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THE CO-EVOLUTION OF INDUSTRY 4.0 AND INDUSTRY 5.0: A COMPREHENSIVE EMPIRICAL STUDY ON SUSTAINABILITY AND QUALITY PERFORMANCE IN MANUFACTURING

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ABSTRACT

This study empirically examines the relationship between the paradigms of Industry 4.0 and Industry 5.0, along with their combined impact on sustainability and quality performance in manufacturing organizations. Industry 4.0, defined by cyber-physical systems, IoT, AI, and big data analytics, enhances operational efficiency and product quality through interconnected, autonomous production environments. However, its technology-centric approach has been criticized for not adequately addressing human and social sustainability aspects. Industry 5.0 complements this by focusing on human-centricity, ethical governance, and resilience, promoting collaboration between humans and intelligent machines to achieve sustainable manufacturing excellence. A cross-sectional survey of 248 manufacturing firms across various sectors employed Partial Least Squares Structural Equation Modelling (PLS-SEM) to test a conceptual framework integrating Industry 4.0 and Industry 5.0 practices. The results indicate that Industry 4.0 practices significantly enhance sustainability and quality performance and strongly predict the adoption of Industry 5.0. Industry 5.0 practices have an even stronger direct effect on these outcomes and partially mediate the relationship between Industry 4.0 and performance. Interaction effects confirm a synergistic coexistence, with combined adoption leading to superior sustainability and quality performance compared to Industry 4.0 alone. The findings position Industry 5.0 as an evolutionary extension of Industry 4.0, enriching the technological foundation with human-centric and ethical dimensions essential for long-term sustainability and resilience. The integrative framework underscores the necessity of balancing technological innovation with human and social considerations to achieve holistic manufacturing excellence. Practically, the study offers strategic insights for firms aiming to enhance sustainable quality performance through phased, synergistic integration of Industry 4.0 and Industry 5.0 practices, providing a robust empirical basis for policy and industry frameworks supporting this co-evolution.

KEYWORDS: Industry 4.0; Industry 5.0; Sustainability Performance; Quality Performance; Human-Centric Manufacturing; Structural Equation Modelling; Manufacturing Excellence.

1. INTRODUCTION

The rapid advancement and diffusion of digital technologies have fundamentally transformed manufacturing paradigms, culminating in the emergence of Industry 4.0. Originating as a strategic initiative to bolster industrial competitiveness, Industry 4.0 integrates cyber-physical systems, the Internet of Things (IoT), cloud computing, artificial intelligence (AI), and big data analytics to establish highly interconnected, autonomous, and data-driven production environments (Kagermann, Wahlster, & Helbig, 2013; Lasi et al., 2014). These technologies enable real-time data exchange, decentralized decision-making, and predictive analytics, collectively enhancing operational efficiency, reducing downtime, and improving quality performance across manufacturing value chains (Frank, Dalenogare, & Ayala, 2019).

Empirical research substantiates the positive impact of Industry 4.0 adoption on operational and quality outcomes. For instance, IoT-enabled real-time monitoring and AI-driven quality analytics have been shown to significantly reduce defect rates and enhance process reliability (Sony & Naik, 2020). Furthermore, smart manufacturing technologies contribute to increased production flexibility and heightened customer satisfaction (Tortorella et al., 2020). From a sustainability perspective, Industry 4.0 facilitates optimized energy consumption, waste minimization, and improved resource utilization through advanced algorithms and digital twin technologies (Kamble, Gunasekaran, & Gawankar, 2018).

Despite these advancements, the technology-centric orientation of Industry 4.0 has been critiqued for insufficiently addressing human and social sustainability dimensions. The relegation of human roles to system supervision rather than active participation raises concerns regarding social sustainability, employee well-being, ethical governance, and the resilience of manufacturing systems (Longo, Padovano, & Umbrello, 2020; Rada, 2021). In response to these limitations, Industry 5.0 has emerged as a complementary paradigm that emphasizes human-centricity, ethical governance, and resilience within manufacturing processes (Breque, De Nul, & Petridis, 2021).

Industry 5.0 promotes collaborative ecosystems wherein humans and intelligent machines, including collaborative robots (cobots), synergistically leverage their respective strengths (Nahavandi, 2019). This paradigm extends beyond operational efficiency to explicitly integrate the triple bottom line—economic, environmental, and social sustainability—thereby broadening the scope of smart manufacturing to encompass societal impact (Mourtzis et al., 2022). Human-centric production systems enhance employee satisfaction, safety, and well-being, while resilient manufacturing structures improve robustness against global disruptions such as pandemics and supply chain crises (Xu, David, & Kim, 2018). Moreover, Industry 5.0 reconceptualizes quality as a socio-technical achievement that incorporates human creativity, tacit knowledge, and collaborative problem-solving (Nahavandi, 2019).

