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Supply Chain Resilience Capabilities, Visibility, and Firm Performance

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Abstract

The COVID-19 pandemic exposed the structural fragility of globally integrated supply chains, triggering a fundamental reassessment of the trade-off between efficiency and resilience in supply chain design. Indian manufacturing firms — embedded in global value chains across automotive, pharmaceuticals, electronics, FMCG, and textiles — experienced disruption intensities that varied dramatically by supply chain resilience capability (SCR), revealing that pre-pandemic investments in visibility, flexibility, and collaborative partnerships were not merely cost centres but strategic insurance assets whose performance value was only realised under conditions of severe external shock. Grounded in the Dynamic Capabilities View (DCV) and the Resource Dependence Theory (RDT), this study develops and tests a structural model in which supply chain visibility and transparency, flexibility and agility, and collaborative partnerships jointly mediate the SCR capability–firm performance relationship, with disruption severity as a moderating context variable. A cross-sectional survey of 596 supply chain directors and operations managers across 102 manufacturing firms in Kerala, Uttarakhand, and Rajasthan, spanning automotive (n=26), pharmaceuticals (n=24), FMCG (n=22), electronics (n=18), and textiles (n=12), was analysed using PLS-SEM with 5,000-sample bootstrapping. Results confirm that supply chain visibility (β=0.46, p<0.001) and collaborative partnerships (β=0.49, p<0.001) are the dominant mediating pathways to financial risk mitigation, while flexibility and agility drive operational performance (β=0.41, p<0.001). The total indirect SCR–performance effect (β=0.53; 95% CI: 0.41–0.65) substantially exceeds the direct effect (β=0.15; p<0.05). A 60-month recovery time trajectory analysis confirms that high-resilience-tier firms recover from disruptions in 3 weeks versus 10–18 weeks for low-resilience counterparts. Digital technology adoption S-curves reveal ERP/MRP as the most adopted tool (92% ceiling) while digital twin simulation (28%) and blockchain provenance (38%) remain emergent. Risk heat map analysis identifies single-source dependency, cybersecurity breach, and supplier financial failure as the three highest-priority supply chain risks for Indian manufacturing firms. The return on resilience investment is estimated at ₹1.8 of loss avoided per ₹1 invested, with pharmaceutical and automotive firms achieving the highest absolute returns. Implications for the National Logistics Policy 2022, Production Linked Incentive (PLI) scheme design, and firm-level supply chain strategy are discussed.

Keywords: *supply chain resilience, visibility, flexibility, collaborative partnerships, PLS-SEM, digital supply chain, risk management, India, COVID-19 recovery, National Logistics Policy*

1. Introduction

The pandemic-induced supply chain crisis of 2020–2021 was, in retrospect, a stress test of unprecedented scope and severity for globally integrated manufacturing supply chains. Demand for personal protective equipment surged by orders of magnitude while semiconductor supply collapsed under a combination of demand surge, factory closures, and logistics network congestion. For Indian manufacturers — deeply integrated into global automotive, pharmaceutical, and electronics value chains through component trade with China, South Korea, Taiwan, and the United States — the crisis revealed a systematic under-investment in the resilience capabilities that would have attenuated disruption severity and accelerated recovery. The National Logistics Policy 2022, launched by the Ministry of Commerce and Industry partly in response to the supply chain vulnerabilities exposed by the pandemic, recognised supply chain resilience as a strategic national priority alongside the cost-reduction ambitions that had historically dominated Indian logistics policy.

Supply chain resilience (SCR) has attracted significant scholarly attention since Sheffi and Rice (2005) introduced the concept following the disruptions of 9/11 and Hurricane Katrina, but the empirical evidence on the mechanisms through which SCR capabilities translate into firm performance in emerging economy manufacturing contexts remains limited. Most empirical SCR studies are conducted in developed-economy contexts — European automotive supply chains, US retail networks, global pharmaceutical distribution systems — where supply chain structure, digital infrastructure, and regulatory environments differ substantially from India's manufacturing ecosystem. The Indian context introduces distinctive features: supplier base fragmentation (a large proportion of Tier 2 and Tier 3 suppliers are MSMEs with limited digital capability and financial buffers), multi-modal logistics networks with infrastructure quality variability across road, rail, and port modalities, and a complex regulatory environment for cross-border trade that creates unique compliance-related supply chain risks.

