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## DIGITAL–GREEN TRANSFORMATION IN MANUFACTURING MSMEs IN TAMIL NADU: IMPLICATIONS FOR SUSTAINABLE PERFORMANCE

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### ABSTRACT

**Purpose:** The research examines the mediation role of digital transformation in the adoption of green manufacturing practices and introduction of sustainable performance in micro, small, and medium enterprises (MSMEs) manufacturing in Tamil Nadu in India. There are more than 3.5 million registered MSMEs in Tamil Nadu (textiles, automotive parts, leather products and precision engineering) with a total contribution of about 8% to the Gross State Domestic Product (GSDP) of the state and more than 25 million employments. Although with this industrial role, the opportunities of Industry 4.0 technologies to boost MSME competitiveness and environmental performance in the same direction have not been properly investigated in the context of the regional emerging-economy. **Methodology:** A PRISMA-based systematic literature review (SLR) was undertaken in four large databases (Scopus, Web of Science, ScienceDirect, and Google Scholar) that included peer-reviewed articles to support the years 2015 to 2024. After screening had taken place according to a four-step process, a final corpus of 33 studies underwent thematic analysis.

**Findings:** The following three mutually reinforcing themes were found: (1) Industry 4.0 technologies as the sources of manufacturing transformation; (2) digital technologies as structural enablers of green manufacturing, through real-time monitoring, predictive optimisation and integration of the cycle economy; and (3) sustainable outcomes in performance measured by the triple-bottom-line (TBL) framework. An imagined framework of Digital-Green Transformation (DGT) and five propositions of research that can be tested is created. The main challenges to adoption are financial constraints, the complexity of technology and lack of digital skills.

**Originality / Value:** The paper is the first attempt at combining Industry 4.0, green manufacturing, and TBL performance in the context of a particular institutional and industrial setting, i.e., in Tamil Nadu manufacturing MSMEs. The research propositions and DGT framework promote the context-heavy viewpoint of sustainability transition theory in emerging economy manufacturing and furnish contextually appropriate policy production straight to regional policy makers, managers of MSME, and furnish technology suppliers. The results of the study are explicitly mapped to the UN Sustainable



Development Goals 8, 9, 12, 13, and 17.

**KEYWORDS:** Digital transformation, green manufacturing, MSMEs, Industry 4.0, Sustainable performance

## INTRODUCTION

Industry 4.0 is the fourth industrial revolution but it had radically reformed the structure of modern manufacturing. The Internet of Things (IoT), cyber-physical systems (CPS), big data analytics, cloud computing, and sophisticated automation into production processes allow Industry 4.0 to develop intelligent, self-optimising and interconnected manufacturing systems that feature real time communication, autonomous decision rules, and never-before-seen flexibility of operation (Frank et al., 2019; Liao et al., 2017). These potentials present transformative opportunities not to merely large-scale industrial businesses but, importantly, to the micro, small, and medium enterprises (MSME) that are the meat and potatoes of the manufacturing sector of emerging economies.

At the same time, environmental sustainability has been transformed into a fringe corporate responsibility issue to an industry imperative. The combination of mounting regulatory pressure, scarcity of resources, risks associated with climate in the operation of the company and a change in the expectations of the stakeholders is forcing manufacturers of all sizes to entrench the concept of environmental performance in their strategic and operational levels (Morelli, 2011). The conceptual architecture found in the key to be the triple-bottom-line conceptual framework that operationalises sustainability as the balanced fulfillment of the economic, environmental, and social performance as the concept of sustainable manufacturing performance evaluation and reporting has become dominant (Elkington, 1998; Norman and MacDonald, 2004). The ability to achieve both competitive performance and environmental friendliness at the same time is becoming known as a long-term source of industrial advantage (Ghobakhloo, 2020).

MSMEs in India are the main drivers of the national industrial environment with about 30 percent and 48 percent of GDP, more than 110 million jobs and export rates respectively (Deloitte, 2025). India The second-largest manufacturing state, Tamil Nadu, has more than 3.5 million registered MSMEs in major industries: precision engineering in Coimbatore (almost 30,000 units), knitwear in Tiruppur (exports worth more than 32,000 crores every year), automotive components in Chennai, and leather goods in the Ambur-Ranipet cluster (approximately 400,000 workers) (Government of Tamil Nadu, 2024; MSME Included is the MSME segment within the state, which has been key in driving industrialization in the region as it stands at about 8 per cent of GSDP and it provides above 25 million people with employment (Kinara Capital, 2024).