The academic discourse remains divided regarding whether Industry 5.0 constitutes a radical new industrial revolution or an evolutionary extension of Industry 4.0. Some scholars posit that Industry 5.0 builds upon the technological foundation of Industry 4.0 by embedding human and sustainability dimensions (Rojko, 2021), while others argue that it represents a paradigm shift towards value-driven manufacturing ecosystems that redefine quality and performance through socio-technical integration (Carayannis & Morawska-Jancelewicz, 2022). This ambiguity is particularly salient in quality management literature, where Industry 4.0 is associated with technological advancements such as predictive maintenance and AI-based defect detection (Chiarini, 2020), whereas Industry 5.0 emphasizes human creativity and collaboration as integral to quality excellence (Nahavandi, 2019).

Despite the conceptual richness of these perspectives, empirical validation remains limited. Most existing studies are theoretical or descriptive, lacking rigorous empirical examination of the distinct or complementary roles of Industry 4.0 and Industry 5.0. Furthermore, integrative frameworks that assess whether Industry 5.0 mediates or strengthens Industry 4.0's impact on sustainability and quality performance are scarce (Kamble et al., 2021). The combined effects and potential synergistic co-existence of Industry 4.0 and Industry 5.0 practices on manufacturing excellence have yet to be comprehensively explored.

This study addresses these critical gaps by developing and empirically testing a conceptual framework that positions Industry 4.0 as the technological enabler and Industry 5.0 as the human-centric and ethical extension driving sustainable quality excellence. Through this integrative lens, the research investigates how these paradigms individually and jointly influence sustainability and quality performance within manufacturing organizations, thereby providing a rigorous foundation for advancing theory and informing strategic practice in contemporary industrial transformation.

While prior studies have predominantly examined Industry 4.0 and Industry 5.0 in isolation or from a conceptual perspective, empirical evidence explaining their combined and complementary effects remains limited. Addressing this gap, the present study empirically validates Industry 5.0 as a human-centric and ethical extension of Industry 4.0 and examines their mediating and synergistic coexistence within a single integrative framework linking technological and human-centric practices to sustainability and quality performance.

2. LITERATURE REVIEW

2.1. Industry 4.0: Technological Foundations and Performance Outcomes

Industry 4.0 represents a transformative manufacturing paradigm grounded in cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, enabling interconnected, autonomous, and data-driven production environments (Kagermann et al., 2013; Lasi et al., 2014). These technologies facilitate real-time data exchange, decentralized decision-making, and predictive analytics, resulting in improved operational efficiency, defect reduction, production flexibility, and enhanced quality performance (Frank et al., 2019; Sony & Naik, 2020).

From a sustainability perspective, Industry 4.0 supports optimized resource utilization, energy efficiency, and waste reduction through advanced analytics and digital twin technologies (Kamble et al., 2018). However, despite these performance gains, its predominantly technology-centric orientation has been critiqued for underrepresenting human, ethical, and social sustainability dimensions, raising concerns regarding employee well-being and system resilience (Longo et al., 2020; Rada, 2021).

2.2. Industry 5.0: Human-Centric and Sustainable Manufacturing

Industry 5.0 has emerged as a complementary and human-centric extension of Industry 4.0, integrating ethical governance, resilience, and human well-being into manufacturing system design (Breque et al., 2021). Rather than redefining digital infrastructure, Industry 5.0 builds upon it by emphasizing collaborative human–machine interaction, worker empowerment, and value-sensitive system architectures (Nahavandi, 2019).

This paradigm embeds the triple bottom line—economic, environmental, and social sustainability—within smart production systems (Mourtzis et al., 2022). Human-centric environments enhance safety, satisfaction, and creativity, while resilient system design strengthens robustness against disruptions (Xu et al., 2018). Consequently, Industry 5.0 reframes quality excellence as a socio-technical outcome achieved through the integration of advanced technologies with human judgment and ethical decision-making.

2.3. Relationship Between Industry 4.0 and Industry 5.0

Recent scholarship increasingly conceptualizes Industry 5.0 as an evolutionary extension of Industry 4.0 that enriches technological capabilities with human-centric and sustainability-oriented dimensions (Rojko, 2021). This perspective emphasizes complementarity rather than replacement: digital automation enables efficiency and precision, while human-centric practices enhance adaptability, ethical governance, and sustainable quality outcomes.

