

Digital Technology Adoption, Sustainability Maturity and Supply Chain Resilience in Chemical Manufacturing: A Mixed-Methods Study from Western India

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Abstract

Chemical manufacturers in Western India are being asked to digitise, report on sustainability and stay operational through supply disruptions at the same time, yet firm-level evidence on how these demands interact is thin. This study tests a model in which digital technology adoption (DTA) improves environmental, social and economic performance, sustainable supply chain management (SSCM) maturity strengthens the environmental pathway, and the three performance dimensions in turn support supply chain resilience. A sequential exploratory mixed-methods design was followed. Interviews with managers in supply chain, plant operations, quality, sustainability and IT, together with a plant field visit, informed a six-construct survey of 42 items analysed by PLS-SEM. All constructs met reliability and convergent validity thresholds (Cronbach's α 0.856 to 0.893; AVE 0.571 to 0.612), and all nine structural paths were supported. DTA had its largest effect on environmental performance ($\beta = 0.61$) and was associated with fewer safety incidents ($\beta = -0.49$). The SSCM $\times$ DTA interaction was positive ($\beta = 0.28$, $p = 0.002$), and economic performance showed the strongest link to resilience ($\beta = 0.57$). The interviews indicated that regulation drives adoption, that technology is often bought before it is tied to sustainability goals, and that small firms trail large firms in maturity. The results are translated into a five-stage maturity roadmap. The evidence is cross-sectional, partly self-reported and drawn from one region.

Index Terms: chemical manufacturing, digital transformation, India, PLS-SEM, supply chain resilience, sustainable supply chain management

I. INTRODUCTION

A chemical plant has little room for error. A hazardous consignment that arrives late, a batch record that cannot be found or an effluent reading that was never logged can each become a regulatory problem, and some become safety events. Supply chains in this sector are therefore judged on more than cost and delivery speed. They are expected to stay safe, traceable and compliant while absorbing shocks, which is close to what the literature describes as resilience [1], [2].

Industry 4.0 technologies are widely presented as the means to that end [3], [4]. Sensors can feed emissions and safety monitoring, analytics can support reporting, and distributed ledgers can in principle record the movement of hazardous material. The difficulty is that technology does not deliver these benefits by being installed. Digitalisation in sustainability-sensitive settings carries its own risks [5], and capabilities such

as blockchain depend on suppliers and regulators being ready to take part [6]. Practitioners we interviewed described a common sequence: a system is bought for operational efficiency, and environmental or social indicators are attached later, if at all.

The question is sharper in Western India. Maharashtra's chemical clusters hold large listed groups alongside many small and medium enterprises (SMEs), and the two face quite different constraints. Reporting expectations such as India's Business Responsibility and Sustainability Reporting (BRSR) framework have raised the volume of environmental, social and governance (ESG) evidence that larger firms must produce, which pushes data quality up the management agenda. Empirical work that connects digital adoption, sustainability practice and resilience in this setting is scarce. We identify five gaps: limited attention to the chemical sector, to emerging economies, to SMEs, to tested (rather than conceptual) models, and to guidance that tells a firm what to do first.

This paper addresses four research questions. RQ1: to what extent does DTA improve environmental, social and economic performance? RQ2: does SSCM maturity change the strength of the DTA–environment relationship? RQ3: how are the three performance dimensions related to supply chain resilience? RQ4: what drivers and barriers do firms of different size report, and can the findings be organised into a staged path?

The contribution is threefold. First, we test an integrated model that links DTA, SSCM maturity, three performance dimensions and resilience in one structural specification. Second, we provide evidence on interaction: the same technology yields more environmental benefit where sustainability routines already exist. Third, we convert the quantitative and field evidence into a five-stage roadmap that managers and cluster-level policymakers can use. Section II develops the hypotheses, Section III describes the method, Sections IV and V report qualitative and quantitative findings, and Sections VI to VIII discuss implications, limits and conclusions.

II. BACKGROUND AND HYPOTHESES

A. Sustainability management in process industries

The triple bottom line asks firms to account for environmental, social and economic outcomes together [7]. The natural-resource-based view adds that capabilities in pollution prevention and product stewardship can become hard-to-copy sources of advantage [8]. Sustainable supply chain management extends those ideas across organisational boundaries, covering supplier selection, collaboration and the coordination of material, information and capital flows [9], [10]. Chemical manufacturing has a long engineering tradition of designing hazards out of a process, as seen in the green chemistry principles [11] and in inherently safer design [12]. Customers are also asking suppliers for emissions data more often [13]. In this study, SSCM maturity refers to how fully a firm has built the routines behind these ideas, such as targets, monitoring, supplier engagement and escalation.