Although manufacturing MSMEs in Tamil Nadu operate in a central location economically, they are still structurally barred to adoption of Industry 4.0. The lack of access to capital and technical skills and poor digital infrastructure all hamper adoption among a micro-enterprise-based segment with a thin margin and low in-house innovation capacity (Moeuf et al., 2018; Horváth and Szabo, 2019). The presence of these barriers is especially relevant considering that the intersection of the digital transformation and green manufacturing the so-called nexus digital-green is one of the biggest sources of competitiveness and increased sustainability of MSMEs in the next decade (Kamble et al., 2018). However, the available academic literature is largely based in the context of large companies and developed economies, and the digital green relationship at the MSME level in the regionally situated industrial sectors of developing nations is relatively slim (Moeuf et al., 2018). This is a material knowledge gap, considering that in most developing economies, MSMEs are the largest contributor to world businesses of more than 90 percent and the main source of employment and industrial output. None of the past systematic reviews has combined Industry 4.0 adoption, green manufacturing practices, and triple-bottom-line performance in the region of an actual emerging economy, MSME segment of the industrial ecosystem. The gap of this paper is straight to the point.

The paper has four particular contributions: (1) it synthesises 33 scholarly studies on the subject to build one of the most comprehensive evidence bases about the digitalgreen nexus among MSMEs; (2) it suggests one of the transformative concepts Digitalgreen Transformation (DGT) framework related to Industry 4.0 technologies and TBL performance through the mediating role of the green manufacturing practices; (3) it derives five empirically testable research propositions based on the framework and contributes to the global sustainability agenda as claimed by UN SDGs 8, 9, All the rest of the paper is organized in the following way: Section 2 literature review, Section 3 SLR methodology, Section 4 thematic findings, Section 5 creates the DGT framework and research propositions, Section 6 discussion, Section 7 and implications, and finally conclusion.

## **2. LITERATURE REVIEW**

### **2.1 Industry 4.0 Technology and Change of Manufacturing.**

Industry 4.0 is the fourth significant shift in industry, which implies the integration of digital, physical, and biological processes in the form of coherent and intelligent manufacturing (Liao et al., 2017). The technological elements that define the concept of smart factories, including the IoT, CPS, big data analytics, and cloud computing, additive manufacturing, and autonomous robotics allow creating self-optimising production processes, real-time decision-making, and a continuous flow of machine-to-machine communication (Frank et al., 2019). The benefits of the adoption of Industry 4.0 are always recorded through empirical evidence. Dalenogare et al. (2018) have determined that automation and data-driven production are important factors in improving the productivity of the industry, whereas Buechi et al. (2020) have shown that smart factory technologies increase the flexibility and market



responsiveness of the manufacturing. Brettel et al. (2016) also demonstrated that, digital manufacturing technologies also facilitate combative agility and customisation of products. Another benefit recorded through supply chain reconfiguration is the ability to create supply chains that provide real-time visibility, collaborative production, and demand-based production (Dev et al., 2020; Tirabeni et al., 2019).

### **2.2 Digital Technologies -Green Manufacturing Enablers.**

Green manufacturing aims at reducing the cost impact on the environment and at maintaining the efficiency of the production processes economically (Morelli, 2011). It has been established in the literature that digital technologies facilitate green manufacturing in three major ways. To start with, real-time monitoring realized through the IoT envisages detailed insights into energy usage, material use and emissions to implement the waste-reduction intervention (Ghobakhloo, 2020; Frank et al., 2019). Second, predictive maintenance and optimisation of yield with the help of big data analytics will decrease the defect rates and corresponding material waste (Zhong et al., 2015). Third, CPS allows to control production parameters automatically in real time and reduce the number of resources (Liao et al., 2017).