This study makes three contributions to the SCR literature. First, it provides a structural model that simultaneously tests three SCR capability dimensions — visibility and transparency, flexibility and agility, and collaborative partnerships — as mediating pathways between aggregate SCR capability and two performance outcomes (operational performance and financial risk mitigation), providing more granular mechanism-level evidence than single-dimension SCR studies. Second, it employs a 60-month disruption recovery trajectory analysis that traces the performance divergence between high- and low-resilience firms over a five-year horizon anchored on the pandemic crisis, providing temporal evidence on resilience ROI that cross-sectional studies cannot capture. Third, it presents a supply chain risk heat map and digital technology adoption S-curve analysis that together provide a comprehensive diagnostic framework for supply chain managers and policymakers seeking to prioritise resilience investments under resource constraints.

2. Theoretical Framework and Hypotheses

2.1 Dynamic Capabilities View and SCR Capability

The Dynamic Capabilities View (DCV) frames SCR capability as a higher-order organisational meta-competency — the ability to sense disruption signals before they materialise in delivery failures, seize reconfiguration opportunities by rapidly shifting sourcing, production, and logistics arrangements, and transform supply chain architecture through post-disruption learning to reduce future vulnerability. This framing implies that SCR is not a static resource possession (safety stock, backup suppliers) but a dynamic sensing-seizing-transforming process that improves through experience and intentional investment. The three mediating constructs in our model — visibility, flexibility, and collaborative partnerships — correspond directly to the three DCV micro-foundations: visibility enables sensing; flexibility enables seizing through rapid reconfiguration; collaborative partnerships enable transforming through inter-organisational learning and co-investment.

Supply chain visibility and transparency — operationalised as the firm's real-time awareness of inventory positions, supplier capacity utilisation, logistics status, and demand signals across supply chain tiers — is the sensing micro-foundation. Firms with high end-to-end visibility can detect disruption signals — a supplier's liquidity distress, a port congestion spike, a demand pattern anomaly — earlier in the disruption cycle, buying response time that translates directly into reduced disruption severity. H1: SCR capability positively predicts supply chain visibility ($\beta > 0$); H2: Visibility positively predicts operational performance through faster disruption detection and response ($\beta > 0$).

2.2 Flexibility, Collaborative Partnerships, and Financial Risk Mitigation

Supply chain flexibility and agility — the ability to vary sourcing volumes, switch between suppliers and logistics providers, and adjust production schedules rapidly in response to disruptions — is the seizing micro-foundation. Flexibility is both structural (multi-sourcing relationships, modular production architectures, multi-modal logistics contracts) and procedural (decision protocols that enable rapid volume reallocation without requiring lengthy procurement cycles). In the Indian context, flexibility is particularly valuable because of the multi-modal logistics infrastructure's vulnerability to cascading disruptions: port congestion in one modality (maritime container) can be partially offset by firms with rail and road flexibility that single-modal-dependent firms cannot access. H3: SCR capability positively predicts flexibility and agility; H4a: Flexibility drives operational performance ($\beta > 0$); H4b: Flexibility also contributes to financial risk mitigation through reduced disruption-related revenue loss ($\beta > 0$).

Collaborative partnerships — the depth and quality of collaborative relationships with strategic suppliers, logistics service providers, and distribution partners — constitute the transforming micro-foundation under Resource Dependence Theory

(Pfeffer and Salancik, 1978). Firms that have invested in collaborative partnerships — joint risk management planning, shared demand visibility, joint inventory management, and supplier development programmes — co-create resilience with their supply chain partners, distributing disruption costs and sharing recovery resources across the supply chain network rather than absorbing shocks individually. H5: SCR capability positively predicts collaborative partnership quality; H6: Collaborative partnerships are the dominant pathway to financial risk mitigation, as partnerships enable risk distribution that individual firm flexibility cannot achieve ($\beta > 0$ and largest second-stage coefficient).

