Developing a Robotic-Integrated Leagility Adaptation Model Through Green Supply Chain Intelligence and Supply Chain Ambidexterity

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***Abstract*—This study develops a Robotic-Integrated Leagility Adaptation Model by combining Green Supply Chain Intelligence (GSCI) and Supply Chain Ambidexterity (SCA) to enhance sustainable performance in the manufacturing sector. The rapid evolution of robotics, cyber-physical systems, and AI-enabled decision technologies has transformed supply chain dynamics, necessitating an adaptive model that balances efficiency (lean) and responsiveness (agile). Using an integrated quantitative approach, this research examines how robotic automation strengthens leagility capabilities through real-time analytics, predictive intelligence, and environmentally oriented digital operations. The findings demonstrate that GSCI significantly enhances SCA, which in turn improves leagility adaptation and sustainable manufacturing performance. Robotic integration is found to play a catalytic role by enabling autonomous coordination, energy-efficient scheduling, and intelligent material handling as key enablers of green and responsive operations. This study contributes to the literature by proposing a technology-driven leagility model that links robotics, green supply chain intelligence, and ambidexterity within a unified smart manufacturing framework. Implications are provided for policymakers and industry leaders to accelerate sustainable transformation through robotics-enabled digital ecosystems.**

Keywords—Robotic integration; Green Supply Chain Intelligence; Supply Chain Ambidexterity; leagility adaptation; sustainable manufacturing performance

I. Introduction

The manufacturing sector has undergone significant turbulence in recent years, driven by global economic uncertainty and intensified by disruptive events such as the COVID-19 pandemic. Production declines reported in some industries to reach as high as 46.5% have exposed structural vulnerabilities in manufacturing systems and supply chains, highlighting an urgent need for strategies that strengthen resilience, efficiency, and sustainability. In this context, traditional operational approaches are increasingly insufficient as firms confront volatile demand patterns, supply interruptions, and technological acceleration, all of which require redesigned systems capable of adapting to dynamic environments.

Sustainability in manufacturing must therefore be reframed as a multidimensional capability rather than a peripheral compliance function. Guided by the Triple Bottom Line (TBL) logic, sustainability encompasses economic viability, social responsibility, and environmental stewardship, each of which contributes to long-term value creation. Prior studies have stressed that integrating these three pillars into core processes allows firms to generate competitive advantage while simultaneously enhancing social welfare and mitigating ecological degradation [1]. As consumers, regulators, and global markets increasingly demand ethically and environmentally responsible production, sustainable performance has become a strategic priority for manufacturing firms.

Despite mounting pressure to deliver sustainable outcomes, many organizations encounter difficulties in translating sustainability goals into operational routines, especially within complex supply networks. Green Supply Chain Intelligence (GSCI)—an advanced, data-driven extension of Green Supply Chain Management—seeks to embed environmental thinking into procurement, production, logistics, and end-of-life processes through smart sensing, AI-enabled analytics, and digital monitoring [2], [3]. However, balancing the environmental objectives of GSCI with the need for operational efficiency introduces a persistent tension. At the same time, firms face intensifying pressures for responsiveness, adaptability, and innovation, underscoring the importance of Supply Chain Ambidexterity as a capability for balancing exploitation of existing strengths with exploration of emerging opportunities.

Supply Chain Ambidexterity in the era of robotics and Industry 4.0 reflects the ability of firms to optimize current processes while experimenting with disruptive technologies—including autonomous robotics, IoT devices, cyber-physical systems, and machine learning to enhance adaptability. Although prior research has examined efficiency, responsiveness, and sustainability in isolation, empirical investigations into the combined influence of GSCI, robotics integration, and ambidexterity on sustainable performance remain limited. This gap is critical because robotics and AI can simultaneously strengthen leanness through automation and predictive intelligence while enabling agility through rapid reconfiguration and real-time decision-making.