Although theoretical discussions have expanded, empirical investigation of this integrative relationship remains limited (Kamble et al., 2021). This gap underscores the need for unified frameworks examining how these paradigms jointly influence sustainability and quality performance.

2.4. Empirical Research Gaps and the Need for Integrative Frameworks

Despite extensive conceptual discourse, empirical studies systematically examining the distinct and complementary roles of Industry 4.0 and Industry 5.0 remain scarce (Kamble et al., 2021). Most existing research either focuses on technological adoption or discusses sustainability and human-centricity descriptively, without rigorously testing integrative models.

Specifically, limited evidence exists regarding whether Industry 5.0 mediates or strengthens the impact of Industry 4.0 on sustainability and quality outcomes. Furthermore, the synergistic co-existence of Industry 4.0 and Industry 5.0 practices in driving manufacturing excellence has not been comprehensively validated.

2.5. Summary

The literature establishes Industry 4.0 as a technological enabler of operational efficiency, quality enhancement, and environmental sustainability (Frank et al., 2019; Kamble et al., 2018), while also recognizing its limitations in addressing social and human dimensions (Longo et al., 2020; Rada, 2021). Industry 5.0 emerges as a human-centric and ethical extension that complements Industry 4.0 by embedding resilience, worker well-being, and socio-technical integration into smart manufacturing systems (Breque et al., 2021; Mourtzis et al., 2022).

Theoretical debates highlight the need for empirical frameworks clarifying whether Industry 5.0 co-exists with or evolves from Industry 4.0 and how their combined adoption influences sustainability and quality performance (Rojko, 2021; Kamble et al., 2021). Responding to this need, the present study develops and empirically tests an integrative model examining the direct, mediating, and interaction effects of Industry 4.0 and Industry 5.0 practices on manufacturing outcomes.

3. RESEARCH METHODOLOGY

3.1. Research Design

This study employs a quantitative, cross-sectional survey design to empirically test the proposed conceptual framework examining the co-existence and evolutionary relationship between Industry 4.0 and Industry 5.0 paradigms in influencing sustainability and quality performance within manufacturing organizations. The cross-sectional approach facilitates capturing current organizational practices and perceptions across diverse manufacturing sectors, enabling robust analysis of direct, mediating, and interaction effects among latent constructs.

3.2. Population and Sampling

The target population comprises medium- to large-scale manufacturing firms operating in sectors characterized by significant Industry 4.0 adoption and emerging Industry 5.0 interest, including automotive, electronics, machinery, pharmaceuticals, and process industries. The unit of analysis is the manufacturing organization, with key informants being senior and middle management professionals—such as operations managers, production managers, quality managers, supply chain managers, and digital innovation leads—possessing comprehensive knowledge of manufacturing technologies, sustainability initiatives, and quality management systems. A purposive sampling strategy was employed to ensure inclusion of firms with at least partial implementation of Industry 4.0 practices, ensuring relevance to the research objectives. Data collection targeted 300 firms, yielding 248 valid responses (response rate: 82.7%), exceeding minimum sample size recommendations for Partial Least Squares Structural Equation Modeling (PLS-SEM) and ensuring adequate statistical power for hypothesis testing.

Non-response bias was assessed by comparing early and late respondents on key constructs following established procedures. Independent sample t-tests revealed no statistically significant differences between the two groups, indicating that non-response bias is unlikely to affect the study's findings.

3.3. Measurement Instrument

The structured questionnaire was developed by adapting validated scales from extant literature on Industry 4.0, human-centric manufacturing, sustainability, and quality performance, with modifications to capture Industry 5.0 constructs in line with recent theoretical and policy frameworks. All constructs were operationalized reflectively and measured on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree).

Table

Construct	No. of Items	Sample Measurement Items
Industry 4.0 Practices (I4P)	5	Real-time data captured using IoT; AI supports production decisions
Industry 5.0 Practices (I5P)	4	Cobots assist employees; Human safety prioritized in system design
Sustainability Performance (SP)	3	Reduced energy use; Improved employee well-being
Quality Performance (QP)	3	Reduced defect rate; Improved customer satisfaction

All constructs were operationalized as reflective constructs and measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

During measurement model evaluation using Partial Least Squares Structural Equation Modelling (PLS-SEM), indicators with inadequate outer loadings were removed in accordance with established guidelines to ensure reliability and convergent validity. The final measurement model retained a parsimonious set of indicators for each construct, as described below.