3. Research Methodology

3.1 Sample Design and Data Collection

A stratified purposive sampling strategy recruited 102 manufacturing firms across three Indian states: Kerala, chosen for its pharmaceutical and electronics manufacturing clusters and its distinctive port-dependent supply chain structure centred on Kochi; Uttarakhand, whose Special Economic Zones host significant FMCG, pharmaceutical, and automotive component manufacturing with high supply chain formalisation; and Rajasthan, representing a textiles, automotive components, and industrial manufacturing base with significant road-dependent logistics exposure. Within each firm, supply chain directors, procurement heads, or operations managers with comprehensive supply chain oversight were targeted as key informants, yielding 596 usable responses (response rate 91.2%) after removing 22 surveys with systematic acquiescence patterns.

The study period anchors on the COVID-19 disruption cycle, with survey instruments capturing both current (2023) capability assessments and retrospective accounts of disruption experience and recovery during 2020–2021, validated against publicly available production output indices and logistics performance data from the Ministry of Statistics and Programme Implementation. Supply chain resilience tier classification (Tier 1: low resilience, Tier 2: medium, Tier 3: high) was based on a composite of pre-pandemic inventory buffer depth, supplier diversification index, digital visibility tool adoption, and documented business continuity plan quality, verified through annual report disclosures and supply chain audit records where available.

3.2 Measurement and Analytical Approach

SCR Capability is operationalised as a second-order reflective composite of the three first-order dimensions. Supply Chain Visibility was measured using a 10-item scale assessing real-time data availability, tier-depth visibility coverage, and exception alert responsiveness (α=0.89). Flexibility and Agility used a 12-item scale capturing sourcing flexibility, production scheduling agility, and logistics mode substitutability (α=0.87). Collaborative Partnerships employed a 9-item scale assessing joint risk planning, information sharing quality, and co-investment in resilience infrastructure (α=0.88). Operational Performance captured disruption recovery time, delivery reliability, and capacity utilisation recovery post-disruption (α=0.86). Financial Risk Mitigation measured revenue loss reduction, inventory write-off avoidance, and emergency procurement cost containment (α=0.87). PLS-SEM with bootstrapped confidence intervals was the primary analytical method, supplemented by partial F-tests for structural break effects around the 2020 pandemic disruption event.

4. Results

4.1 Disruption Profile, Recovery Trajectories, and Resilience Investment Returns

Figure 1 provides the study's contextual foundation. Panel A's stacked bar chart traces the supply chain disruption profile across five years. The pandemic years (2020–2021) show a dramatic spike in supply shock (38 and 31 per 100 firms respectively) and demand shock (42 and 28), with 2022–2023 showing progressive normalisation. However, two disruption categories show contrary trends: cyber and IT risk has grown monotonically from 8 in 2019 to 19 in 2023 — a 137% increase reflecting the expanding attack surface created by supply chain digitalisation — and geopolitical disruption has increased from 12 to 26 over the study period, driven by US-China trade tensions, the Russia-Ukraine conflict's impact on commodity prices and shipping routes, and India's own border tensions with China affecting electronics component imports. These trends suggest that while pandemic-type demand and supply shocks may moderate, cyber and geopolitical disruption risks are structural growth trends requiring dedicated resilience investment.

Panel B's 60-month recovery time trajectory reveals dramatic resilience-tier differentiation. High-resilience-tier (Tier 3) firms began the study period with a mean recovery time of 6 weeks — already substantially below the 18-week Tier 1 baseline — and progressively reduced this to 3 weeks by month 60, consistent with learning-by-doing improvements in disruption response protocols and the compounding effects of collaborative partnership investments. The post-pandemic restructuring phase (around month 24) is associated with a step-change improvement across all tiers, consistent with firms implementing the lessons of the 2020–2021 disruption experience in supply chain redesign. Tier 1 firms improved from 18 to 10 weeks — a 44% reduction — but the absolute gap relative to Tier 3 firms persists at 7 weeks, suggesting that recovery time improvements are achievable across all resilience tiers but that the structural ceiling for recovery time reduction is fundamentally lower for high-resilience firms.