Both Bonilla et al. (2018) and Stock and Seliger (2016) have given strong empirical evidence to support the hypothesis that Industry 4.0 promotes the shift towards an environmentally conscious production. As illustrated by Fysikopoulos et al. (2014), the novel manufacturing technologies contribute to the reduction of waste and waste at the same time improve energy efficiency. Most importantly, both Dev et al. (2020) and Jensen and Remmen (2017) related transformations in the digital world with the creation of the circular economy and revealed that Industry 4.0 technologies put into a practicum the creation of closed-loop production by improving reverse logistics and resource recovery.

### **2.3 Sustainable Performance and the Triple Bottom Line.**

The TBL framework is the operationalised approach through which sustainable performance in manufacturing is realised (Elkington, 1998; Norman and MacDonald, 2004), in which three dimensions require achieving balances. The economic performance includes competition, cost efficiency and productivity. The environment performance focuses on energy intensity, carbon emission, waste production, and material efficiency. Social performance deals with wellbeing of workforce, safety of health and safety of occupations, competence development, and communal influence.

Digital transformation provides contributions to all three TBL dimensions. Automation and efficiency benefit lower operation costs and enhance competitiveness in the market (Ghobakhloo, 2020).



Monitoring and control systems limits the use of energy, emissions, and waste in an environmental context (Fysikopoulos et al., 2014; Stock and Seliger, 2016). Industry 4.0, socially, assists in skills development, workplace safety through hazard automation, and the new technology-oriented jobs (Kiel et al., 2017). Rodrigues et al. (2016) stressed the importance of the use of sustainability performance indicators (SPIs) to measure these cross-dimensional results.

#### **2.4 Digital Transformation in MSMEs: Opportunities and Barriers**

The structural barriers to Industry 4.0 within MSMEs are also a peculiarity. Moeuf et al. (2018) cited lack of money, technical know-how and lack of a digitised infrastructure as the main limitations whereas Horváth and Szabo (2019) reported organisational resistance and limitation of management capacity as other intermediating factors. Muller et al. (2018) also were referring to the difficulty of aligning sustainability goals with the technology investment decisions in resource limited SMEs. Nevertheless, despite these challenges, the process of digital transformation has tremendous opportunities. The author stated that modular, cloud-based Industry 4.0 could provide the MSMEs with the available entry points without necessitating an enormous amount of money, as in the case of a large enterprise (Ghobakhloo, 2020). As Prause (2015) emphasized, digital business models can be made sustainable to meet the resource constraints of the MSMEs. Jena et al. (2020) explicitly reported the industry 4.0 applications in Indian manufacturing sector towards a sustainable manufacturing.

#### **2.5 The Tamil Nadu Manufacturing MSME Ecosystem Contextual Framing.**

Tamil Nadu offers one of the most relevant and less studied environments in which the digital-green nexus can be studied. It is an indicator of the character of the manufacturing MSME industry in the state where industrial-specific clusters with unique environmental exposure are common. The Coimbatore precision engineering cluster (~30,000 MSME units) is energy-consuming, and it is under pressure by regulatory forces to limit its use of electricity and compressed air efficiency. The knitwear cluster of Tiruppur and annual textile exports of over 32000 crores is faced with serious effluent control problems and water usage due to the dyeing of textiles. The Chennai belt automotive parts has provided the automatic parts to an OEM such as Hyundai, Ford and renault-Nissan that has built a quality and emissions compliance mandatory. The leather cluster of Ambur-Ranipet which hires about 400, 000 people is under extreme environmental control concerning tannery effluents (Government of Tamil Nadu, 2024; MSME Development Institute Chennai, 2024; Godrej Capital, 2025). These cluster-level environmental exposures form discriminated yet substantial incentives of IoT-based monitoring, energy management, and green manufacturing adoption. The institutional basis of supporting programmes on Industry 4.0 clusters at the level of Tamil Nadu has a relatively developed policy infrastructure on industrial policy, such as MSME development institutes, industrial estates and technology parks. Nonetheless, on-ground implementation is still limited by micro-enterprise control over the industry and the institutional bottlenecks explained in Section 2.4. 2.6



## **2.6 Gap in Research and Theoretical Positioning.**

The analysis conducted above demonstrates that there is a noticeable and considerable gap: most Industry 4.0 and the concept of sustainable manufacturing are studied regarding large companies in developed nations (Moeuf et al., 2018). In particular, the adoption of Industry 4.0, green manufacturing practices, and TBL performance has not been previously integrated within a single conceptual framework focused on manufacturing MSMEs; no testable research propositions were proposed between these constructs, and no particular institutional and industrial setting of Tamil Nadu was examined through the proposed conceptual framework. This paper is a direct answer to all of these gaps.

