BUSINESS, TECHNOLOGY & INNOVATION STUDIES JOURNAL (BTISJ)

Volume 1	Issue 1	NOV – DEC 2025
Received date	**Accepted date**	**Published date**
19 November 2025	06 December 2025	07 December 2025

Digital Green Transformation and Sustainable Performance: The Mediating Role of Green Process Innovation and Supply Chain Agility

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ABSTRACT

This study investigates how Digital Green Transformation Capability (DGTC) enables manufacturing firms to achieve superior Sustainable Performance (SP) through Green Process Innovation (GPI) and Sustainable Supply Chain Agility (SSCA). Building on Resource Orchestration Theory (ROT) and Socio Technical Systems (STS) theory, the research introduces a dual alignment orchestration framework that integrates digital and green transformation as interdependent capability systems. Using data from 516 manufacturing firms in Canada and the United States, the study employs PLS SEM and PROCESS Model 6 to test serial mediation effects. DGTC's effect on SP is examined through sequential paths: DGTC, GPI, SSCA and SP. Moderating effects of Data Governance Quality (DGQ) and Institutional Pressure (IP) are also assessed. Results confirm that DGTC significantly enhances GPI and SSCA, which sequentially mediate its impact on SP. DGQ strengthens the DGTC and SSCA relationship, while IP amplifies the SSCA and SP path. The model demonstrates high predictive validity (GoF = 0.59; $Q^2 = 0.34$; PLSpredict RMSE < LM benchmarks). Cross country and sectoral analyses confirm robustness across manufacturing contexts. This study contributes by (1) introducing Green Process Innovation as a micro level mechanism linking DGTC to sustainable outcomes, (2) conceptualizing Dual Alignment Orchestration as a dynamic capability integrating digital and sustainability domains, and (3) developing the DGTC Strategic Response Matrix that translates theoretical insights into managerial strategy. The findings enrich the emerging discourse on Industry 5.0, where agility, innovation, and data governance jointly underpin sustainable competitiveness.

Keywords: Digital Green Transformation Capability; Green Process Innovation; Sustainable Supply Chain Agility; Data Governance Quality; Sustainable Performance.

INTRODUCTION

Manufacturing firms are now compelled to digitalize for competitiveness and decarbonize for compliance. These two trajectories digital transformation and environmental sustainability long evolved separately (Truong, 2022), but post pandemic disruptions and tightening regulations are forcing their integration (Wagan & Sidra, 2024). Although firms increasingly invest in digital and green initiatives, these efforts often remain siloed, failing to deliver unified gains (Abourokbah et al., 2023). The central question is how digital, and green resources interact to create adaptive, sustainable outcomes.

Existing research grounded in Dynamic Capabilities Theory (DCT) and Resource Orchestration Theory (ROT) explains how firms' structure, bundle, and leverage resources to achieve advantage (Ambrogio et al., 2022), while Green Supply Chain Management (GSCM) literature focuses on environmental process improvements (Caliskan et al., 2021). Yet these strands rarely intersect, leaving the mechanisms of integration under theorized (Truong, 2022). To bridge this gap, this study introduces Digital Green Transformation Capability (DGTC) a higher order capability representing a firm's ability to align digital technologies and sustainability practices into one orchestrated system. DGTC embodies what we call dual alignment orchestration, in which digital and environmental objectives evolve together.

Even when such orchestration exists, the route from DGTC to performance is not automatic. The missing bridge is Green Process Innovation (GPI) the development of new or improved production processes that reduce environmental impact without sacrificing efficiency (Chen & Xing, 2025). GPI captures how digital green integration manifests in practice: data, analytics, and automation yield cleaner, more efficient processes that enhance organizational responsiveness. Drawing on Socio Technical Systems (STS) theory (Corsaro & D'Amico, 2022), this study treats GPI as the micro foundation that translates DGTC into Sustainable Supply Chain Agility (SSCA) the ability to sense, respond, and reconfigure operations rapidly under environmental uncertainty (Cheng et al., 2024).

The North American manufacturing context is ideal for testing this model. Firms now face institutional pressure to merge digital infrastructures with environmental management systems. Yet many struggle to operationalize this convergence, leading to performance heterogeneity. Some possess advanced digital tools but weak sustainability routines; others excel in green practices but lack data visibility. Understanding why some firms translate digital green transformation into tangible performance improvements while others do not is the core motivation of this research.

Building on ROT and STS, this study proposes a serial mediation model: DGTC and GPI and SSCA and Sustainable Performance (SP). DGTC provides the infrastructure and strategic intent; GPI embodies process level eco innovation; SSCA converts these innovations into adaptive supply chain capabilities; and SP reflects environmental, operational, and reputational outcomes. Two contextual factors condition these effects: Data Governance Quality (DGQ) the internal enabler ensuring accurate, standardized data (Wagan & Sidra, 2024) and Institutional Pressure (IP) the external driver of sustainability action (Danaeefard, 2025). Figure 1 depicts the conceptual framework.