B. Technology adoption and its context

The technology–organisation–environment framework [14] and diffusion of innovations theory [15] both hold that adoption depends on more than the technology: organisational resources, external pressure and perceived complexity all matter. Institutional theory explains why external pressure matters. Coercive pressure from regulators, and normative pressure from customers and professional bodies, can lead firms to adopt practices to secure legitimacy [16], and empirical work on green supply chain practices supports this reading [17]. For chemical firms, regulation is therefore expected to act both as a driver of adoption and as a reason for adopted systems to produce audit-ready data.

C. Hypotheses

Continuous measurement allows deviations in emissions, effluent and energy use to be detected earlier, and we expect this to improve environmental performance (EP) and green logistics efficiency (GLE). Digital records and monitoring of process parameters should support safer operation, so social performance (SP) is expected to improve and safety incidents (SI) to fall. Reduced waste, rework and compliance cost should improve economic performance (EcP). We therefore state:

H1a: DTA is positively related to EP. H1b: DTA is positively related to GLE. H3a: DTA is positively related to SP. H3b: DTA is negatively related to SI. H4: DTA is positively related to EcP.

Data alone changes little if nobody acts on it. Firms with mature SSCM routines have the targets, owners and supplier channels through which monitoring data becomes corrective action. This leads to a moderation hypothesis, which we write in regression form as

$$EP = \beta_0 + \beta_1 DTA + \beta_2 SSCM + \beta_3 (DTA \times SSCM) + \varepsilon \quad (1)$$

and hypothesise H2: the interaction coefficient β_3 is positive.

Resilience concerns the capacity to prepare for, respond to and recover from disruption [1]. A firm that controls its emissions, protects its people and keeps its finances healthy is better placed on each of those counts. We expect H5a, H5b and H5c: EP, SP and EcP are each positively related to supply chain resilience (SCR). Fig. 1 summarises the model.

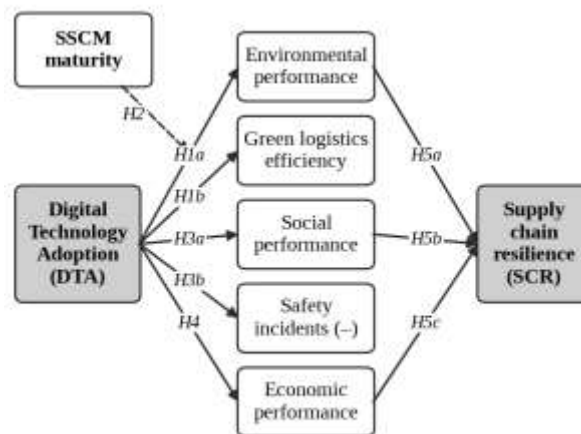


Fig. 1. Conceptual model. Solid arrows are direct hypotheses; the dashed arrow is the moderating effect of SSCM maturity on the DTA → EP path.

III. RESEARCH METHOD

A. Design

A pragmatist stance was adopted because the problem needs both interpretive depth and statistical testing. We used a sequential exploratory mixed-methods design [18]: qualitative work came first so that constructs and item wording would reflect plant vocabulary, and the survey followed to test the resulting model.

B. Qualitative phase

Semi-structured interviews were held with senior personnel in supply chain, plant operations, sustainability, quality and IT. The guide covered the digital transformation journey, ESG linkages, management of regulatory data, traceability of hazardous material and readiness of the wider ecosystem. Transcripts were analysed thematically following the familiarisation, coding, theme generation, review

and write-up sequence described by Braun and Clarke [19]. One chemical manufacturing facility in Western Maharashtra was also visited. The observations were coded against the survey constructs rather than kept as loose notes. Participation was voluntary and informed, and firms are anonymised.

C. Instrument and measures

Six constructs were measured with multi-item Likert-scale questions adapted from established scales and reworded in managerial language, so that, for example, IoT, SAP integration and safety monitoring were described in terms of processes respondents actually run. Environmental items covered emissions, water, waste and compliance deviations. Social items covered safety, near-miss learning, community and sourcing practices. Resilience items covered disruption response and restoration. Table I lists the constructs and item counts. Respondents were managers familiar with supply chain, operations, digital systems, sustainability or compliance, and the sample deliberately included both SMEs and large firms from Western Maharashtra and related industrial clusters. The final usable sample comprised $n = [\text{insert } n]$ responses.