## **3. METHODOLOGY**

### **3.1 Research Design and Approach**

This study employs standardized methods and questionnaires to obtain the required data. The research design and approach used in this research will be quantitative owing to the fact that this approach will utilize standardized procedures and questionnaires to collect the necessary data. The proposed study is based on the systematic literature review (SLR) methodology that will synthesize the available information on the connections between digital transformation, green manufacturing, and sustainable performance in manufacturing MSMEs. The best suitable methodology in this aim is a SLR, which offers a rigorous, transparent, and replicable way of collating heterogeneous results in a scattered literature (Kamble et al., 2018). The review is guided by PRISMA (Preferred Reporting Items to systemic Reviews and Meta-Analyses), according to which the methodology is of high quality and can be replicated (Liao et al., 2017).

### **3.2 Search Strategy**

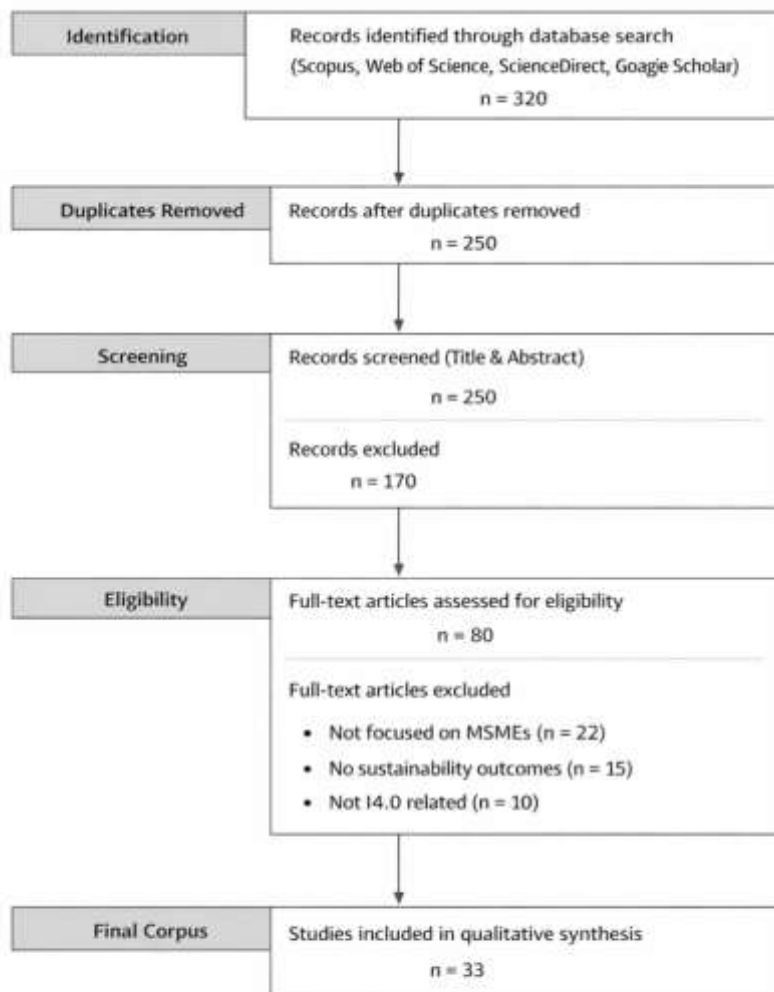
Four major academic databases have been searched including Scopus, Web of Science, science direct and Google Scholar.