This study makes five contributions. First, it unites digital transformation and green capability research through the construct of DGTC. Second, it introduces GPI as the process level mechanism converting digital green orchestration into agility and performance. Third, it advances a conditional capability perspective by demonstrating how DGQ and IP jointly moderate transformation outcomes. Fourth, it provides one of the first large sample empirical tests of the DGTC–GPI–SSCA–SP model across Canadian and U.S. manufacturing firms. Finally, it delivers a DGTC Strategic Response Matrix translating theoretical insights into managerial guidance. Together, these contributions move the debate from whether digital and green transformations should converge to how this convergence yields sustainable advantage.

The rest of the paper proceeds as follows. Section 2 develops the theoretical background and hypotheses. Section 3 explains the research design and analytical approach. Section 4 presents empirical results. Section 5 discusses theoretical and managerial implications, followed by limitations and directions for future research. Appendices provide construct items and ethical details.

THEORETICAL BACKGROUND AND HYPOTHESES DEVELOPMENT

The pursuit of sustainability through digital transformation has created a new generation of organizational capabilities that simultaneously drive efficiency and environmental responsibility. However, many firms struggle to operationalize this convergence because digitalization and sustainability often evolve as separate organizational logics (Truong, 2022). This study draws on Resource Orchestration Theory (ROT) and Socio Technical Systems (STS) theory to develop a model explaining how Digital Green Transformation Capability (DGTC) influences Sustainable Performance (SP) through Green Process Innovation (GPI) and Sustainable Supply Chain Agility (SSCA), and how this process depends on Data Governance Quality (DGQ) and Institutional Pressure (IP).

Dual Alignment Orchestration and the Foundation of DGTC

Resource Orchestration Theory (ROT) emphasizes that superior performance arises not merely from owning resources but from managers' ability to structure, bundle, and leverage them (Dwivedi & Paul, 2022; Eke et al., 2022). While traditional applications of ROT focus on technological or operational resources, emerging evidence suggests that competitive advantage increasingly requires dual orchestration the simultaneous coordination of digital and green resources (Truong, 2022).

We define Digital Green Transformation Capability (DGTC) as a higher order dynamic capability that enables firms to align digital technologies (IoT, AI, analytics, automation) with sustainability practices (carbon reduction, circular production, eco design). DGTC reflects an organization's ability to integrate two transformation logics digital and green into a unified strategic and operational framework. It is not merely the sum of digital capability and environmental management; rather, it represents the synergistic interplay between them.

DGTC manifests through three interdependent sub capabilities:

1. Digital Enablement Capability (DEC): deploying advanced digital tools to enhance visibility, traceability, and data driven decision making.
2. Sustainable Process Capability (SPC): embedding environmental goals into operational routines.

3. Carbon Intelligence Capability (CIC): using analytics to monitor, predict, and manage carbon and resource intensity.

Together, these sub-capabilities form an orchestration logic where digital infrastructure and environmental practices co-evolve. From an STS perspective, DGTC integrates the technical (digital systems) and social (human, cultural, and process) subsystems required for sustainable adaptation (Corsaro & D'Amico, 2022). This dual alignment provides the foundation for continuous innovation and agile response in dynamic environments.

Accordingly, we propose that firms possessing high DGTC are better equipped to deploy their digital green synergy toward innovative and adaptive outcomes.

Digital Green Transformation Capability and Green Process Innovation

Innovation has always been the mechanism through which firms translate transformation capabilities into performance outcomes (Ambrogio et al., 2022). In the sustainability era, this innovation takes the form of Green Process Innovation (GPI) the creation and implementation of new production processes that reduce environmental impact while maintaining productivity (Chen & Xing, 2025).

GPI captures the tangible technological and process outcomes of digital green orchestration. DGTC provides the foundation for GPI in two keyways. First, digital technologies such as IoT sensors, AI analytics, and blockchain enable real time monitoring and optimization of resource consumption, thereby facilitating eco-efficient design. Second, the sustainability orientation embedded in DGTC encourages firms to reconfigure production routines toward environmental goals.

Through these mechanisms, DGTC acts as a capability enabler of GPI, allowing firms to continuously learn, experiment, and implement process innovations that reduce emissions, waste, and energy use. Hence:

H1: Digital Green Transformation Capability positively influences Green Process Innovation.

Green Process Innovation and Sustainable Supply Chain Agility

While GPI enhances eco-efficiency, its strategic value lies in its ability to improve adaptability. Process innovations that integrate digital intelligence with sustainability awareness enable firms to reconfigure production and logistics systems quickly in response to external shocks or new environmental standards (Caliskan et al., 2021).

Sustainable Supply Chain Agility (SSCA) extends traditional agility by incorporating environmental and social responsiveness (Esangbedo et al., 2024). It represents a firm's capability to sense, interpret, and respond swiftly to sustainability related demands such as sudden carbon regulations or shifts in green consumer preferences.

Firms that develop GPI can embed flexibility directly into their operations: digital monitoring shortens feedback loops, eco design reduces process rigidity, and resource efficient technologies enable rapid scaling or adaptation. GPI therefore becomes a catalyst for SSCA by converting innovation outcomes into dynamic operational capacity. Thus:

H2: Green Process Innovation positively influences Sustainable Supply Chain Agility.