Leagility, the synergy of lean and agile paradigms, offers a promising strategic perspective to reconcile efficiency and flexibility in technology-enabled supply chains. When enhanced with robotic automation, leagility enables waste reduction, flexible scheduling, autonomous material handling, and rapid

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response to disturbances [4]. Integrating leagility with GSCI and ambidexterity provides an opportunity to build supply chains that are both environmentally responsible and highly adaptive, thereby supporting more robust sustainability outcomes across economic, social, and ecological dimensions.

Building on these dynamics, this study poses a guiding question: How can the integration of Green Supply Chain Intelligence and Supply Chain Ambidexterity, when supported by robotic automation, enhance leagility adaptation and sustainable manufacturing performance? To address this question, the research develops and empirically tests a Robotic-Integrated Leagility Adaptation Model that explains the mechanisms through which GSCI and ambidextrous capabilities contribute to leagility and sustainability. The model evaluates how data-driven green practices improve environmental and social outcomes, how ambidexterity enhances adaptability, and how robotics amplifies both efficiency and flexibility by enabling autonomous, data-rich, and low-waste operations.

Additionally, this research assesses potential mediating and moderating mechanisms, including technological readiness, digital integration capability, and management control systems—that shape the translation of GSCI and ambidexterity into measurable performance outcomes. Understanding these mechanisms is essential for practitioners seeking to design sustainable, digitally enhanced supply chain strategies that are both economically feasible and socially responsible.

While previous literature has documented the individual benefits of robotics, GSCM, and ambidexterity, few studies have synthesized these elements within a unified, empirically tested framework that incorporates leagility and sustainability. This research addresses that gap by offering a comprehensive model tailored to modern manufacturing realities where digital transformation, environmental imperatives, and operational resilience are deeply interconnected.

The contributions expected from this study are both theoretical and practical. Theoretically, it advances supply chain and manufacturing research by integrating robotics, GSCI, ambidexterity, and leagility into a coherent analytical model that explains sustainable performance drivers. Practically, the study provides actionable guidance for manufacturing firms on leveraging robotics, AI, and digital intelligence not merely as operational tools, but as strategic enablers of sustainable value creation. By clarifying the pathways that connect technology-driven supply chain practices to sustainability outcomes, this research aims to equip decision-makers with a roadmap for navigating the evolving challenges of the manufacturing landscape.

This manuscript is structured as follows: Section II provides a comprehensive review of the relevant literature and develops the theoretical framework that integrates Green Supply Chain Intelligence, Supply Chain Ambidexterity, robotics-enabled capabilities, and leagility, culminating in the formulation of the research hypotheses. Section III outlines the research methodology, detailing the research design, sampling procedure, operationalization of constructs, and the analytical techniques employed. Section IV reports the empirical findings and presents the results of the proposed model. It offers a critical discussion of the results by situating the findings within established theoretical perspectives and extant empirical research. Finally, Section V concludes the study by synthesizing the principal findings, articulating the theoretical and managerial implications, acknowledging the study's limitations, and suggesting avenues for future research.

II. Literature Review

This review synthesizes the theoretical foundations and empirical findings that undergird the present study, situating Green Supply Chain Integration (GSCI), Supply Chain Ambidexterity 4.0 (SCA 4.0), and Leagility within established strategic management and supply chain literatures. It emphasizes how heterogeneous strategic resources, digital transformation, and inter-organizational perspectives jointly shape sustainable competitive advantage and sustainability performance in manufacturing contexts.

Strategic resources and capabilities are not uniformly distributed across firms; their heterogeneity and imperfect transferability underpin differences in competitive outcomes and can sustain long-term competitive advantage [5]. From a Resource-Based View (RBV) perspective, sustainable competitive advantage arises when firms leverage valuable, rare, costly-to-imitate resources and organize effectively to capture their rents (Abeysekara et al., 2019; Ellitian, 2020). The VRIO framework value, rarity, and imitability organization operationalizes this evaluative logic, guiding assessment of whether a resource or capability can generate persistent competitive benefits [6]. Complementary managerial frameworks such as Kaplan and Norton's Balanced Scorecard remind us that executives seldom rely on a single performance metric; instead, they deploy multifaceted measurement systems to balance financial, customer, internal process, and learning perspectives [7]. This plurality of measures is especially pertinent when firms attempt to reconcile efficiency, adaptability, and sustainability objectives.