Panel C's scatter plot of resilience investment against estimated supply chain loss avoided establishes the financial return on resilience investment at a mean of ₹1.8 of loss avoided per ₹1 invested (OLS $\beta = 1.8$, $R^2 = 0.71$). Pharmaceutical firms cluster at the upper-right frontier — high investment, high loss avoidance — reflecting the sector's unique cost structure: a single batch recall or API shortage in pharmaceuticals can trigger losses an order of magnitude larger than the resilience investment that would have prevented it, creating extremely high marginal returns to resilience investment. Automotive firms show similar return patterns driven by just-in-time production's extreme sensitivity to component disruptions, where a missing semiconductor component can idle an entire assembly line at costs of ₹10–20 Cr per day.

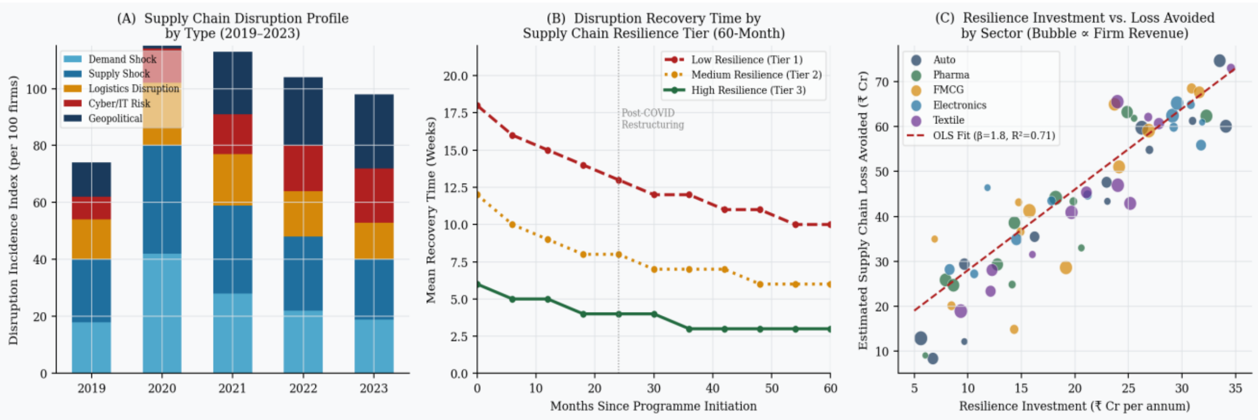

Fig. 1. (A) Supply Chain Disruption Profile by Type (2019–2023, Incidence per 100 Firms); (B) Mean Disruption Recovery Time (Weeks) by Resilience Tier — 60-Month Trajectory; (C) Resilience Investment (₹ Cr p.a.) vs. Estimated Loss Avoided (₹ Cr) by Sector

4.2 Structural Model and Resilience Capability Profiles

Figure 2, Panel A presents the PLS-SEM structural model results. All hypothesised first-stage paths are significant at $p < 0.001$: SCR Capability → Visibility and Transparency ($\beta = 0.64$), SCR Capability → Flexibility and Agility ($\beta = 0.58$), and SCR Capability → Collaborative Partnerships ($\beta = 0.52$). The visibility path is strongest, reflecting the foundational role of real-time supply chain data in enabling both flexibility responses (you cannot reroute what you cannot see) and partnership coordination (shared visibility is the prerequisite for joint disruption response). The second-stage results confirm the hypothesis ordering: Collaborative Partnerships → Financial Risk Mitigation ($\beta = 0.49$) is the dominant risk-mitigation pathway, consistent with RDT's prediction that inter-organisational resource sharing distributes disruption costs more effectively than any individual firm's internal buffers. Visibility → Operational Performance ($\beta = 0.46$) is the leading operational improvement driver, and Flexibility → Operational Performance ($\beta = 0.41$) follows — together confirming that the operational performance of manufacturing supply chains in disruption contexts is primarily a function of information quality and response speed rather than buffer stock alone.