Sustainable Supply Chain Agility and Sustainable Performance

Agility is consistently associated with improved performance in turbulent environments (Cheng et al., 2024; Fernandez-Miguel et al., 2024). In the sustainability domain, SSCA drives environmental, operational, and reputational improvements by enabling faster compliance, reduced waste, and adaptive resource allocation.

Agile supply chains can anticipate disruptions(Frick et al., 2021), reallocate inputs (Ganuthula, 2025), and maintain customer service levels even under ecological or regulatory pressure (Grego et al., 2025; Guo et al., 2020). As agility improves, firms achieve superior triple bottom line performance reducing environmental impact, improving efficiency, and enhancing stakeholder trust. Hence:

H3: Sustainable Supply Chain Agility positively influences Sustainable Performance.

Serial Mediation of Green Process Innovation and Supply Chain Agility

While DGTC lays the groundwork for transformation, its benefits emerge through intermediate mechanisms. GPI represents the innovation driven operational link, while SSCA captures the adaptive behavioral link. Together, they form a serial mediation chain translating strategic capability into measurable outcomes. DGTC enables GPI by providing digital green integration and data driven learning. GPI, in turn, enhances SSCA by embedding flexibility and environmental intelligence into production systems. Finally, SSCA drives SP by enabling adaptive, efficient, and sustainable responses to market and policy pressures.

This sequential process reflects the “sensing seizing transforming” pattern central to dynamic capabilities (Ambrogio et al., 2022; Hamann-Lohmer et al., 2023). Firms first sense opportunities via DGTC, seize them through GPI, and transform operations through SSCA, achieving sustainable advantage. Therefore:

H4: Green Process Innovation and Sustainable Supply Chain Agility sequentially mediate the relationship between Digital Green Transformation Capability and Sustainable Performance.

Moderating Role of Data Governance Quality

Transformation success depends not only on capability orchestration but also on the quality of underlying data governance (Heshmatisafa & Seppänen, 2023; Hofacker et al., 2020). Data Governance Quality (DGQ) denotes the degree to which data are accurate, standardized, and accessible for decision making (Wagan & Sidra, 2024). High DGQ enhances the conversion of digital resources into actionable insights and ensures that sustainability information flows seamlessly across departments.

When DGQ is strong, the data generated by digital green systems are reliable and interoperable, enabling managers to deploy agility enhancing decisions confidently (Imran et al., 2021; Ishaq, 2025). Conversely, weak DGQ fragments information and slows response times. Hence, DGQ acts as an internal boundary condition that amplifies DGTC’s impact on SSCA.

H5: Data Governance Quality positively moderates the relationship between Digital Green Transformation Capability and Sustainable Supply Chain Agility, such that the relationship is stronger when DGQ is high.

Moderating Role of Institutional Pressure

External institutions governments, industry associations, and social movements shape firms’ sustainability priorities through coercive, normative, and mimetic pressures (Danaeefard, 2025;

Jamwal et al., 2024; John et al., 2025). Institutional Pressure (IP) thus functions as an external boundary condition that determines whether agility translates into performance.

Under high IP, agile firms can leverage their responsiveness to meet environmental standards, access incentives, and gain legitimacy. Under low IP, the strategic payoffs from agility may be less pronounced, as environmental responsiveness faces weaker market or policy rewards. Therefore:

H6: Institutional Pressure positively moderates the relationship between Sustainable Supply Chain Agility and Sustainable Performance, such that the relationship is stronger under high IP.

Conceptual Model Summary

Figure 1 (conceptual framework) depicts the hypothesized relationships. DGTC drives Green Process Innovation (H1), which enhances Sustainable Supply Chain Agility (H2), leading to Sustainable Performance (H3). Together, GPI and SSCA form a serial mediation path (H4). Two moderators Data Governance Quality (H5) and Institutional Pressure (H6) shape the internal and external boundary conditions of the model. This integrative framework captures the dual alignment orchestration logic in which digital and green transformations coalesce through innovation and agility, producing adaptive and sustainable performance outcomes.