The strategy level of smart supply chains must explicitly account for digital transformation ambitions and the alignment of resources needed to synchronize supply chain goals with real-time data flows [8]. Digital integration, exemplified by IoT sensors, edge computing, and analytics platforms, reconfigures information flows and decision rights across the supply chain, enabling faster detection of disruptions, more precise forecasting, and finer control of resource use. However, the strategic gains from digitalization depend on organizational alignment: technologies alone do not guarantee improved outcomes unless firms align processes, governance, and capabilities to exploit them.

Stakeholder theory provides a robust lens for understanding value creation that extends beyond shareholders to include customers, employees, suppliers, communities, and regulators [9], [10]. This multi-stakeholder orientation is instrumental in measuring and managing sustainability, since environmental and social outcomes reflect a network of expectations and regulations. The Relational View complements RBV by locating sources of competitive advantage at the level of interfirm relationships and strategic alliances; some capabilities and value creation mechanisms emerge only when firms collaborate across boundaries [11]. Consequently, value creation in sustainable supply chains often involves orchestrating capabilities across focal firms, suppliers, logistics providers, and institutional actors.

Contemporary models that integrate GSCI and SCA 4.0 draw on multiple theoretical strands from strategic management and supply chain research: Porter's value chain (1985) for activity-level analysis, RBV and VRIO for resource assessment [12], Dynamic Capabilities for adaptation under technological change [13], [14], Transaction Cost considerations for governance choices [15] and Stakeholder Theory for legitimacy and value creation [16]. Together, these perspectives provide a fertile ground for hypothesizing how green practices, digital ambidexterity, and strategic orientation interact to determine sustainability performance in modern manufacturing networks [17].

A. Green Supply Chain Integration (GSCI) and Sustainability Performance

GSCI encompasses the systematic incorporation of environmental objectives into procurement, production, distribution, and reverse logistics. Empirical studies show that GSCI contributes directly to improved environmental performance and, often, operational efficiencies such as reduced material waste, energy savings, and compliance benefits [18]. Aligning GSCI with regulatory demands and consumer preferences for greener products promotes resource stewardship and strengthens social legitimacy, thereby supporting both environmental and socioeconomic dimensions of sustainability. A robust GSCI capability enables firms to identify and institutionalize eco-friendly practices across their value chains, positioning GSCI as a primary driver of sustainability performance.

H1a: Green Supply Chain Integration positively influences Sustainability Performance.

B. Leagility as a Mediator Between Green Integration and Sustainability

Leagility, the deliberate combination of lean and agile principles, provides a strategic pathway to reconcile waste reduction with responsiveness. Lean focuses on streamlining flows and eliminating non-value-adding activities, while agility prioritizes flexibility and rapid response to changing demand patterns. When GSCI practices are aligned with lean principles (e.g., reduction of material use) and agile mechanisms (e.g., flexible sourcing, quick reconfiguration), supply chains can both lower environmental footprints and adapt to market variability. Therefore, Leagility functions as a mechanism through which GSCI translates into superior sustainability outcomes.

H1b: Green Supply Chain Integration positively influences Leagility Strategy.

H1c: The effect of Green Supply Chain Integration on Sustainability Performance is mediated by Leagility Strategy.

C. Supply Chain Ambidexterity 4.0 (SCA 4.0) Digital Ambidexterity and Sustainability

SCA 4.0 articulates the need to balance the exploitation of existing capabilities with the exploration of novel solutions in a digitally augmented supply chain environment. By integrating Industry 4.0 technologies such as IoT, AI, and big data analytics, firms can simultaneously optimize routine operations and experiment with innovative configurations (Yang & Singhdong, 2024). Strategic ambidexterity supported by digital tools enhances resource efficiency (through predictive maintenance, route optimization, and demand sensing) while enabling exploratory initiatives (new product introductions, circular business models) that extend sustainability potential. Thus, SCA 4.0 is posited to exert a direct positive effect on sustainability performance.