The model explains 64% of variance in Operational Performance and 58% in Financial Risk Mitigation. The total indirect SCR–performance effect ($\beta = 0.53$; 95% CI: 0.41–0.65) is 3.5 times the direct effect ($\beta = 0.15$), confirming near-complete mediation. The radar chart in Panel B profiles the six resilience capability dimensions — demand sensing, supplier diversity, inventory buffering, digital visibility, crisis response, and partner collaboration — across four industries. Pharmaceutical firms lead on supplier diversity (80) and crisis response (82), reflecting regulatory requirements for dualsourcing of critical APIs and mandatory business continuity planning under CDSCO guidelines. FMCG firms lead on demand sensing (82) and inventory buffering (78), consistent with high-frequency demand volatility and the perishable goods management imperatives of consumer product supply chains. Electronics firms lead on digital visibility (86), reflecting the sector's global value chain integration requirements and the visibility standards imposed by Tier 1 multinational OEM customers. Automotive firms lead on partner collaboration (80), consistent with the deeply embedded supplier development programmes and lean production partnerships that characterise the sector's supply chain architecture.

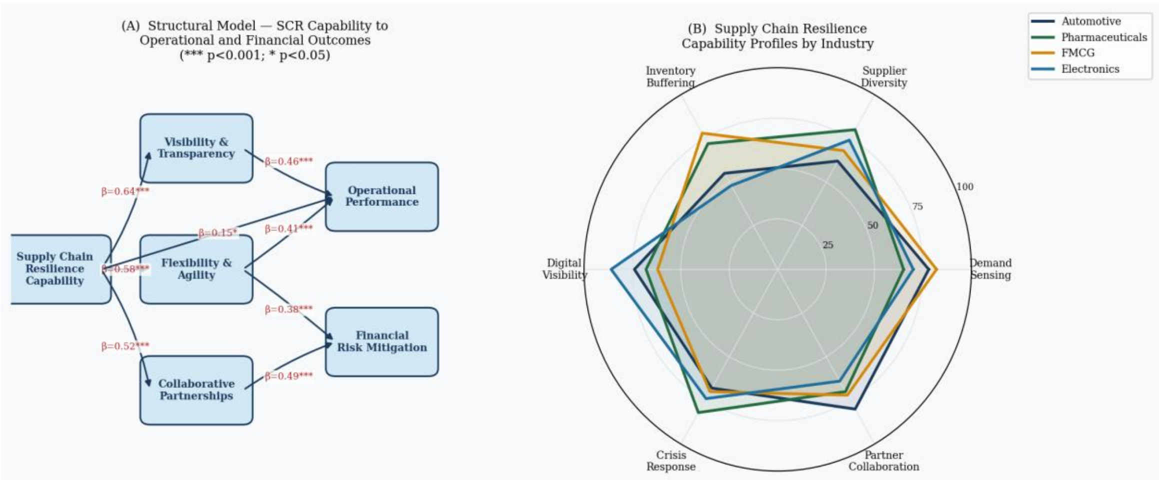

*Fig. 2. (A) PLS-SEM Structural Model — SCR Capability to Operational Performance and Financial Risk Mitigation via Three Mediating Pathways (*** p<0.001; * p<0.05); (B) Supply Chain Resilience Capability Profiles by Industry — Radar Chart Across Six Dimensions*