Industry 4.0 Practices (I4P) were measured using five items capturing the adoption of key digital manufacturing technologies, including cyber-physical systems, IoT-enabled real-time data collection, AI-supported decision-making, cloud manufacturing, and digital analytics. These items reflect the core technological foundations of Industry 4.0 and were adapted from established smart manufacturing studies (Kamble et al., 2018; Tortorella et al., 2020).

Industry 5.0 Practices (I5P) were operationalized using four items representing human-centric and ethical manufacturing dimensions, namely human–machine collaboration (e.g., cobot usage), ethical and resilient system design, worker empowerment, and human-centric production. These indicators were developed based on recent Industry 5.0 literature and European Commission policy frameworks emphasizing human-centricity, sustainability, and resilience (Breque et al., 2021; Mourtzis et al., 2022).

Sustainability Performance (SP) was measured using three items reflecting key sustainable manufacturing outcomes like energy efficiency, waste reduction, and employee well-being, thereby capturing the environmental and social pillars of the triple bottom line (Elkington, 1997; Kamble et al., 2021).

Quality Performance (QP) was assessed using three items representing core quality outcomes, namely defect reduction, process consistency, and customer satisfaction. These indicators reflect both internal process quality and external customer-oriented performance and were adapted from prior quality management and Industry 4.0-related studies (Chiarini, 2020; Sony & Naik, 2020).

All retained indicators demonstrated satisfactory outer loadings, internal consistency reliability, and convergent validity, as reported in the measurement model results section. Content validity was ensured through expert reviews by academic researchers and industry professionals, followed by a pilot test to refine item clarity and contextual relevance. Consistent with prior studies in smart manufacturing and sustainability research, all constructs were modelled reflectively, as the indicators represent manifestations of the underlying latent variables and are expected to covary.

3.4. Data Collection Procedure

Data were collected over a three-month period using a combination of online surveys and self-administered questionnaires. The survey link and instrument were disseminated through professional networks, industry associations, and direct organizational contacts. The study involved an anonymous questionnaire survey of organizational respondents and did not collect personal or sensitive data. Participation was voluntary, with assurances of confidentiality and anonymity to minimize social desirability and response biases. In accordance with institutional guidelines, formal ethical approval was not required.

3.5. Data Analysis

Data analysis employed Partial Least Squares Structural Equation Modelling (PLS-SEM) using SmartPLS software, selected for its suitability in theory development, handling complex mediation and moderation effects, and robustness with moderate sample sizes. The analysis proceeded in two stages:

Measurement Model Evaluation: Reliability and validity were assessed through internal consistency metrics (Cronbach's alpha, rho_A, composite reliability), convergent validity (Average Variance Extracted, AVE), indicator reliability (outer loadings), and discriminant validity (Heterotrait-Monotrait ratio, HTMT).

Structural Model Assessment: Hypotheses were tested by examining path coefficients, significance via bootstrapped t-values and p-values (5,000 resamples), mediation effects (indirect effects and Variance Accounted For, VAF), moderation effects (interaction terms), explanatory power (R^2), effect sizes (f^2), predictive relevance (Q^2 via blindfolding), and overall model fit (Standardized Root Mean Square Residual, SRMR; Normed Fit Index, NFI)._

This rigorous analytical approach provides a comprehensive empirical foundation to evaluate the direct, mediating, and synergistic relationships among Industry 4.0 practices, Industry 5.0 practices, sustainability performance, and quality performance, elucidating their co-existence and evolutionary dynamics in manufacturing excellence.

Partial Least Squares Structural Equation Modelling (PLS-SEM) was selected due to its suitability for theory development, prediction-oriented research, and complex models involving mediation and moderation effects. Additionally, PLS-SEM is robust to non-normal data distributions and performs well with moderate sample sizes, making it appropriate for the present study's exploratory examination of the co-evolutionary relationship between Industry 4.0 and Industry 5.0 practices.

To assess the potential impact of common method bias, Harman's single-factor test was conducted. The results indicated that no single factor accounted for the majority of variance, with the largest factor explaining less than 40% of the total variance, suggesting that common method bias is unlikely to be a significant concern. Variance inflation factor (VIF) values for all constructs were below the recommended threshold, further indicating the absence of serious common method bias. In addition, procedural remedies such as respondent anonymity, voluntary participation, and careful item wording were employed during survey design to further mitigate the risk of common method bias.