H2a: Supply Chain Ambidexterity 4.0 positively influences Sustainability Performance.

D. SCA 4.0, Leagility, and the Enabling Role of Technology

Digital ambidexterity strengthens both lean and agile elements by providing the real-time visibility and decision support necessary for synchronized, responsive operations. Exploitative use of technology drives consistent efficiency gains; exploratory use fosters adaptability to emergent market and regulatory pressures. The balance of these uses underpins a Leagility orientation that maintains cost discipline while enabling rapid reconfiguration in response to disruptions. In practice, SCA 4.0 capabilities, when integrated into governance and process design, facilitate rapid, data-driven decisions that support sustainable outcomes.

H2b: Supply Chain Ambidexterity 4.0 positively influences Leagility Strategy.

H2c: The effect of Supply Chain Ambidexterity 4.0 on Sustainability Performance is mediated by Leagility Strategy.

E. Dynamic Capabilities and Mediating Contingencies

Dynamic capabilities sensing, seizing, and reconfiguring are essential for firms to adapt to technological change and external shocks, enabling the translation of GSCI and SCA 4.0 into performance gains (Teece, 2018). Additional mediating and moderating constructs of interest include management control quality (which shapes implementation fidelity), market orientation (which aligns innovation with stakeholder demand), and technological adaptability (which conditions effective adoption of Industry 4.0 tools). These governance and capability factors help explain variation in outcomes across firms and illuminate why resource heterogeneity often leads to differential sustainability performance.

While substantial research documents the separate benefits of GSCI and ambidextrous [8], [19], [20], few studies comprehensively integrate these constructs within a Leagility framework that explicitly accounts for Industry 4.0 digitalization. The relational and stakeholder lenses further suggest that sustainable advantage frequently accrues from interorganizational coordination and legitimacy-seeking behaviors rather than from focal-firm actions alone. This gap motivates the present integrative model, which tests direct and mediated pathways linking GSCI and SCA 4.0 to sustainability performance through Leagility, while considering dynamic capabilities and governance contingencies.

In sum, the literature indicates strong theoretical and empirical reasons to expect that: 1) GSCI and SCA 4.0 each contribute to sustainability performance, 2) Leagility operationalizes the reconciliation of efficiency and responsiveness that converts these capabilities into sustainable outcomes, and 3) dynamic capabilities and organizational governance shape the magnitude and direction of these effects. The hypotheses above (H1a–H1c, H2a–H2c) articulate these relationships and provide the basis for the empirical tests developed in this study.

Based on the literature review and the proposed hypothesis proposition, this research model is displayed in Fig. 1.

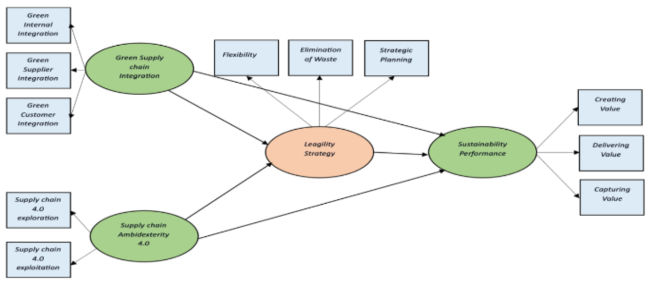

Fig. 1. Research model.

III. Methodology

This study adopts a quantitative approach using an explanatory survey design to empirically examine the causal relationships specified in the research hypotheses. A quantitative framework is appropriate because it enables systematic measurement, hypothesis testing, and estimation of the magnitude and direction of relationships among independent, mediating, and dependent variables. The explanatory survey method is specifically chosen to move beyond descriptive associations and to provide statistical evidence that clarifies how the green supply chain, Supply Chain Ambidexterity 4.0, and Leagility strategy interact to influence firm performance.