The search states of Booleans used were: Keywords: (digital transformation) OR (Industry 4.0) OR (digitalisation) OR (smart manufacturing) AND (green manufacturing) OR (sustainable manufacturing) OR (circular economy) AND (MSME) OR (SME) OR (small and medium enterprise). Secondary string: (Sustainability performance: Industry 4.0) AND (IoT) AND (cyber-physical systems) AND (Sustainable performance: Industry 4.0) AND (Environmental performance: manufacturing) The time frame was 2015-2024 that encompassed the time frame of the emergence of Industry 4.0 as a recognised research paradigm up to the present scholarship. Additional policy documents were received in government of Tamil Nadu, MSME Development Institute Chennai, and other related institutional sources to provide a context of findings.

### **3.3 Inclusion and Exclusion Criteria.**

Inclusion criteria: (1) English-language, peer-reviewed journal articles or official institutional/policy reports; (2) content area; (3) manufacturing sector focus; and (4) MSME-focus. Inclusion criteria: Only articles published within five years were included; conference papers; book chapters; duplicate records; articles that dealt with non-manufacturing industries; articles dealing with none of the three data points (digital transformation, green manufacturing, sustainable performance).

**Figure 1. PRISMA Systematic Review Process**



### 3.4 Thematic Analysis

The 33 identified studies went through the thematic analysis after an iterative process of coding. In the first step, open coding of the entire research samples has revealed the existence of 47 different codes, which were grouped into greater thematic levels using the axial coding method. Three key themes were identified, namely, Industry 4.0 technologies in manufacturing, digitization technologies that make green manufacturing practices possible, and sustainable performance outcomes. The findings (Section 4) and the conceptual framework of DGT (Section 5) are based on these themes, and their relationships with one another.

**4. THEMATIC FINDINGS**

The synthesis of all 33 studies used, including the approach, area of interest, and contribution of each study to the thematic analysis and frameworks of this review, is described in Table 2 below.

**Table 1. Synthesis of Studies Included in the Systematic Review (n = 33)**

Author(s)	Year	Method	Focus	Key Contribution to This Review
<b>Dalenogare et al.</b>	2018	Quantitative survey	Industry 4.0 → industrial performance	Documents that automation and data-driven systems significantly improve manufacturing productivity; underpins Theme 1
<b>Büchi et al.</b>	2020	Mixed methods	Smart factory performance	Smart factory technologies enhance production flexibility and market responsiveness; supports Theme 1
<b>Frank et al.</b>	2019	Case study / survey	I4.0 implementation patterns	Identifies IoT and cloud computing as dominant technologies in manufacturing; referenced in all three themes
<b>Ghobakhloo</b>	2020	SLR	I4.0 and sustainability	Establishes I4.0 as structural enabler of sustainability performance in manufacturing; underpins DGT framework
<b>Bonilla et al.</b>	2018	Scenario	I4.0 and	Confirms digital technologies

Author(s)	Year	Method	Focus	Key Contribution to This Review
		analysis	sustainability implications	catalyse environmentally responsible production systems; Theme 2
<b>Stock &amp; Seliger</b>	2016	Conceptual	Sustainable manufacturing in I4.0	Documents energy conservation and resource optimisation opportunities; Theme 2 & 3
<b>Kamble et al.</b>	2018	SLR	Sustainable Industry 4.0 framework	Develops sustainability framework for I4.0; directly informs DGT framework design
<b>Dev et al.</b>	2020	Conceptual / case	I4.0 and circular economy	Links I4.0 to reverse supply chain and resource recovery; Theme 2 (circular economy pathway)
<b>Moeuf et al.</b>	2018	SLR	SME management in I4.0 era	Identifies financial and skill barriers as primary MSME constraints; underpins Section 4.4
<b>Horváth &amp; Szabó</b>	2019	Survey	Drivers and barriers of I4.0	Organisational resistance and management capacity as MSME-specific barriers; Section 4.4
<b>Liao et al.</b>	2017	SLR	Past, present, future of I4.0	Comprehensive I4.0 technology taxonomy; foundational reference for Theme 1
<b>Brettel et al.</b>	2016	Conceptual	Manufacturing flexibility in I4.0	Digital technologies promote agility and customisation; supports Theme 1
<b>Fysikopoulos</b>	2014	Experimental	Manufacturing	Advanced technologies