3.6. Hypotheses Development

Table

Hypothesis	Purpose
H1: Industry 4.0 practices have a significant positive effect on sustainability performance. **H2:** Industry 4.0 practices have a significant positive effect on quality performance	**Direct Effects of Industry 4.0**
H3: Industry 5.0 practices have a significant positive effect on sustainability performance. **H4:** Industry 5.0 practices have a significant positive effect on quality performance	**Direct Effects of Industry 5.0**
H5: Industry 4.0 practices positively influence the adoption of Industry 5.0 practices	**Interrelationship between Industry 4.0 and Industry 5.0**
H6: Industry 5.0 practices mediate the relationship between Industry 4.0 and sustainability performance. **H7:** Industry 5.0 practices mediate the relationship between Industry 4.0 and quality performance.	**Mediating / Complementary Effects**
H8: The combined adoption of Industry 4.0 and Industry 5.0 practices has a stronger positive effect on sustainability performance than Industry 4.0 alone. **H9:** The combined adoption of Industry 4.0 and Industry 5.0 practices has a stronger positive effect on quality performance than Industry 4.0 alone.	**Co-existence / Synergy Effect**

3.7. Conceptual Interaction Model

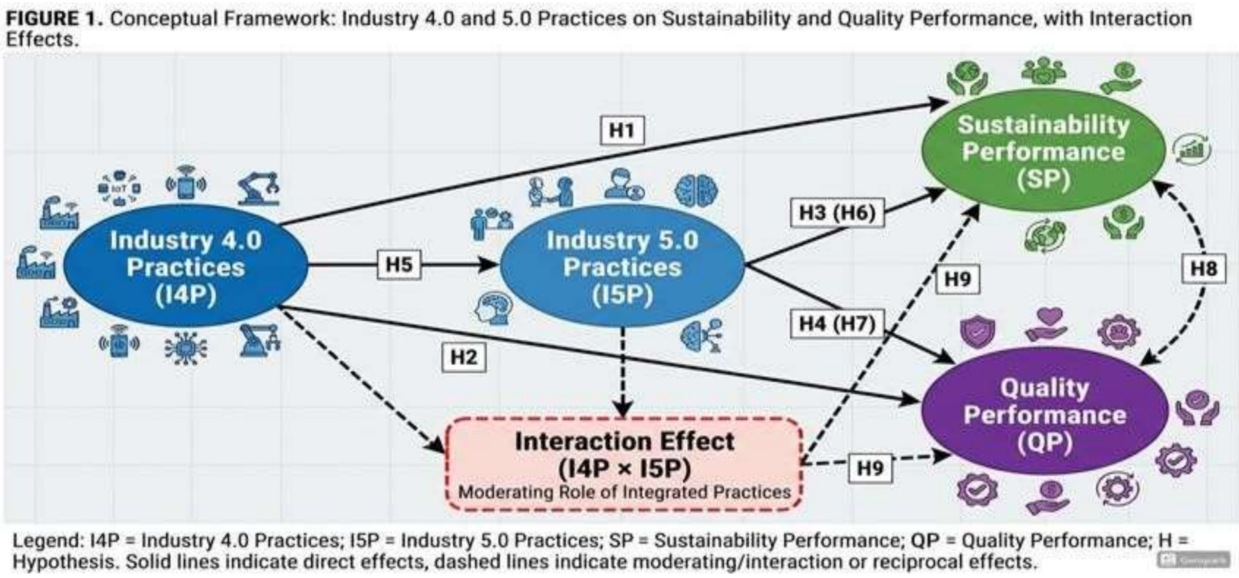

Figure 1:

Explanation

- Industry 4.0 practices (I4P) directly influence sustainability performance (SP) and quality performance (QP).
- Industry 4.0 practices positively influence Industry 5.0 practices (I5P).
- Industry 5.0 practices have direct positive effects on SP and QP.
- Industry 5.0 practices partially mediate the effect of Industry 4.0 on SP and QP.

The interaction between Industry 4.0 and Industry 5.0 practices enhances sustainability and quality performance beyond individual effects, confirming synergistic co-existence.

4. RESULTS

4.1. Measurement Model Evaluation

Table 1 presents the construct reliability and convergent validity assessment. All constructs demonstrate strong internal consistency, with Cronbach's alpha, rho_A (ρA), and composite reliability exceeding the 0.70 threshold. Average Variance Extracted (AVE) values surpass 0.50, confirming adequate convergent validity

Table 1: Construct Reliability and Convergent Validity

Construct	Cronbach's Alpha	ρA	Composite Reliability	AVE
Industry 4.0 Practices (I4P)	0.881	0.889	0.912	0.634
Industry 5.0 Practices (I5P)	0.893	0.898	0.925	0.672
Sustainability Performance (SP)	0.867	0.873	0.905	0.613
Quality Performance (QP)	0.854	0.861	0.899	0.641

Indicator reliability was verified through outer loadings (Table 2), with all indicators exceeding the 0.70 benchmark and significant at $p < 0.001$. *Table 4: Outer Loadings*