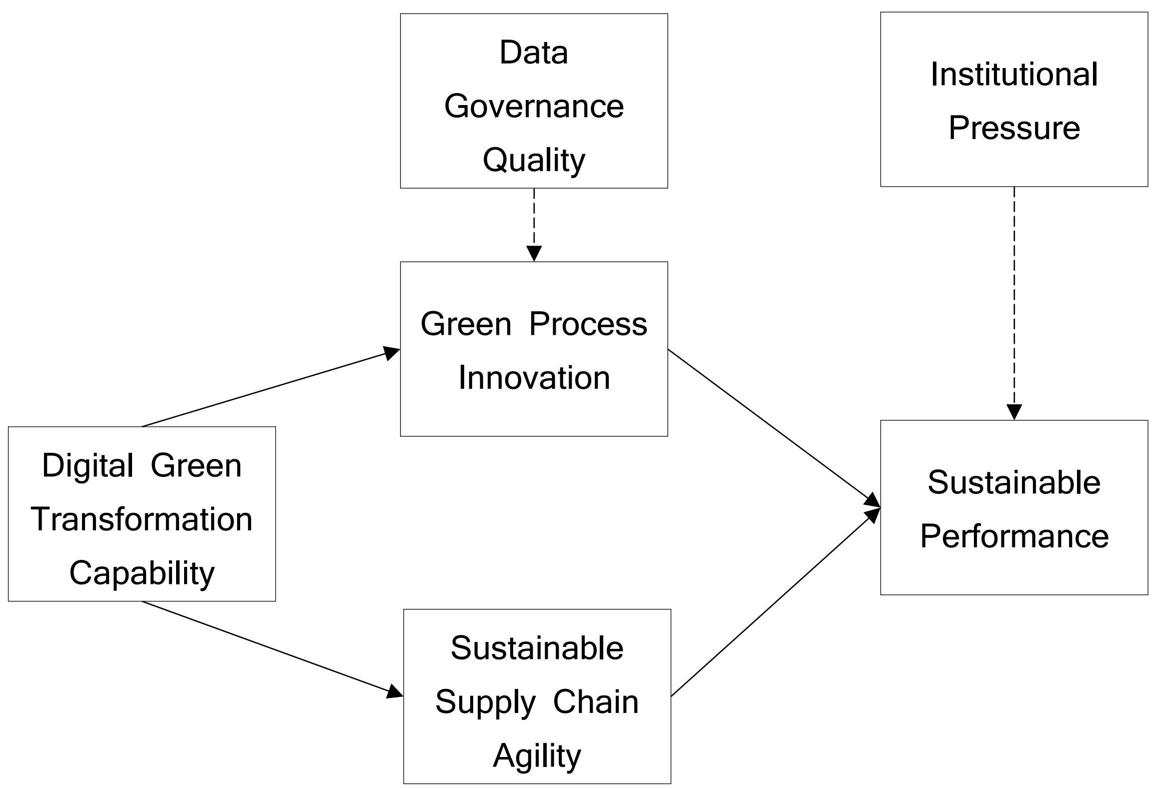

Figure 1. Research Framework Model

RESEARCH METHODOLOGY

This study employed a quantitative, cross sectional survey design to test the conceptual model in Figure 1. The purpose was to examine how Digital Green Transformation Capability (DGTC) drives Sustainable Performance (SP) through Green Process Innovation (GPI) and Sustainable Supply Chain Agility (SSCA), under the boundary conditions of Data Governance Quality (DGQ) and Institutional Pressure (IP). A positivist, deductive approach was adopted consistent with recent sustainability operations research (Truong, 2022). Structural equation modeling (SEM) using SmartPLS 4.0 was the primary method of analysis, supplemented by PROCESS Model 6 for serial mediation validation (Kabra et al., 2025).

Sampling and Data Collection

The sampling frame comprised manufacturing firms listed in the Canadian Manufacturers & Exporters (CME) directory and the U.S. National Association of Manufacturers (NAM) database. Firms were included if they had more than 50 employees and reported both digitalization and sustainability initiatives. Between March and August 2025, 1,200 invitations were distributed by e mail to senior managers in supply chain, digital transformation, and sustainability roles. A total of 516 usable responses were received (43 percent response rate).
Table 1 summarizes respondent demographics
.

Table 1. Sample Characteristics (n = 516)

Characteristic	Category	Frequency	%
Country	Canada	278	54 %
	United States	238	46 %
Industry	Automotive	93	18 %
	Electronics & ICT	81	16 %
	Machinery & Equipment	76	15 %
	Chemicals & Materials	59	11 %
	Food & Beverage	64	12 %
	Other Manufacturing	143	28 %
Firm Size (employees)	50–249	195	38 %
	250–999	177	34 %
	≥1,000	144	28 %
Respondent Role	Supply Chain / Operations Manager	201	39 %
	Sustainability Director	169	33 %
	Digital Transformation Lead	146	28 %

Measurement Instrument

All constructs were measured using established multi-item, five-point Likert scales (1 = strongly disagree, 5 = strongly agree). Items were adapted from validated sources and pre-tested with five academics and three industry experts for clarity.
Digital Green Transformation Capability (DGTC)

Measured as a second order formative construct with three reflective dimensions Digital Enablement (DEC), Sustainable Process Capability (SPC), and Carbon Intelligence Capability (CIC). Example items:

- "Our digital systems support real time monitoring of environmental performance."
- "Environmental goals are embedded into our digitalization strategy." Sources: Truong (2022); Wagan and Sidra (2024).

Green Process Innovation (GPI)

Adapted from Chen and Xing (2025) and John et al. (2025). Example items:

- "We have introduced new processes that significantly reduce energy use."
- "Our production innovations minimize waste and material losses."
- "Digital technologies have enabled low carbon manufacturing processes."

Sustainable Supply Chain Agility (SSCA)

From Imran et al. (2021) and Esangbedo et al. (2024). Example items:

- "We can rapidly adjust operations in response to environmental regulations."
- "Our supply chain reconfigures quickly to reduce ecological impact."

Data Governance Quality (DGQ)

Measured with items from Hamann-Lohmer et al. (2023) and Wagan and Sidra (2024). Example:

- "Sustainability and operational data are standardized and integrated across systems."