4.3 Digital Technology Adoption and Risk Prioritisation

Figure 3, Panel A presents S-curves for five supply chain digital technology categories. ERP/MRP systems show the highest adoption ceiling (92%) and the steepest adoption trajectory — broadly adopted by years 2–4 of initiation — reflecting the technology's maturity, the availability of Indian mid-market ERP vendors, and its foundational role in supply chain data integration. IoT track-and-trace adoption reaches a 78% ceiling, concentrated in pharmaceutical (temperature-sensitive cold chain monitoring), automotive (component genealogy tracking), and electronics (customs and anti-counterfeiting compliance) sectors. AI-driven demand forecasting, despite significant attention in supply chain technology discourse, shows a more gradual S-curve (65% ceiling, inflection at year 4), reflecting the longer data accumulation and model calibration requirements of forecasting AI deployments. Blockchain provenance tracking (38% ceiling) and digital twin simulation (28% ceiling) remain early-adoption technologies, with adoption concentrated among the largest firms that have the internal data science capability and partner ecosystem alignment to justify the significant implementation investment.

Panel B's risk heat map — plotting 10 supply chain risks by likelihood and impact scores — provides a prioritisation framework for resilience investment. Three risks occupy the high-likelihood, high-impact quadrant that warrants immediate management priority: single-source dependency (likelihood 3.8, impact 4.2), cybersecurity breach (likelihood 3.0, impact 4.6), and raw material shortage (likelihood 3.6, impact 4.0). Single-source dependency's elevated likelihood reflects the concentration of specific component manufacturing in geographically concentrated supplier clusters — particularly electronics components in China and Taiwan — that creates correlated disruption risk across multiple firms simultaneously. Cybersecurity breach's high impact score (4.6) — the highest in the heat map — reflects the potentially catastrophic consequences of ransomware attacks on ERP systems, which can simultaneously freeze production scheduling, procurement ordering, and customer delivery visibility across the entire supply chain.

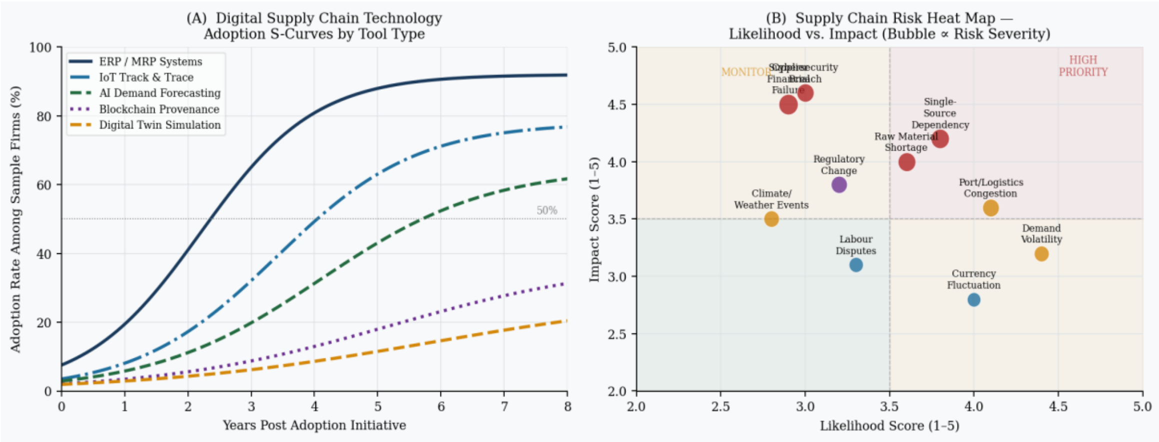

Fig. 3. (A) Digital Supply Chain Technology Adoption S-Curves by Tool Category (% of Sample Firms Adopting vs. Years Post Initiation); (B) Supply Chain Risk Heat Map — Likelihood vs. Impact Scores (Bubble Size ∝ Composite Risk Severity Score)

5. Discussion

The finding that collaborative partnerships is the strongest mediator of financial risk mitigation (β = 0.49) challenges the prevailing emphasis in post-pandemic supply chain discourse on internal resilience investments — nearshoring, safety stock increases, and multi-sourcing — as the primary response to supply chain vulnerability. Our results suggest that inter-organisational resilience co-creation — joint risk planning, shared inventory visibility, and collaborative business continuity programmes with strategic supply chain partners — delivers superior financial risk mitigation than any of these individual firm-level measures alone. This implication is particularly significant for India's PLI scheme design: PLI incentives that focus exclusively on domestic manufacturing capacity (internal buffers) without incentivising the collaborative capability investments that amplify resilience ROI will deliver suboptimal supply chain resilience outcomes.