Table 2: Outer Loadings

Construct	Indicator	Outer Loading
I4P	I4P1	0.81
	I4P2	0.78
	I4P3	0.84
	I4P4	0.79
	I4P5	0.82
I5P	I5P1	0.85
	I5P2	0.83
	I5P3	0.81
	I5P4	0.86
SP	SP1	0.80
	SP2	0.77
	SP3	0.83
QP	QP1	0.82
	QP2	0.85
	QP3	0.79

Discriminant validity assessed via the Heterotrait-Monotrait (HTMT) ratio confirmed empirical distinctiveness of constructs, with all values below the conservative threshold of 0.85 (Table 3).

Table 3: Discriminant Validity (HTMT Criterion)

Constructs	I4P	I5P	SP	QP
I4P	—	0.72	0.65	0.61
I5P		—	0.68	0.66
SP			—	0.69
QP				—

4.2. Structural Model Assessment

Hypothesis testing results (Table 4) indicate that Industry 4.0 practices (I4P) have significant positive effects on sustainability performance (SP) ($\beta = 0.32$, $t = 5.41$, $p < 0.001$) and quality performance (QP) ($\beta = 0.29$, $t = 4.87$, $p < 0.001$), supporting H1 and H2. Industry 5.0 practices (I5P) exert stronger positive effects on sustainability ($\beta = 0.41$, $t = 6.92$, $p < 0.001$) and quality performance ($\beta = 0.38$, $t = 6.11$, $p < 0.001$), supporting H3 and H4. Furthermore, Industry 4.0 practices significantly predict Industry 5.0 adoption ($\beta = 0.56$, $t = 9.38$, $p < 0.001$), supporting H5.

Table 4: Path Coefficients and Hypothesis Testing

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	I4P → SP	0.32	5.41	<0.001	Supported
H2	I4P → QP	0.29	4.87	<0.001	Supported
H3	I5P → SP	0.41	6.92	<0.001	Supported
H4	I5P → QP	0.38	6.11	<0.001	Supported
H5	I4P → I5P	0.56	9.38	<0.001	Supported

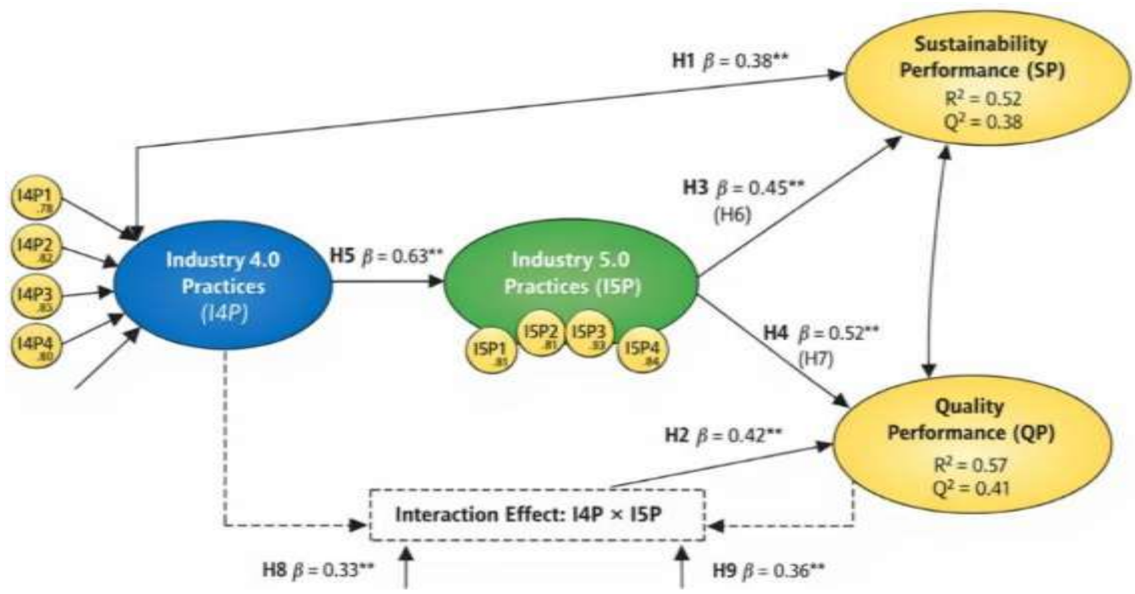

Figure 2

4.3. Mediation Analysis

Bootstrapping results (Table 5) confirm partial mediation by Industry 5.0 practices in the relationship between Industry 4.0 and sustainability performance (indirect effect β = 0.23, t = 4.86, $p < 0.001$; VAF = 41%) and quality performance (indirect effect β = 0.21, t = 4.39, $p < 0.001$; VAF = 42%), supporting H6 and H7.