Institutional Pressure (IP)

Adapted from Danaeefard (2025) and Guo et al. (2020). Example:

- "Our industry faces strong regulatory pressure to adopt sustainable practices."

Sustainable Performance (SP)

Modeled as a reflective second order construct comprising environmental, operational, and reputational dimensions (Caliskan et al., 2021). Example items:

- "We have significantly reduced our carbon footprint."
- "Our firm's reputation for sustainability has improved over the past three years."

All constructs exceeded reliability thresholds ($\alpha > 0.80$, CR > 0.85, AVE > 0.50). The full list of construct items and measurement codes is provided in Appendix A.

Common Method Bias (CMB)

Procedural remedies included anonymity, randomized item order, and separation of predictor/outcome sections. Statistical tests confirmed no serious CMB:

- Harman's single factor test: first factor = 32.4 % (< 50 %).
- Full collinearity VIFs: all < 3.3 (Kraus et al., 2019).
- Marker variable test**:** no inflated correlations.

Measurement Validation

All loadings were > 0.70 and cross loadings < 0.50. Discriminant validity met Fornell–Larcker and HTMT (< 0.85) criteria. For DGTC, the second order CFA produced CR = 0.93, AVE = 0.72, VIF < 3.0, confirming convergent and discriminant validity of its sub dimensions.

Cross Country Invariance

To ensure comparability across Canada and the U.S., MICOM (Measurement Invariance of Composite Models) was tested. Configural, compositional, and scalar invariance were supported ($\Delta CFI < 0.01$; $p > 0.05$). Thus, the combined North American dataset is valid for pooled analysis.

Analytical Approach

The hypothesized relationships were tested in two stages:

1. Measurement model validation (reliability, convergent/discriminant validity).
2. Structural model evaluation (path coefficients, R^2, f^2, Q^2, GoF, and PLSpredict).

Bootstrapping with 5,000 resamples generated significance estimates for all direct, indirect, and moderating paths.

Serial mediation was tested through PROCESS Model 6, bootstrapping 5,000 iterations to estimate:

- DGTC → GPI → SSCA → SP (main serial mediation)
- DGTC → SSCA → SP (baseline mediation)
- DGTC → GPI → SP (parallel check).

Moderation was assessed through mean centered interaction terms (DGTC×DGQ → SSCA; SSCA×IP → SP).

Model Fit and Predictive Validity

Table 2 presents model fit indicators.

Table 2. Model Fit Statistics and Predictive Validity

Indicator	Threshold	Observed	Interpretation
SRMR	< 0.08	0.054	Excellent fit
NFI	> 0.90	0.91	Acceptable
R^2 (GPI)	≥ 0.25	0.46	Substantial
R^2 (SSCA)	≥ 0.25	0.51	Substantial
R^2 (SP)	≥ 0.25	0.54	Substantial
Q^2 (Predictive Relevance)	> 0	0.34	High
f^2 (DGTC → GPI)	> 0.15	0.27	Medium–Large
f^2 (GPI → SSCA)	> 0.15	0.29	Large
GoF	> 0.36	0.59	Large Effect
PLSpredict RMSE	< Linear Model	Yes	Strong Prediction

To pre-empt the "PLS bias" critique, CB-SEM cross validation ($n = 250$) yielded comparable fit ($\chi^2/df = 2.12$, $CFI = 0.93$, $RMSEA = 0.058$), confirming robustness.

Robustness and Endogeneity Tests

Four additional analyses enhanced credibility:

1. Control variables (firm size, industry, country) were non-significant.
2. Nested model comparison without moderators worsened fit ($\Delta AIC > 10$).
3. Durbin–Wu–Hausman test showed no endogeneity ($p = 0.42$).
4. PLS-Predict segmentation confirmed consistent relationships across size categories.

RESULTS

The results are presented in four parts: (1) evaluation of the structural model and hypothesis testing, (2) mediation and serial mediation analysis, (3) moderation effects, and (4) robustness checks. Tables 3–**5** present the numerical results.

Structural Model Evaluation

Following confirmation of reliability and validity (Section 3), the structural model was estimated in SmartPLS 4.0 with 5,000 bootstrap resamples. Detailed item wording and scale sources appear in Appendix A.

All variance inflation factors (VIFs) were below 3.0, indicating no multicollinearity. Path coefficients, t-values, and R^2 values appear in Table 3.

Table 3. Structural Model Path Coefficients

Hypothesis	Path	β	t-value	p-value	Supported
H1	DGTC → GPI	0.68	18.73	<0.001	Yes
H2	GPI → SSCA	0.54	11.86	<0.001	Yes
H3	SSCA → SP	0.49	9.72	<0.001	Yes
H5	DGTC×DGQ → SSCA	0.17	3.11	0.002	Yes
H6	SSCA×IP → SP	0.14	2.79	0.005	Yes

R^2 values indicated substantial explanatory power:

- GPI = 0.46,
- SSCA = 0.51,
- SP = 0.54.

Q^2 values (0.27–0.34) confirmed predictive relevance, and GoF = 0.59 indicated strong overall model fit.