Author(s)	Year	Method	Focus	Key Contribution to This Review
et al.			energy efficiency	simultaneously improve energy efficiency and reduce waste; Theme 2 & 3
Rodrigues et al.	2016	Framework dev.	Sustainability performance indicators	KPIs for environmental and economic manufacturing outcomes; supports TBL assessment in Theme 3
Giret et al.	2015	SLR	Sustainability in operations scheduling	Digital scheduling reduces resource consumption; Theme 2
Kiel et al.	2017	Qualitative	Sustainable industrial value creation	I4.0 social performance benefits for workforce; TBL social dimension in Theme 3
Müller et al.	2018	Survey	Drivers of I4.0 implementation	Opportunities and challenges in sustainability context; informs Table 2 barrier analysis
Beier et al.	2017	Comparative	Digitalisation and sustainability	China–Germany comparison; digital twin technology sustainability benefit; Table 1
Jena et al.	2020	Review	I4.0 for sustainable manufacturing	IoT application in Indian manufacturing context; directly relevant to Tamil Nadu framing
Tirabeni et al.	2019	SLR	Business models and sustainability	Digital supply chain sustainability; Theme 2 circular economy pathway
Zhong et al.	2015	Empirical	Big data in logistics	RFID-enabled production data for waste reduction; Theme 2 analytics pathway
Jensen & Remmen	2017	Conceptual	Circular economy and	Product stewardship enabling circular economy in

Author(s)	Year	Method	Focus	Key Contribution to This Review
			product stewardship	manufacturing; Theme 2
<b>Gebler et al.</b>	2014	LCA / modelling	3D printing and sustainability	Additive manufacturing near-zero waste; Table 1 additive manufacturing row
<b>Peukert et al.</b>	2015	Empirical	Smart modular manufacturing	Sustainability and flexibility in modular machine tools; Theme 1
<b>Prause</b>	2015	Conceptual	Business models for I4.0	Sustainable digital business models; managerial implications
<b>Elkington</b>	1998	Conceptual	Triple Bottom Line	Foundational TBL framework; central theoretical basis for Theme 3 and DGT framework
<b>Norman &amp; MacDonald</b>	2004	Theoretical critique	TBL framework	Critically extends TBL to operational measurement; Theme 3 performance assessment
<b>Morelli</b>	2011	Conceptual	Environmental sustainability definition	Definitional grounding for green manufacturing construct; Introduction and Section 2.2
<b>Markley &amp; Davis</b>	2007	Conceptual	Sustainable supply chains	Competitive advantage through sustainable supply chains; supports TBL economic dimension
<b>Bonilla et al.</b>	2018	Conceptual	I4.0 sustainability scenarios	Scenario-based analysis of I4.0 sustainability impacts across sectors; Theme 2
<b>Kamble et al.</b>	2018	Framework	Sustainable I4.0	Systematic identification of I4.0 sustainability trends;

Author(s)	Year	Method	Focus	Key Contribution to This Review
				methodology validation
<b>Gov. of Tamil Nadu</b>	2024	Policy report	MSME policy note 2024–25	Authoritative data on Tamil Nadu MSME ecosystem; contextual framing Section 2.5
<b>MSME Dev. Inst.</b>	2024	Institutional report	Annual report 2023–24	Employment and enterprise statistics for Tamil Nadu; Section 1 and 2.5

**4.1 Theme 1: Industry 4.0 Technologies as Drivers of Manufacturing**

The initial theme determines the initial role of I4.0 technologies as the means of changing the architecture and performance of the manufacturing systems. IoT provides real-time data collection throughout the production floor; CPS involves digital control with physical manufacturing objects; big data analytics transforms the operational data into usable production data; automation gets rid of bottlenecks and minimizes human error (Frank et al., 2019; Liao et al., 2017). Collectively the technologies form an integrated digital manufacturing infrastructure supporting the improvement of efficiency and sustainability. The considered papers all show a tangible positive effect in regard to productivity and operational performance of the adoption of Industry 4.0 (Dalenogare et al., 2018; Bueschi et al., 2020; Brettel et al., 2016). They also regularly add, though, that such advantages are not available to most MSMEs because of the limitations in financial and human resources (Moeuf et al., 2018; Horváth and Szabo, 2019). This strain between potential and limited adoption is the key problem which the DGT system works at the policy and management level.