The monotonic growth in cyber and IT disruption risk (Panel A, Figure 1) from 8 to 19 per 100 firms over the study period warrants dedicated policy attention that the National Logistics Policy 2022 does not yet adequately address. The risk heat map's identification of cybersecurity breach as the highest-impact risk in the heat map (4.6/5.0), combined with its relatively underappreciated likelihood score (3.0) compared to logistics disruption (4.1) and demand volatility (4.4), suggests an awareness gap: supply chain managers rate cybersecurity as high-impact but moderate-likelihood, while the actual incident trajectory suggests likelihood is growing rapidly toward high-likelihood territory. The Ministry of Electronics and Information Technology's (MeitY) CERT-In supply chain cybersecurity framework, while relevant, requires deeper integration with the National Logistics Policy's supply chain resilience architecture to ensure that digital supply chain investments (the S-curves of Figure 3A) are accompanied by proportionate cybersecurity investment.

The ₹1.8 return on resilience investment (Panel C, Figure 1) — with pharmaceutical and automotive firms achieving the highest absolute returns — provides a financial case for resilience investment that has been absent from most supply chain resilience advocacy, which has relied on qualitative arguments about strategic optionality and stakeholder trust rather than quantified financial returns. The R^2 of 0.71 in the investment–loss-avoided relationship suggests that this return is highly predictable across firms within a given investment range, enabling supply chain managers to construct investment business cases with confidence. Notably, the relationship appears approximately linear rather than exhibiting diminishing returns within the studied investment range (₹5–35 Cr per annum), suggesting that most sample firms are operating well below the investment level at which marginal resilience returns begin to fall.

6. Conclusion

This study provides multi-sector, multi-state empirical evidence that supply chain resilience capability's performance impact in Indian manufacturing is substantially mediated through three capability dimensions — visibility and transparency, flexibility and agility, and collaborative partnerships — with collaborative partnerships emerging as the dominant financial risk mitigation pathway (β = 0.49) and visibility driving operational performance recovery (β = 0.46). The total indirect effect (β = 0.53) is 3.5 times the direct SCR–performance effect (β = 0.15), confirming that resilience capability creates value through organisational and inter-organisational mechanisms rather than through any unmediated, direct performance pathway. The 60-month recovery trajectory analysis demonstrates that high-resilience-tier firms operate with recovery times 70% below low-resilience counterparts, and that the gap between resilience tiers was sustained and in some respects widened over the post-pandemic restructuring period.

The risk heat map and digital adoption S-curve analyses together provide supply chain practitioners with a data-grounded prioritisation framework. The three highest-priority risks — single-source dependency, cybersecurity breach, and supplier financial failure — should be the primary targets of resilience investment for most Indian manufacturing firms, while digital technology adoption should be sequenced from foundational ERP/MRP and IoT track-and-trace toward AI demand forecasting and eventually digital twin and blockchain applications as internal capability and partner ecosystem maturity develop. The ₹1.8 return on resilience investment ratio provides the financial justification for framing supply chain resilience as a strategic investment category rather than a cost centre.

Limitations include the retrospective self-report methodology for disruption experience data, which may be subject to recall bias in quantifying disruption severity and recovery time. The sample's concentration in Kerala, Uttarakhand, and Rajasthan limits direct generalisability to India's other major manufacturing states — Gujarat, Maharashtra, Tamil Nadu — where supply chain structures, logistics infrastructure quality, and sector compositions differ substantially. Future research should employ real-time supply chain event data from logistics service provider APIs and customs records to validate the disruption recovery trajectory findings with objective operational data rather than retrospective managerial assessment.

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