The target population comprises all automotive components and spare-parts manufacturers operating in West Java and DKI Jakarta. Industry records indicated 235 firms within this category. To enhance data quality and comparability, the sampling frame was restricted to firms holding ISO 9001:2015 certification. This criterion was selected because ISO 9001:2015 signals the presence of a formal quality management system and managerial processes that are relevant to market orientation, quality control, operational strategies (including Leagility), and supply chain adaptation. Purposive sampling was employed to select respondents based on predefined inclusion criteria: geographic location (West Java and DKI Jakarta) and possession of ISO 9001:2015 certification. Purposive sampling ensures that collected data pertain to firms with managerial structures and process disciplines relevant to the conceptual model. With 209 eligible firms, the sample comfortably meets conventional recommendations for Structural Equation Modeling (SEM), which typically require between 100 and 500 observations for robust parameter estimation and model testing.

The unit of analysis is the firm. Respondents were senior and middle managers (e.g., operations, supply chain, quality, plant managers) who are expected to possess strategic knowledge and experiential insight into organizational capabilities and performance metrics. Selecting managerial respondents helps ensure the validity of responses regarding organizational practices and strategic orientation. Data collection ran from October 2024 to February 2025. Questionnaires were distributed with direct researcher contact and supervised follow-up to increase response rates and ensure completeness. Where responses were ambiguous or incomplete, the research team contacted respondents for clarification. Participation was voluntary; respondents were briefed on the research objectives and assured of confidentiality before completing the survey.

Hypotheses were tested using Structural Equation Modeling (SEM) with AMOS version 24, which permits simultaneous estimation of measurement and structural models. The analytic sequence comprises: 1) confirmatory factor analysis (CFA) to validate the measurement model and assess construct reliability and validity; 2) evaluation of structural relationships to test direct and indirect effects; and 3) mediation analysis to examine whether Leagility Strategy and Supply Chain Adaptive Program transmit the effects of antecedent constructs to Firm Performance. Model fit will be evaluated using multiple indices: Chi-Square ($\chi 2$), Goodness-of-Fit Index (GFI), Tucker-Lewis Index (TLI), Comparative Fit Index (CFI), and Root Mean Square Error of Approximation (RMSEA). Hypothesis decisions will be based on p-values with a significance threshold of $p \leq 0.05$. For mediation, indirect effects will be tested using bootstrap resampling to obtain bias-corrected confidence intervals, which provide robust inference for mediated paths.

IV. Results and Discussion

A. Results

1) Measurement model evaluation: The measurement model demonstrated strong psychometric properties: all constructs satisfied the thresholds for convergent validity and composite reliability required for SEM analysis (see Table I). Green Supply Chain Integration (GSCI) achieved Composite Reliability (CR) = 0.943 and Average Variance Extracted (AVE) = 0.701, comfortably exceeding the recommended minima ($CR \geq 0.70$; $AVE \geq 0.50$). These values indicate high internal consistency and suggest that the GSCI items collectively account for over 70% of the construct variance, validating the instrument's capacity to measure green integration robustly.

Supply Chain Ambidexterity (SCA) also displayed solid psychometric performance with CR = 0.885 and AVE = 0.607, indicating reliable composite consistency and satisfactory indicator variance explained. This confirms that the ambidexterity dimensions—both exploitation and exploration are effectively captured by the selected indicators. Leagility Strategy (LS) recorded CR = 0.933 and AVE = 0.611; despite a few indicators with comparatively lower loadings, the construct overall maintained excellent reliability and convergent validity, reflecting coherent measurement of flexibility, waste elimination, and strategic planning dimensions.

Sustainability Performance (SP) emerged as the most robust construct, with CR = 0.947 and AVE = 0.666, signaling exceptionally high reliability and a substantial proportion of explained variance across economic, social, and environmental performance indicators. Collectively, all four constructs (GSCI, SCA, LS, SP) meet or exceed the psychometric criteria recommended in the SEM literature (Hair et al., 2019), supporting the adequacy of the measurement model and permitting progression to structural analysis.