Table 5: Mediation Analysis (Bootstrapping Results)

Mediation Path	Indirect Effect	t-value	p-value	VAF	Mediation type
I4P → I5P → SP	0.23	4.86	<0.001	41%	Partial
I4P → I5P → QP	0.21	4.39	<0.001	42%	Partial

4.4. Moderation Analysis

Interaction effects (Table 6) demonstrate that the combined adoption of Industry 4.0 and Industry 5.0 practices significantly enhances sustainability performance (β = 0.18, t = 3.27, p = 0.001) and quality performance (β = 0.16, t = 2.94, p = 0.003), supporting H8 and H9.

Table 6: Moderation Analysis (Interaction Effects)

Hypothesis	Interaction Path	β	t-value	p-value	Decision
H8	I4P × I5P → SP	0.18	3.27	0.001	Supported
H9	I4P × I5P → QP	0.16	2.94	0.003	Supported

4.5. Model Fit and Predictive Power

Table 7: Coefficient of Determination (R^2)

Endogenous Construct	R^2
Industry 5.0 Practices	0.31
Sustainability Performance	0.58
Quality Performance	0.54

The model explains substantial variance in endogenous constructs (Table 7).

Table 8: Effect Size (f^2)

Relationship	f^2	Effect Magnitude
I4P → SP	0.12	Small–Medium
I4P → QP	0.10	Small
I5P → SP	0.29	Medium
I5P → QP	0.25	Medium
I4P → I5P	0.46	Large

Effect size (f^2) analysis (Table 8) indicates medium effects of Industry 5.0 practices on sustainability and quality performance, and a large effect of Industry 4.0 on Industry 5.0 adoption

Table 9: Predictive Relevance (Q^2 – Blindfolding)

Construct	Q^2
Sustainability Performance	0.36
Quality Performance	0.33
Industry 5.0 Practices	0.22

Predictive relevance (Q^2) values obtained via blindfolding (Table 9) exceed zero, confirming strong predictive capability.

Table 10: Model Fit Indices

Fit Index	Value	Recommended
SRMR	0.061	< 0.08
NFI	0.91	> 0.90

Model fit indices indicate satisfactory overall model adequacy (Table 10). Consistent with Partial Least Squares Structural Equation Modelling (PLS-SEM) guidelines, global model fit was evaluated using the Standardized Root Mean Square Residual (SRMR) and the Normed Fit Index (NFI), which are appropriate for assessing approximate fit in prediction-oriented PLS-SEM models. Covariance-based goodness-of-fit indices (e.g., CMIN, DF, GFI, PFI, RMSEA) were not employed, as PLS-SEM does not aim to reproduce the covariance matrix but instead emphasizes explained variance and predictive relevance, which were assessed through R^2, f^2, and Q^2 measures.

5. DISCUSSION

The empirical findings substantiate and extend theoretical understanding of the interplay between Industry 4.0 and Industry 5.0 paradigms in manufacturing organizations, particularly regarding sustainability and quality performance. Industry 4.0 practices serve as a critical technological foundation that directly enhances sustainability and quality outcomes while significantly enabling Industry 5.0 adoption. This aligns with extant literature emphasizing Industry 4.0's role in operational efficiency, defect reduction, and resource utilization through cyber-physical systems, IoT, AI, and digital analytics (Frank et al., 2019; Kamble et al., 2018).

Industry 5.0 practices exhibit stronger direct positive effects on both sustainability and quality performance, underscoring the rise of human-centric, ethical, and resilient manufacturing approaches. This corroborates emerging discourse positioning Industry 5.0 as transcending the technology-centric focus of Industry 4.0 by embedding social sustainability, worker empowerment, and ethical governance, thereby fostering holistic manufacturing excellence (Breque et al., 2021; Mourtzis et al., 2022). The pronounced impact on sustainability reflects Industry 5.0's explicit integration of the triple bottom line—economic, environmental, and social dimensions—broadening smart manufacturing's scope to societal well-being and organizational resilience (Xu et al., 2018).