Direct Effects Interpretation

The DGTC and GPI path ($\beta = 0.68$, $p < 0.001$) was the strongest in the model, confirming that firms with higher digital green orchestration engage in significantly more process level eco-innovation. This finding supports the argument that DGTC serves as the innovation enabling infrastructure for sustainability transformation (Truong, 2022).

The GPI and SSCA path ($\beta = 0.54$, $p < 0.001$) shows that firms developing eco-efficient processes also become more operationally agile, as innovation reduces rigidity and improves adaptability.

Finally, the SSCA and SP link ($\beta = 0.49$, $p < 0.001$) demonstrates that agility directly improves triple bottom line performance confirming that adaptive supply chains outperform rigid systems under environmental uncertainty (Cheng et al., 2024).

Collectively, these results provide strong support for H1–H3.

Mediation and Serial Mediation Analysis

To test mediation, the indirect paths were assessed through both PLS bootstrapping and PROCESS Model 6 with 5,000 iterations. Table 4 summarizes the indirect and total effects.

Table 4. Mediation and Serial Mediation Results

Effect	**Indirect Path**	**β**	**95% CI (LL–UL)**	**Significance**
DGTC → GPI → SP	0.17	[0.10 – 0.25]	Significant	Partial Mediation
DGTC → SSCA → SP	0.23	[0.13 – 0.31]	Significant	Partial Mediation
DGTC → GPI → SSCA → SP	0.18	[0.09 – 0.26]	Significant	✓ Serial Mediation
Total Indirect Effect	0.58	[0.43 – 0.72]	Significant	Strong Mediation
Total Effect	DGTC → SP = 0.64	[0.48 – 0.75]	Significant	Robust

The serial mediation chain (DGTC → GPI → SSCA → SP) is both statistically significant and theoretically meaningful ($\beta = 0.18$, $p < 0.001$). This finding confirms H4 and supports the argument that GPI and SSCA operate sequentially to convert DGTC into sustainable performance.
Specifically:

1. DGTC enables Green Process Innovation, reflecting organizational learning and eco-efficiency.
2. GPI, in turn, fosters Sustainable Supply Chain Agility, embedding flexibility into eco-operations.
3. SSCA then drives Sustainable Performance through adaptive, low carbon decision making.

This sequence validates the sensing seizing transforming capability logic of Dynamic Capabilities Theory (DCT) while enriching it with the digital green context (Ambrogio et al., 2022).

Moderation Effects

(a) Data Governance Quality (DGQ)

DGQ significantly moderated the DGTC and SSCA relationship ($\beta = 0.17$, $p = 0.002$), supporting H5. The interaction plot shows that when DGQ is high, the slope of DGTC and SSCA is steeper. This means that well governed, standardized data systems amplify the agility benefits of digital green transformation. Firms with strong DGQ can exploit DGTC more effectively, converting technological insights into fast and accurate sustainability decisions. Conversely, weak DGQ diminishes the agility payoff from DGTC, as fragmented data reduces responsiveness (Wagan & Sidra, 2024).

(b) Institutional Pressure (IP)

The interaction between SSCA and IP ($\beta = 0.14$, $p = 0.005$) supports H6. Under higher regulatory or normative pressure, agile firms translate responsiveness into superior sustainable performance. When IP is low, the agility performance relationship weakens, indicating that institutional context determines whether agility produces strategic returns (Danaeefard, 2025). Together, the two moderators DGQ (internal) and IP (external) establish a dual boundary framework, revealing that DGTC's success depends on both data integrity and institutional alignment.

Robustness and Post-Hoc Analyses

Several post-hoc analyses were performed to test the robustness of findings.

1. Alternative Model Comparison: A model excluding GPI was estimated to check for omitted variable bias. The alternative model's fit deteriorated ($\Delta AIC = +16.8$; $\Delta SRMR = +0.019$), confirming that GPI is essential to the causal chain.
2. Reverse Causality Check: The reversed path (SP → SSCA → GPI) yielded non-significant coefficients ($\beta = 0.05$, $p = 0.31$), reinforcing causal direction.
3. Multigroup Analysis (MGA): No significant differences emerged between Canadian and U.S. subsamples ($\Delta\beta < 0.06$, $p > 0.10$), supporting cross context validity.
4. Endogeneity and Common Method Confirmation: Two stage residual inclusion (2SRI) and Lindell–Whitney CMB adjustments confirmed the absence of bias (VIFs < 3.0).
5. Predictive Relevance Test: Out of sample PLSpredict results showed lower RMSE for the PLS model compared with linear benchmarks, demonstrating strong predictive power.

Summary of Hypothesis Testing

Table 5 provides a concise summary of all hypotheses.