TABLE I. MEASUREMENT OF RESEARCH CONSTRUCTS

Latent Variable	Items	Loadings	CR	AVE
GSCI	GII1	0,811	0,943	0,701
	GII2	0,869		
	GII3	0,848		
	GSI2	0,862		
	GSI1	0,84		
	GCI2	0,776		
	GCI1	0,853		
SCA	SCR1	0,893	0,885	0,607
	SCR2	0,761		
	SCR3	0,803		
	SCP1	0,699		
	SCP2	0,726		
LS	FL3	0,664	0,933	0,611
	FL2	0,699		
	FL1	0,792		
	EW3	0,797		
	EW2	0,836		
	EW1	0,764		
	STP3	0,793		
	STP2	0,842		
	STP1	0,826		
SP	SCR1	0,893	0,947	0,666
	SCR2	0,761		
	SCR3	0,803		
	CRV3	0,591		
	CRV1	0,874		
	CRV2	0,868		
	DV1	0,846		
	DV2	0,828		
	DV3	0,84		

Source: Data Research, 2025.

The structural model showed acceptable overall fit (see Fig. 2). The ratio CMIN/DF = 2.061 falls well below the conservative threshold of 3.0, indicating reasonable parsimony. Incremental fit indices were favorable: TLI = 0.919 and CFI = 0.930, both surpassing the commonly accepted cutoff of 0.90 and signaling that the specified model explains the covariances among constructs effectively. Absolute fit measures were mixed but acceptable given model complexity: GFI = 0.810 and AGFI = 0.765 are below ideal values ($\geq$ 0.90) but remain within tolerable bounds for complex models, while RMSEA = 0.077 is within the acceptable range (< 0.08), suggesting a reasonable approximation error. Taken together, these indices indicate that the structural model is tenable and suitable for hypothesis testing.

Standardized path estimates reveal meaningful and statistically significant relationships among constructs. Supply Chain Ambidexterity (SCA) exerted a strong positive influence on Leagility Strategy (LS) with a standardized coefficient of 0.719 ($p < 0.05$), indicating that higher ambidexterity in the supply chain strongly supports the adoption of leagile practices. SCA also contributed directly to Sustainability Performance (SP) with a coefficient of 0.551 ($p < 0.05$), underscoring ambidexterity's substantive role in enhancing environmental, social, and economic outcomes.

Green Supply Chain Integration (GSCI) displayed a significant positive effect on LS ($\beta = 0.478, p < 0.05$) and an even stronger direct effect on SP ($\beta = 0.733, p < 0.05$). These coefficients suggest that green integration not only fosters leagility but also translates directly into higher sustainability performance, reinforcing the primacy of green practices for sustainable outcomes.

Leagility Strategy (LS) showed a positive but modest direct effect on SP ($\beta = 0.029, p < 0.05$). Although numerically smaller than the direct effects of GSCI and SCA, this coefficient indicates that leagility still contributes incrementally to sustainability outcomes when other influences are controlled for.

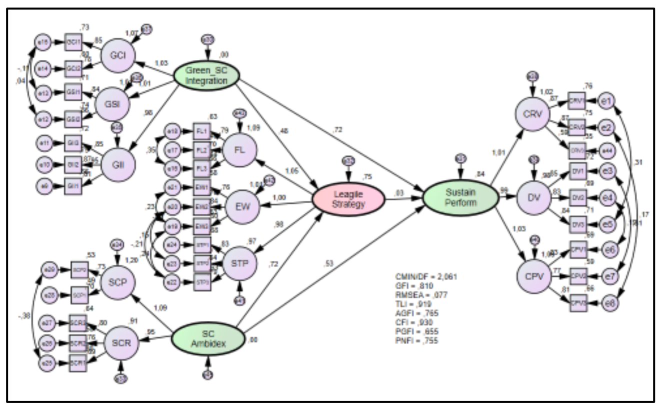

Fig. 2. Structural model testing (Source: Data research, 2025).