**4.2 Theme 2: Digital Technologies Enabling Green Manufacturing Practices**

The second theme develops three major avenues, by which the digital technologies can be used to promote the green manufacturing adoption. The sight of operations: IoT monitoring will allow us to see the actual state of energy usage and material use in real-time and provide a way to introduce a specific environmental intervention, without reducing the production level (Ghobakhloo, 2020; Frank et al., 2019). The predictive optimisation route: predictive maintenance and production optimisation The predictive optimization route is supported by big data analytics and CPS, which decrease the rates of defects, unplanned downtime, and material waste (Zhong et al., 2015; Liao et al., 2017). The circular integration process: Industry 4.0 solutions (especially digital supply chains and IoT reverse logistics) provide the possibility of closing the material circles, providing a means to implement the concept of the circular economy in manufacturing supply chains (Dev et al., 2020; Jensen and



Remmen, 2017). Bonilla et al. (2018) and Stock and Seliger (2016) gave substantial evidence to the fact that these pathways together trigger sustainable manufacturing on a large scale. Notably, the literature reviewed confirms that digital technologies do not have the direct influence on the environmental outcomes, but provide the conditions under which green manufacturing practices become integrated in a structured way, i.e. the role of green manufacturing in the DGT framework is mediating.

### **4.3 Theme 3: Sustainable Performance Results through Triple Bottom Line.**

The third theme summarises the evidence of TBL performance results of digital-green transformation. Economic performance is always recorded: automation and efficiency improvement will lower the operational costs of the organization; quality control through data allows improving the output value, and competitive position will be enhanced due to market responsiveness (Ghobakhloo, 2020; Büchi et al., 2020). In case of Tamil Nadu MSMEs, the issue of cost reduction is quite critical since the operating margins are compressed. The positive impact on environmental performance is also well-proven: the use of IoT mechanisms, predictive maintenance and optimised production planning will lead to a decrease in energy consumption, industrial waste, and carbon emissions (Fysikopoulos et al., 2014; Stock and Seliger, 2016). The role of sustainability performance indicators in the quantification of these environmental improvements was results of research by Rodrigues et al. (2016). Social performance is not examined in as much depth as at MSME but is positively engaged with automation of hazardous work, digital upskilling and employment stabilisation that occurs due to better firm competitiveness (Kiel et al., 2017; Müller et al., 2018).

## **5. Digital-Green transformation (DGT) conceptual framework.**

### **5.1 Framework Architecture Based on the three thematic findings.**

This section introduces the Digital -Green Transformation (DGT) conceptual framework. The DGT framework explains the theoretical framework where Industry 4.0 technology adoption optimizes the TBL sustainable performance gains in MSMEs manufacturing, through the mediating process of green manufacturing practices through the mediating contextual barriers influencing MSMEs. The framework involves the four layered hierarchical structure:

**Layer 1 - Antecedent (Industry 4.0 Technology Adoption):** The technology of the enabling IoT, big data analytics, CPS, smart manufacturing systems, cloud computing, digital supply chain systems, and energy monitoring systems, the digital twin technology, and additive manufacturing are included in this layer. These technologies are described in Table 1 (Section 4 / below).

