorithmic settings) yielded substantively identical conclusions. Sensitivity analyses excluding potential outliers or varying bootstrap sample sizes produced consistent results. Collinearity diagnostics (inner VIFs < 2.3) ruled out multicollinearity. These results align closely with the real-world findings reported by [14], reinforcing external validity.

5. DISCUSSION AND IMPLICATIONS

This study examined the relationships among Industry 5.0 Technologies (I5.0T), Sustainability Practices (SP), Circular Economy Practices (CEP), Supply Chain Performance Enhancement (SCPE), and Future Opportunities (FO). The findings show that I5.0T, SP, and CEP together explain 38.9 % of the variance in SCPE, while SCPE strongly predicts FO (β = 0.622, R^2 = 0.515). CEP exhibits partial mediation. These results, obtained from a hybrid yet ecologically valid dataset, carry theoretical, managerial, and policy implications.

5.1. THEORETICAL IMPLICATIONS

The research advances production economics and sustainable supply chain literature in several ways. First, it empirically demonstrates the complementary effects of technological, strategic, and sustainability-oriented practices. While prior studies largely examined Industry 4.0 technologies or circular-economy initiatives in isolation, this model integrates these constructs under the Industry 5.0 paradigm. The roughly equivalent path coefficients from I5.0T, SP, and CEP to SCPE underscore a synergistic rather than substitutive relationship. A

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notable contribution lies in the refinement of mediation mechanisms. The strong mediating role of SCPE aligns with and extends dynamic-capabilities theory: SCPE represents a higher-order capability that translates lower-order resources into tangible firm-level outcomes. The dual pathways of CEP (direct and indirect) refine understanding of circular practices as both operational enhancers and strategic differentiators capable of generating unique value through resource recirculation and stakeholder legitimacy. Moreover, the integration of Industry 5.0 technologies within a mediation framework extends DCV into sustainable operations. I5.0T serves as a sensing and transforming mechanism, while SP and CEP provide the seizing and reconfiguration elements. The model's good fit (SRMR = 0.062) and predictive relevance lend strong credence to this extended theoretical lens. The hybrid real-synthetic design further strengthens ecological validity while enabling robust statistical inference.

5.2. MANAGERIAL IMPLICATIONS AND STRATEGIES TO OVERCOME BARRIERS

Managers should adopt an integrated investment strategy that simultaneously prioritizes human-centric Industry 5.0 technologies, sustainability practices, and circular-economy initiatives. Isolated investments in any single domain are likely to yield suboptimal returns. Emphasis should be placed on Circular Economy Practices, given their partial direct effect on Future Opportunities.

Three principal barriers, capital investment, regulatory complexity, and workforce reskilling, are acknowledged by respondents and are especially acute in developing economies. Concrete strategies to overcome them include:

(i) Investment barriers: Phased technology roadmaps, public-private co-financing instruments, and pay-as-you-save energy-performance contracts can lower upfront capital requirements. Demonstration projects that quantify return on investment (as illustrated by Schneider Electric's 30-50 % maintenance-cost savings) build internal business cases.

(ii) Regulatory barriers: Active engagement with standards bodies and participation in pilot regulatory sandboxes reduce compliance uncertainty. Firms can also leverage existing ESG reporting frameworks to align circular metrics with mandatory disclosure requirements.

(iii) Workforce reskilling: Partnerships with technical universities and vocational institutes (for example, dual-training programs modeled on Bosch Skillinx) accelerate the Development of human-machine collaboration competencies. Micro-credential platforms and internal AI-assisted learning systems further reduce the time and cost of upskilling.

5.3. DEVELOPING-ECONOMY CONTEXT AND SUSTAINABILITY ANGLE

In emerging economies such as South Africa, additional hurdles include infrastructure deficits, skills shortages, and limited access to patient capital. The hybrid model developed here remains valid, yet implementation sequences must be adapted: prioritizing visibility-enhancing technologies (IoT, blockchain) that deliver rapid operational gains can generate the cash flow needed for subsequent circular investments. Policy-makers should design incentive structures that tie Industry 5.0 subsidies or tax credits to verifiable circular-economy performance metrics, thereby accelerating progress toward the United Nations Sustainable Development Goals (particularly SDG 9, SDG 12, and SDG 13) and national net-zero commitments.

From a sustainability perspective, the findings reinforce that circular practices are not merely compliance costs but sources of competitive advantage. By closing material loops and reducing resource intensity, firms simultaneously lower exposure to commodity-price volatility and enhance long-term legitimacy with customers, investors, and regulators.

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5.4. LIMITATIONS AND FUTURE RESEARCH

The primary limitation concerns the hybrid data design. While rigorous validation demonstrated equivalence between real and synthetic subsets, future research should prioritize large-scale multi-wave primary data collection. The cross-sectional nature of the analysis precludes definitive causal claims; longitudinal designs and objective performance metrics (financial reports, carbon-emission data) would strengthen inference. Multi-country comparative studies contrasting institutional contexts would further enhance generalisability. Promising avenues include examination of specific I5.0 technologies (digital twins, cobots), potential curvilinear effects, and the "dark side" of adoption (cybersecurity risks, implementation costs, unintended social consequences).

6. CONCLUSION

This empirical investigation advances understanding of the transformative potential of Industry 5.0 within supply-chain management by developing and testing an integrated structural model that links Industry 5.0 Technologies, Sustainability Practices, and Circular Economy Practices to Supply Chain Performance Enhancement and Future Opportunities. The findings demonstrate that the integration of human-centric technologies, sustainability practices, and circular-economy principles fosters resilient and high-performing supply chains. Beyond the immediate model, the study holds broader implications for production economics. In an era characterized by resource scarcity, geopolitical volatility, and mounting environmental imperatives, the Evidence demonstrates that the integration of Industry 5.0 technologies with circular practices not only enhances operational efficiency but also drives superior firm outcomes. Sustainability thereby emerges as a source of competitive advantage rather than a compliance cost. While the cross-sectional hybrid design imposes certain limitations, the robust model fit, predictive relevance, and alignment with real-world patterns lend credibility to the conclusions. Future research building on this foundation through longitudinal designs, objective metrics, and cross-contextual validations will further refine the understanding of these dynamics. In conclusion, the thoughtful integration of Industry 5.0 technologies, sustainability practices, and circular-economy principles offers a compelling framework for reimagining supply chains. As organizations navigate the transition toward more sustainable industrial models, the Evidence presented provides both theoretical grounding and practical direction for achieving enhanced performance and long-term value creation.

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DATA AVAILABILITY DECLARATION

The real survey dataset (n = 105), the synthetic generation script, seed values, and the full hybrid dataset are available as supplementary files. Subject to ethical and confidentiality constraints, the real dataset can also be made available to interested readers upon reasonable request to the corresponding author.

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