D. Analysis

Partial least squares structural equation modelling (PLS-SEM) was chosen because the aim is prediction-oriented and the model has several latent constructs and one interaction, a setting for which the method is commonly recommended [20]. The measurement model was evaluated with Cronbach's α and composite reliability (CR), both against a 0.70 threshold, average variance extracted (AVE) against 0.50, indicator loadings, and discriminant validity from inter-construct correlations compared with the square root of AVE. Common method bias was checked with standard diagnostics. Path significance was assessed by bootstrapping. Because standard errors are reported, we also give approximate 95% intervals as $\beta \pm 1.96$ SE, which are normal-theory approximations and not percentile bootstrap intervals.

IV. QUALITATIVE FINDINGS

A. Participants and coding

Each function saw digital transformation differently. Operations talked about continuity, quality about process discipline, IT about integration and sustainability about measurable outcomes. Coding also showed that a single practice could carry several meanings at once. A worksheet, for example, was described as a pragmatic control point, a compliance risk, a data-quality constraint and a stage on the way to automation. This ambiguity shaped the maturity model in Section VI.

B. Five themes

Regulation drives adoption. Managers linked digital projects to audit readiness, emissions evidence and incident prevention more often than to productivity. This fits the institutional account in Section II-B and suggests regulatory scrutiny may also moderate how much value firms extract.

Technology first, sustainability later. ERP, warehouse management and dashboard investments were typically justified by efficiency. Environmental and social indicators were added afterwards or handled separately, so data existed but was not reused for sustainability, resilience or reporting decisions. We call this the untapped-synergy problem.

Uneven maturity. As Fig. 2 shows, 73% of SMEs sit at Stage 1 or 2 of the maturity scale used in this study (Section VI-B), against 34% of large firms. Two-thirds of large firms (66%) are at Stage 3 or above, compared with 27% of SMEs, and 31% of large firms have reached Stage 4 or 5 against 9% of SMEs.

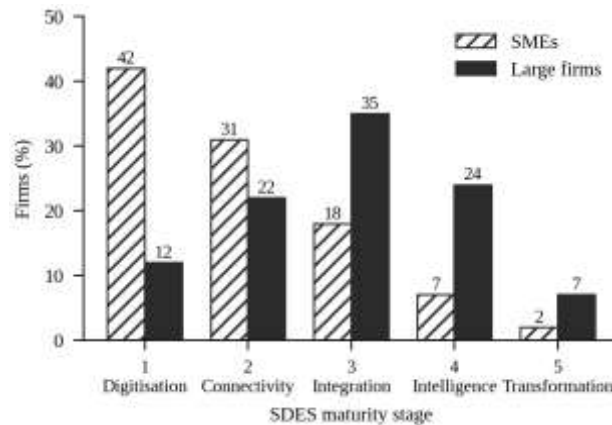


Fig. 2. Distribution of firms across SDES maturity stages by firm size (percentage of firms in each size group).

Barriers differ by size. Small firms reported cost, skills and infrastructure as the binding limits, with the gap to large firms widest for financial constraints and IT infrastructure. Large firms pointed instead to legacy integration, resistance to change and enterprise-wide governance. Both groups rated regulatory complexity, skill shortage and data silos as obstacles, but at lower severity among large firms.

Traceability is early. Large firms recognised the relevance of immutable records for hazardous material and export assurance, but deployment was limited by cost and by how many suppliers were ready to participate. Traceability has to be built from reliable capture and integration first.

C. Field visit

At the visited facility, material inflow and outflow, quality assurance and human safety routines were well established. Transactions were entered in SAP, but IoT use was limited, sustainability data was kept in worksheets, and operations were seen as vulnerable during natural calamities. Mapped to the constructs, this describes a plant with transactional digitisation in place and with continuous monitoring and data integration still to come. It also suggests that water, electricity and waste data could be analysed far more finely than the worksheets currently allow.

V. QUANTITATIVE RESULTS

A. Measurement model

Table I shows that every construct clears the conventional thresholds. Cronbach's α ranges from 0.856 to 0.893 and CR from 0.886 to 0.913. AVE ranges from 0.571 to 0.612, so each construct explains more than half the variance of its indicators, and loadings lie between 0.71 and 0.84. The square root of AVE falls between 0.756 and 0.782 for all constructs, and the inter-construct correlations supported the view that the constructs are related but distinct. Common method bias diagnostics did not point to a serious problem.