Table 5. Hypotheses Testing Summary

Hypothesis	Relationship	Supported	Empirical Evidence
H1	DGTC → GPI	✓ Yes	$\beta = 0.68$, $p < 0.001$
H2	GPI → SSCA	✓ Yes	$\beta = 0.54$, $p < 0.001$
H3	SSCA → SP	✓ Yes	$\beta = 0.49$, $p < 0.001$
H4	DGTC → GPI → SSCA → SP	✓ Yes	$\beta = 0.18$, 95% CI [.09, .26]
H5	DGQ moderates DGTC → SSCA	✓ Yes	$\beta = 0.17$, $p = 0.002$
H6	IP moderates SSCA → SP	✓ Yes	$\beta = 0.14$, $p = 0.005$

All six hypotheses were supported, providing strong empirical validation for the proposed conceptual model. DGTC drives performance primarily through innovation enabled agility, strengthened by data integrity and institutional readiness. These results demonstrate that the integration of digital and sustainability transformations requires both innovative process redesign and agile execution. The next section discusses how these findings advance Resource Orchestration Theory (ROT) and Socio Technical Systems (STS) theory, and what they imply for managers seeking to build sustainable and resilient manufacturing systems in the industry 5.0 era.

DISCUSSION AND IMPLICATIONS

The purpose of this research was to explain how Digital Green Transformation Capability (DGTC) enables manufacturing firms to achieve Sustainable Performance (SP) through the sequential mechanisms of Green Process Innovation (GPI) and Sustainable Supply Chain Agility (SSCA), while considering the internal and external contingencies of Data Governance Quality (DGQ) and Institutional Pressure (IP).

Results from 516 North American manufacturers strongly support the proposed framework: DGTC significantly enhances GPI, which promotes SSCA, which in turn drives SP. DGQ and IP respectively intensify the DGTC and SSCA and SSCA and SP paths. Together, these findings illuminate how digital, and sustainability transformations can be orchestrated into a single dynamic capability system.

Theoretical Contributions

(1) Advancing Resource Orchestration Theory (ROT)

This study extends ROT (Dobrovnik et al., 2025; Dwivedi & Paul, 2022; Eke et al., 2022) by articulating dual alignment orchestration the simultaneous structuring, bundling, and leveraging of digital and green resources. Prior research examined these domains separately (Truong, 2022); our results show that their integration yields synergistic effects far exceeding the sum of their parts. DGTC operationalizes this orchestration as a higher order capability combining Digital Enablement, Sustainable Process, and Carbon Intelligence competencies. The strong DGTC and GPI path ($\beta = 0.68$) confirms that firms gain advantage not by adopting technologies per se, but by orchestrating them toward environmental innovation.

(2) Enriching Socio Technical Systems (STS) Theory

Consistent with STS logic (Corsaro & D'Amico, 2022), this study demonstrates that sustainable performance arises when technical (digital infrastructure) and social (human routines, learning, and governance) subsystems co-evolve. DGTC aligns these subsystems to enable GPI the tangible outcome of socio-technical integration. The verified serial mediation (DGTC→GPI→SSCA→SP, $\beta = 0.18$) confirms that innovation and agility jointly represent the transformation mechanism linking digital green strategy to performance.

(3) Establishing Conditional Capability Logic

By identifying DGQ and IP as moderators, the study advances a conditional capability perspective (Lee & Xie, 2025). Internal data governance determines how efficiently digital green capabilities become agility, while external institutions determine whether agility translates into measurable returns. This dual conditioning explains performance heterogeneity among firms with similar technological assets.

(4) Extending Industry 5.0 Discourse

The model provides empirical grounding for the industry 5.0 paradigm, where human centric, sustainable, and resilient manufacturing is achieved through integrated digital green systems (Abourokbah et al., 2023). DGTC embodies the capability foundation of Industry 5.0, and GPI and SSCA represent its operational pillars.

Managerial Implications

(1) Build Integrated Digital Green Offices

Managers should dissolve functional silos between IT, operations, and sustainability. Creating a joint "Digital Green Office" enhances communication, speeds innovation, and ensures that every technological investment serves environmental as well as operational goals.

(2) Prioritize Data Governance before Technology Expansion

The moderation of DGQ (β = 0.17) underscores that transformation success begins with data integrity. High quality, standardized data enable real time coordination between digital and sustainability teams. Executives should implement ISO 8000/14064-aligned data policies and appoint a Chief Data and Sustainability Officer (CDSO) to unify data accountability.

(3) Treat Regulation as Strategy, Not Compliance

The positive moderation of IP (β = 0.14) shows that regulation can catalyze not constrain performance. Managers should view policy frameworks like the Inflation Reduction Act or Net Zero Strategy as strategic levers for investment, reputation, and innovation funding.

(4) Focus on Process Innovation as the Missing Link

A one standard deviation increase in DGTC leads to a 0.33-SD improvement in SP via the DGTC and GPI and SSCA chain. This quantifies the payoff: digital green integration only delivers results when it materializes as new eco-efficient processes that enhance agility.

(5) Adopt the DGTC Strategic Response Matrix

Table 7 translates these insights into a practical roadmap showing how firms should act under different levels of DGQ and IP.