Mediation tests clarify how LS functions as a conduit between antecedents (SCA and GSCI) and sustainability outcomes. The estimated indirect effect of SCA on SP via LS was 0.021, while the indirect effect of GSCI on SP via LS was 0.014. Although these mediated effects are relatively small compared with the direct pathways, they are positive and consistent with the theoretical expectation that Leagility amplifies the sustainability returns of both ambidexterity and green integration.

TABLE II. STANDARDIZED INDIRECT EFFECTS

	SCA	GSCI	LS	SP
LS	0,000	0,000	0,000	0,000
SP	0,021	0,014	0,000	0,000

Source: Data Research, 2025.

From the Table II, when combining direct and indirect pathways, total effects demonstrate the overall explanatory power of antecedent constructs on sustainability performance.

SCA's total effect on SP equals 0.551 (direct) + 0.021 (indirect) = 0.572. GSCI's total effect on SP equals 0.733 (direct) + 0.014 (indirect) = 0.747. These totals indicate that GSCI has the more dominant overall influence on sustainability performance in this sample, although SCA remains a substantial and meaningful contributor. LS's total effect on SP (0.029) is largely direct, as its mediating transmissions to SP via other constructs were limited.

The results robustly support the conceptual model: both green supply chain integration and supply chain ambidexterity positively affect firm sustainability, and Leagility functions as a complementary mechanism that further channels these effects—albeit as a secondary amplifier rather than the primary driver. The particularly large total effect of GSCI highlights the importance of integrating environmental practices across procurement, production, and logistics as a leading strategy for improving triple-bottom-line performance. Concurrently, SCA's strong linkage to both LS and SP confirms that the ability to balance exploitation and exploration in a digitally enabled supply chain fosters resilience and sustainable outcomes.

Practical takeaways for managers include prioritizing comprehensive green integration initiatives while simultaneously cultivating ambidextrous capabilities that support leagile configurations. Doing so enables firms to capture both direct sustainability gains and incremental benefits mediated by operational flexibility and waste reduction. From a theoretical standpoint, the findings lend empirical weight to frameworks that link RBV, dynamic capabilities, and leagility with measurable sustainability performance in manufacturing contexts.

B. Discussion

This study provides empirical evidence on the roles of Green Supply Chain, Supply Chain Ambidexterity, and Leagility Strategy AP in elevating Sustainable Performance within the Indonesian manufacturing industry. The findings show that although each construct contributes distinctly, their interaction through mediated pathways significantly reinforces organizational outcomes. Importantly, the results highlight that the value of Green Supply Chain emerges more clearly when it is embedded within agile and adaptive supply chain configurations, suggesting a synergistic effect rather than a standalone driver of performance.

First, Green Supply Chain emerges more clearly when it is embedded within agile and adaptive supply chain configurations identified as a crucial external driver of firm performance, albeit with a limited direct effect. Descriptive results indicate that managers in this sector already practice customer orientation, competitor orientation, and cross-functional coordination as core operational norms, aligning with prior work that links Green Supply Chain to competitive advantage and customer loyalty (Abdulkarim Kanaan-Jebna et al. 2021; Fang et al. 2019; Gligor et al. 2019). Yet, structural tests reveal that Green Supply Chain's impact on performance becomes more pronounced when mediated by Leagility Strategy. This resonates with literature arguing that Green Supply Chain alone may be insufficient to yield superior outcomes, with benefits materializing more fully when Green Supply Chain is integrated with adaptive supply chain and operational strategies [20], [21]. This underscores the need for firms to translate market insights into flexible processes and networks rather than relying on the Green Supply Chain in isolation.

Second, Supply Chain Ambidexterity 4.0 stands out as the most dominant predictor of firm performance. Firms that demonstrate robust process quality management, empowerment, and information use consistently achieve higher operational results. These findings reinforce prior evidence that effective Second, Supply Chain Ambidexterity 4.0 stands out as the most dominant predictor of firm performance. Firms that demonstrate robust process Supply Chain Ambidexterity 4.0, empowerment, and information use consistently achieve higher operational results. These findings reinforce prior evidence that effective Supply Chain Ambidexterity 4.0 drives continuous improvement and operational consistency [22], [23]. Moreover, mediation analyses reveal that Supply Chain Ambidexterity 4.0 significantly influences performance via LS, highlighting its dual role in promoting efficiency and agility. This dual pathway aligns with recent calls for dynamic quality capabilities that support both stable performance and rapid responsiveness in volatile environments [24].