**TABLE I
MEASUREMENT MODEL RELIABILITY AND VALIDITY**

Construct	Items	α	CR	AVE	$\sqrt{\text{AVE}}$	Loadings
Digital technology adoption	8	0.882	0.903	0.571	0.756	0.72–0.81
SSCM maturity	10	0.891	0.912	0.584	0.764	0.74–0.83

Construct	Items	α	CR	AVE	$\sqrt{\text{AVE}}$	Loadings
Environmental performance	6	0.874	0.899	0.599	0.774	0.73–0.82
Social performance	6	0.861	0.893	0.587	0.766	0.71–0.80
Economic performance	5	0.856	0.886	0.612	0.782	0.74–0.82
Supply chain resilience	7	0.893	0.913	0.602	0.776	0.75–0.84

CR: composite reliability; AVE: average variance extracted. $\sqrt{\text{AVE}}$ is computed from the reported AVE.

B. Structural model

Table II and Fig. 3 give the structural results. All nine hypothesised paths were supported. DTA had its largest effect on environmental performance ($\beta = 0.61$, $t = 8.59$), ahead of its effects on green logistics efficiency (0.54), social performance (0.54) and economic performance (0.48). The path to safety incidents was negative ($\beta = -0.49$, $t = 5.98$), which is the desired direction. The interaction in (1) was positive and smaller than the main effect ($\beta = 0.28$, $SE = 0.091$, $t = 3.08$, $p = 0.002$), supporting H2. Its interval is the widest in the model and its lower bound lies close to 0.10, so the moderation effect is real but modest and should be treated with caution.

TABLE II
STRUCTURAL MODEL RESULTS

Hyp.	Path	β	SE	t	95% CI
H1a	DTA $\rightarrow$ EP	0.61	0.071	8.59	[0.47, 0.75]
H1b	DTA $\rightarrow$ GLE	0.54	0.068	7.94	[0.41, 0.67]
H2	SSCM $\times$ DTA $\rightarrow$ EP	0.28	0.091	3.08	[0.10, 0.46]
H3a	DTA $\rightarrow$ SP	0.54	0.073	7.40	[0.40, 0.68]
H3b	DTA $\rightarrow$ SI	-0.49	0.082	5.98	[-0.65, -0.33]
H4	DTA $\rightarrow$ EcP	0.48	0.074	6.49	[0.33, 0.63]
H5a	EP $\rightarrow$ SCR	0.52	0.081	6.42	[0.36, 0.68]
H5b	SP $\rightarrow$ SCR	0.44	0.084	5.24	[0.28, 0.60]
H5c	EcP $\rightarrow$ SCR	0.57	0.077	7.40	[0.42, 0.72]

EP: environmental; GLE: green logistics efficiency; SP: social; SI: safety incidents; EcP: economic; SCR: resilience. All paths significant at $p < 0.001$ except H2 ($p = 0.002$). $CI = \beta \pm 1.96 SE$ (normal approximation).

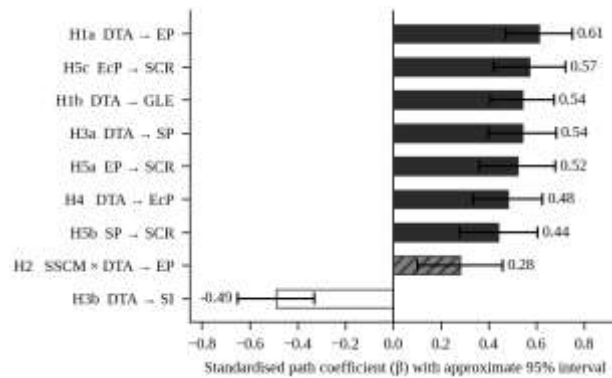


Fig. 3. Standardised path coefficients with approximate 95% intervals. The hatched bar is the SSCM moderation effect.

Among the resilience paths, economic performance had the largest coefficient (0.57), then environmental (0.52) and social performance (0.44). The three intervals overlap substantially, so we do not claim that one dimension matters more than another for resilience. The same caution applies to the ordering of the DTA effects, where the interval for environmental performance overlaps those for social and economic performance.

C. Perceived performance change

Respondents also compared performance before and after digital transformation (Fig. 4). The mean perceived reduction was 31.3% across the four environmental indicators, 38.3% across the four social indicators and 34.3% across the four economic and supply chain indicators. The largest reductions were in near-miss events (45%), safety incidents (42%), lead time (40%) and effluent deviation (39%), and the smallest were in energy intensity (26%) and GHG intensity (28%). These are perceptions and not audited figures. Even so, the pattern is informative: the improvements are concentrated in indicators that depend on detecting a deviation quickly and acting on it, which matches what interviewees said digital tools were for.