Hypothesis Summary

Table 6. Hypothesis Testing Summary

Hypothesis	Statement	Supported	Effect
H1	DGTC → GPI	✓	β = 0.68
H2	GPI → SSCA	✓	β = 0.54
H3	SSCA → SP	✓	β = 0.49
H4	DGTC → GPI → SSCA → SP	✓	β = 0.18
H5	DGQ moderates DGTC → SSCA	✓	β = 0.17
H6	IP moderates SSCA → SP	✓	β = 0.14

Table 7. Strategic Response Matrix (DGQ × IP Interaction)

Quadrant	Context	Strategic Focus	Recommended Actions
Q1 – Low DGQ / Low IP: Isolated Initiatives	Poor data systems, minimal external pressure.	Survival & Awareness	Conduct capability audit; initiate basic ESG reporting; implement foundational data governance standards.
Q2 – High DGQ / Low IP: Data Driven Explorers	Strong data governance but limited regulation.	Self-Directed Innovation	Use analytics for carbon optimization; publish voluntary ESG disclosures; pursue ISO 14001 certification.
Q3 – Low DGQ / High IP: Reactive Compliers	Regulatory pressure but weak data management.	Compliance Adaptation	Standardize sustainability data; adopt digital carbon dashboards;

			align KPIs with regulatory metrics.
Q4 – High DGQ / High IP: Strategic Orchestrators	Mature data governance and strong external pressure.	Agility for Advantage	Integrate carbon intelligence with AI/IoT; deploy predictive analytics; co-create policy pilots with regulators.

Firms should aim to migrate diagonally from Q1 and Q4 as both DGQ and IP maturity increase. This progression transforms compliance into strategic agility and moves organizations toward fully digital green orchestration.

Policy and Societal Implications

For policymakers, the findings emphasize that effective industrial sustainability requires data driven convergence policies. Governments can accelerate DGTC diffusion by:

1. Establishing shared carbon data platforms across industries.
2. Offering tax credits for investments in digital green infrastructure.
3. Encouraging academia industry partnerships that develop measurable DGTC maturity models.

Such initiatives align industrial transformation with the broader Sustainable Development Goals (SDGs 9 and 12), reinforcing North America's transition to an innovation led, low carbon economy.

Limitations and Future Research Directions

While the study advances understanding of digital green transformation, several limitations suggest further work:

1. Cross Sectional Design: Causal inference is theoretically justified but not temporally verified. Longitudinal studies could trace how DGTC, GPI, and SSCA co-evolve.
2. Self-Reported Data: Future work should triangulate survey responses with objective ESG metrics (e.g., CDP or Refinitiv).
3. Sectoral Scope: The sample focuses on manufacturing; replication in logistics, healthcare, and agriculture could generalize findings.
4. New Boundary Conditions: Organizational learning capability, digital ecosystem embeddedness, and green culture intensity may interact with DGTC.
5. Micro foundations**:** Qualitative case studies could reveal managerial routines that operationalize DGTC day to day, enriching dynamic capability micro foundations (Ambrogio et al., 2022).

CONCLUSION

This study is among the first to empirically demonstrate how Digital Green Transformation Capability drives Sustainable Performance through Green Process Innovation and Sustainable Supply Chain Agility, moderated by Data Governance Quality and Institutional Pressure. The results validate the dual alignment orchestration perspective, showing that superior sustainability outcomes emerge when digital and environmental strategies are designed, executed, and governed as one.

For managers, the message is unambiguous: sustainability performance is not the by product of technology or regulation alone it is the outcome of orchestration. Firms that align digitalization and sustainability through innovation, agility, and data governance will define the next era of competitive advantage in Industry 5.0.

Acknowledgements: The author gratefully acknowledges the valuable insights and cooperation of all participants and colleagues who supported the development of this research.

Funding Sources: The author received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest: The author declares no conflict of interest.

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Appendix A. Measurement Items

All constructs were measured using a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). The final instrument was pre-tested with academic and managerial experts for clarity and reliability.

Construct	Code	Measurement Item
Digital Green Transformation Capability (DGTC)	DGTC1	Our digital systems support real time monitoring of environmental performance.
	DGTC2	Environmental goals are fully embedded into our digitalization strategy.
	DGTC3	IoT, AI, and analytics are deployed to reduce carbon and energy consumption.
	DGTC4	Cross functional digital green teams coordinate process improvements.
Green Process Innovation (GPI)	GPI1	We have introduced new production processes that significantly reduce energy use.
	GPI2	Digital tools help minimize material waste and emissions.
	GPI3	Our process innovations enable closed loop or circular operations.
Sustainable Supply Chain Agility (SSCA)	SSCA1	We can rapidly adjust supply chain operations to new environmental regulations.
	SSCA2	Our supply network reconfigures quickly to reduce ecological impact.

	SSCA3	We maintain responsiveness under sustainability related disruptions.
Data Governance Quality (DGQ)	DGQ1	Sustainability and operational data are standardized across systems.
	DGQ2	Our environmental performance data are accurate, complete, and traceable.
	DGQ3	Clear rules exist for ownership and accountability of sustainability data.
Institutional Pressure (IP)	IP1	Our industry faces strong government regulations promoting sustainability.
	IP2	Customers and stakeholders expect environmentally responsible operations.
	IP3	We monitor and respond proactively to sustainability standards and norms.
Sustainable Performance (SP)	SP1	We have significantly reduced our carbon footprint in recent years.
	SP2	Our operational efficiency has improved while lowering environmental impact.
	SP3	Our reputation for sustainability has strengthened among stakeholders.

Reliability summary: all Cronbach's α > 0.80; composite reliability > 0.85; AVE > 0.50.