The partial mediation effects suggest that while Industry 4.0 directly influences sustainability and quality performance, a substantial portion of its impact is realized through Industry 5.0 practices, highlighting the practical importance of integrating human-centric and ethical dimensions alongside digital technologies. The partial mediation by Industry 5.0 practices indicates that digital technologies alone are insufficient for sustainable quality excellence; integration of human-centric and ethical dimensions is essential to fully realize digital transformation benefits. This mediating role highlights how Industry 5.0 amplifies and complements Industry 4.0's technological capabilities, facilitating a socio-technical synergy that enhances organizational performance (Nahavandi, 2019). It empirically addresses a key gap by demonstrating how Industry 5.0 operationalizes the human and social elements often overlooked in Industry 4.0 (Longo et al., 2020).

Significant interaction effects reveal a synergistic co-existence rather than a competitive or replacement relationship between the paradigms. Combined adoption yields superior sustainability and quality outcomes compared to Industry 4.0 alone, validating Industry 5.0 as an evolutionary extension enriching Industry 4.0's technological infrastructure with human creativity, ethical considerations, and resilience (Rojko, 2021; Carayannis & Morawska-Jancelewicz, 2022). This synergy produces operational, environmental, and social benefits unattainable by either paradigm independently.

The model's explanatory power—with 58% variance explained in sustainability and 54% in quality performance—and robust reliability, validity, predictive relevance, and good fit indices affirm the framework's theoretical and practical robustness for guiding sustainable quality excellence in manufacturing.

6. IMPLICATIONS

6.1. Managerial Implications:

Manufacturing firms should strategically pursue phased, integrated adoption of Industry 4.0 and Industry 5.0 practices. While Industry 4.0 technologies establish the digital transformation groundwork, concurrent investment in human-centric initiatives, ethical governance, and resilient systems is critical to fully leverage sustainability and quality benefits. This integrated approach fosters employee engagement, operational robustness, and alignment with evolving stakeholder expectations on social responsibility and sustainability. From a managerial perspective, firms should adopt a phased implementation strategy in which Industry 4.0 technologies such as IoT, analytics, and automation are complemented by Industry 5.0 initiatives, including human–machine collaboration design, workforce upskilling, and ethical governance frameworks. Managers can operationalize Industry 5.0 by redesigning workstations for cobot interaction, integrating employee feedback into digital system design, and embedding safety and well-being metrics into performance dashboards.

6.2. Policy Implications:

Policymakers and industry leaders should develop supportive frameworks promoting co-development of technological and human-centric capabilities. Incentives, standards, and training programs encouraging ethical system design, worker empowerment, and collaborative human-machine ecosystems can accelerate Industry 5.0 adoption while consolidating Industry 4.0 gains. Such policies are vital in emerging economies where resource constraints demand efficient yet socially sustainable industrial development.

6.3. Theoretical Implications:

This study advances academic discourse by providing rigorous empirical evidence on Industry 4.0 and 5.0 co-existence and evolutionary dynamics. It operationalizes Industry 5.0 practices and validates their mediating and moderating roles in sustainable quality performance, encouraging a paradigm shift from purely technology-driven to balanced socio-technical manufacturing research and practice.

7. LIMITATIONS AND FUTURE RESEARCH

This study's cross-sectional design limits causal inference and temporal dynamics assessment. Future research should adopt longitudinal or mixed-method approaches to examine the evolution of Industry 4.0 and 5.0 integration and its impact on organizational resilience and innovation over time. Sector-specific investigations could illuminate contextual variations in paradigm adoption and effects. Expanding the model to include additional performance dimensions—such as financial outcomes, innovation capacity, and supply chain sustainability—would enrich understanding of Industry 4.0 and 5.0 synergies. Furthermore, qualitative studies exploring human-machine collaboration and ethical governance mechanisms could provide deeper insights into Industry 5.0 implementation challenges and best practices. Although the sample size is adequate for robust statistical analysis, the findings are based on manufacturing firms operating within a single national context. As institutional environments, technological maturity, and labor dynamics may vary across regions, caution should be exercised when generalizing the results globally. Future research could replicate the proposed framework across different countries or compare emerging and developed economies to enhance external validity. Although causal relationships were theoretically grounded and statistically supported, longitudinal studies are recommended to validate the dynamic evolution of Industry 4.0 and Industry 5.0 integration over time.

8. CONCLUSION

This study empirically demonstrates that Industry 4.0 and Industry 5.0 paradigms coexist synergistically, with Industry 5.0 enriching Industry 4.0's technological foundation through human-centric and ethical practices essential for sustainable quality excellence. Manufacturing organizations strategically integrating these paradigms achieve superior sustainability and quality outcomes, securing long-term competitive advantage amid increasing industrial complexity and societal expectations. The integrative conceptual framework and robust empirical evidence offer a comprehensive roadmap for firms and policymakers to navigate the transition toward holistic, sustainable manufacturing excellence.

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