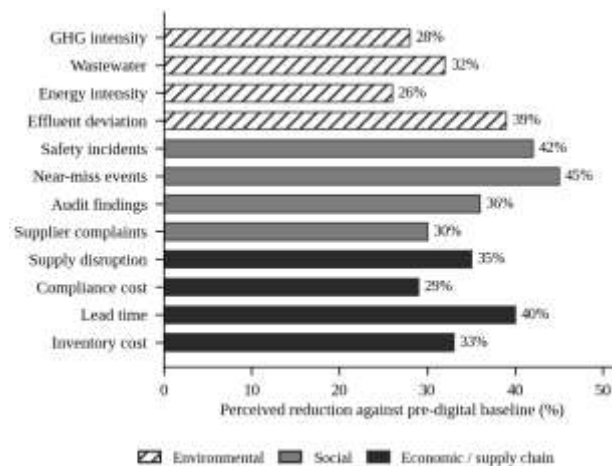


Fig. 4. Perceived reduction in operational indicators after digital transformation (baseline = 0%). Self-reported.

VI. DISCUSSION

A. Interpretation

Three points stand out. The first is the dominance of the environmental pathway. Emissions, effluent and

utility use are measured continuously in principle, so a sensor or an integrated meter changes what managers can see within a shift. That is a plausible reason for the larger coefficient, though the overlapping intervals mean the claim is one of tendency.

The second is the interaction. A positive β_3 agrees with the interview theme that technology and sustainability are often managed apart. Where SSCM routines exist, monitoring data meets a target and an owner. Where they do not, it is stored. For firms, the practical reading is that the return on a sensor network depends partly on decisions made before it is bought.

The third is the link from economic performance to resilience. Financial strength may fund contingency stock, alternative suppliers and recovery capacity, which would explain the result. The reverse is also possible, because resilient firms may simply perform better economically. The cross-sectional design cannot separate the two directions, and the same applies to every path in the model.

B. A staged roadmap

The uneven maturity profile in Fig. 2 argues against a single transformation agenda. Table III sets out the five-stage SDES roadmap derived from the findings. Stages are cumulative: reliable records come before connected sensors, which come before integration, and so on. Placing blockchain-based traceability at Stage 5 follows the interview evidence that distributed records add value only after data capture, integration and supplier participation are in place. Stage 5 also connects to circular-economy aims [21].

TABLE III
SDES FIVE-STAGE MATURITY ROADMAP

Stage	Digital priority	Management outcome
1 Digitisation	Digital records, basic ERP, safety checklists	Less paper; usable data
2 Connectivity	IoT sensors, SCADA links, environmental meters	Earlier deviation detection
3 Integration	ERP–LIMS–WMS integration, ESG data feeds	Integrated BRSR and audit trail
4 Intelligence	AI/ML, predictive maintenance, digital twins	Fewer incidents, less waste and downtime
5 Transformation	Blockchain, product passports, ecosystem platforms	End-to-end transparency; circularity

Derived from the qualitative and quantitative findings of this study.

C. Implications

For managers. Run a digital-sustainability maturity audit before choosing technology, and ask which capability gap carries the greatest operational, compliance or sustainability risk. Connect SAP entries, worksheets, sensor feeds and dashboards to a short list of water, electricity, waste, safety and audit indicators so that they stop being separate administrative activities.

For policymakers and industry associations. Cluster-level support looks well suited to SMEs: shared digital infrastructure, common reporting templates and practical training attack the cost, skills and infrastructure barriers directly. Regulators could also recognise credible digital audit trails and encourage interoperability standards, which would reduce duplicated effort and reward investment in reliable data.

VII. LIMITATIONS AND FUTURE WORK

Several limits apply. The design is cross-sectional, so the paths describe association consistent with theory

and do not prove causation. The sample comes from Western India and may not transfer to other clusters. Performance change is self-reported and should be checked against plant records. Blockchain and digital twins are still rare in the sample, so technology-specific effects for them could not be tested, and they are treated as stage-level capabilities. Finally, the intervals reported here are approximations from the standard errors.

Future work should follow firms across maturity stages over time to see whether digital and sustainability capabilities reinforce each other cumulatively. Comparisons with chemical clusters in other emerging economies, studies of supplier-level readiness, and maturity-assessment tools built on operational process data in place of survey responses would each extend the evidence.

VIII. CONCLUSION

In a mixed-methods study of chemical manufacturers in Western India, digital technology adoption was positively associated with environmental, social and economic performance and with fewer safety incidents, and each performance dimension was positively associated with supply chain resilience. SSCM maturity amplified the environmental benefit of digital adoption, though modestly. Interviews and a plant visit showed why: many firms have digitised transactions without yet connecting the data to sustainability decisions, and small firms are far earlier on the path than large ones. For firms and policymakers, the evidence points to building the sustainability routines and data foundations alongside the technology, and to climbing the maturity stages in order.

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