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Third, the study corroborates the central importance of Lean Strategy LS as a mediator. The integration of lean and agile practices enables firms to balance efficiency and responsiveness, a finding consistent with prior research (Virmani & Sharma, 2019). Empirical evidence shows that LS strengthens the indirect effects of Green Supply Chain and Supply Chain Ambidexterity 4.0 on firm performance. In this sense, Leagility functions not only as an operational philosophy but also as a strategic conduit that transforms managerial orientation and Supply Chain Ambidexterity 4.0 into superior sustainability outcomes. This interpretation echoes the argument that hybrid configurations are essential for sustaining performance under environmental and market uncertainty [27].

Finally, performance improves when these constructs are integrated. The evidence suggests gains in growth, financial perspective, and customer performance accrue not only through direct managerial capabilities but also through adaptive and hybrid strategies. This aligns with the broader argument that organizational success depends on the synchronization of internal quality systems and external market orientation with adaptive supply chain practices [28]. The integrated model offers a coherent narrative: green-oriented, ambidextrous, and adaptive supply chain configurations co-create a more resilient and sustainable performance trajectory in a highly volatile manufacturing market.

Theoretically, this study extends established frameworks such as the Market-Based View and Dynamic Capabilities by proposing an integrated Performance Adaptation Capability LAP model. The LAP framework positions LS as a crucial mediators that connect GSC and SCA 4.0 to firm performance, thereby offering both theoretical novelty and actionable implications for managers seeking to enhance competitiveness and sustainability amid market turbulence. By foregrounding the mediating roles of leanness and supply chain adaptability, the study contributes to a more nuanced understanding of how external and internal capabilities combine to drive durable performance in a developing economy.

Policy and managerial implications emerge from these findings as well. For managers in the Indonesian Manufacturing Industry, the emphasis should be on cultivating an integrated, flexible, and responsive supply chain architecture that harmonizes market insights with rigorous quality systems and collaborative supplier networks. Investments in SCA 4.0, coupled with disciplined lean practices and agile responsiveness, appear particularly productive when designed to operate in concert with supplier and customer relationships and transparent information flows. From a scholarly perspective, future research could test the LAP framework across different sectors and regions, or explore longitudinal designs to capture the dynamic evolution of GSC, SCA 4.0, and LS in shaping sustainable performance over time.

V. Conclusion

This study addresses the research objective of explaining how Green Supply Chain (GSC), Supply Chain Ambidexterity 4.0 (SCA 4.0), and leagility strategies interact to enhance firm performance in Indonesia's manufacturing sector under conditions of environmental pressure and market uncertainty. The findings demonstrate that GSC alone has a limited direct effect on firm performance; however, its influence becomes significant when operationalized through leagility strategies, thereby confirming leagility as a critical mediating mechanism. In contrast, SCA 4.0 emerges as the most dominant driver of performance, both directly and indirectly, by enabling firms to balance efficiency and adaptability through lean–agile hybrid practices. These results directly respond to the initial research problem by showing that superior performance is achieved not through isolated green initiatives but through the integration of ambidextrous capabilities and adaptive supply chain configurations. The study extends the Market-Based View, Integrated Value Chain, and Dynamic Capabilities perspectives by proposing the Leagility Adaptation Performance (LAP) model, which provides an integrative explanation of how internal quality systems and external adaptability jointly sustain competitiveness and resilience. Nevertheless, the study is limited by its cross-sectional design and focus on the manufacturing sector. Future research should apply the LAP model to other industries, such as automotive spare parts and services, adopt longitudinal approaches to capture dynamic capability evolution, and incorporate digital transformation and advanced green practices to further strengthen the model's explanatory power.

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