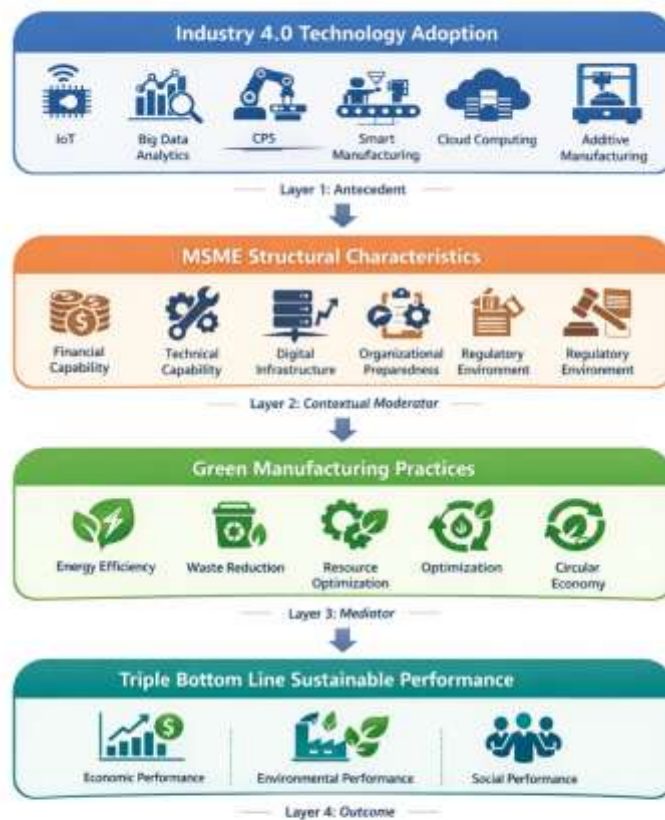
**Layer 2 - Contextual Moderator (MSME Structural Characteristics):** In this layer, the adoption and effect of Industry 4.0 technologies in manufacturing MSMEs are recognised to be moderated by structural forces inclusive of financial capability, technical capability, digital infrastructure, organisational preparedness and regulatory environment that all combine to determine the nature and

the level of digital transformation that can be realised in this segment.

**Layer 3- Mediator (Green Manufacturing Practices):** This layer includes energy efficiency, managing waste of materials, efficient use of resources, and integration of the circular economy. These practices form the ecological channel where digital technologies have sustainability outputs, which attest to the mediating nature of the identified theme 2.

**Layer 4 — Outcome (Triple Bottom Line Sustainable Performance):** This layer of output includes economic performance (cost efficiency, productivity, competitiveness), environmental performance (energy intensity, carbon emissions, waste generation), as well as social performance (workforce wellbeing, skill development, employment stability).

Figure 2: DGT Conceptual Framework



The DGT framework has a particular theoretical contribution that it establishes, in that green



manufacturing practices can serve as an example of a mediator or mediator rather than a paralleling consequence of a digital transformation. This is a significant difference: it suggests that investing in the technologies of Industry 4.0 does not necessarily guarantee the improvement in the sphere of TBL performance, unless it is followed by the intentional use of green manufacturing techniques. This mediation reasoning aligns with the evidence of operations analysis presented in Theme 2 and offers a more accurate theoretical framework than previous models that ensure the operation of a direct relationship between digitalisation and sustainability (e.g., Kamble et al., 2018; Bonilla et al., 2018).

## 5.2 Research Propositions

The DGT-based research propositions generate five formal research propositions. The propositions will serve future empirical testing - especially using quantitative survey research, structural equation modelling (SEM) and longitudinal case studies in Tamil Nadu MSME clusters.

**P1:** Greater Industry 4.0 technology adoption is positively related with increased green manufacturing adoption of MSME manufacturing.

Justification: The pathways of operational visibility, predictive optimisation, and circular integration reported in Theme 2 secure well-articulated mechanisms in which Industry 4.0 technologies can facilitate green manufacturing. This is a formal proposal to this causal direction and is confirmed by Ghobakhloo (2020), Bonilla et al. (2018), and Stock and Seliger (2016).

**P2:** Green manufacturing practices intervene in the relationship between Industry 4.0 and triple-bottom-line manufacturing MSMEs sustainable performance.

Justification: Theme 3 cements the achievements of TBL performance improvements, yet Theme 2 ascertains the same through the tool of green manufacturing practices. Without the intervention of the green manufacturing, the direct sector 4.0 -TBL relationships are weaker. This proposal allows the empirical decomposition of direct and indirect effects (Kamble et al., 2018; Fysikopoulos et al., 2014).

**P3:** The relationship between Industry 4.0 use and green manufacturing practices in manufacturing MSMEs exists at the negative of financial and human capital barriers in the sense that, the positive association is lower in companies with fewer financial and technical capability.

Justification: The literature of the adoption barriers (Moeuf et al., 2018; Horváth and Szabo, 2019) confers that the less fortunate MSMEs accrue reduced performance returns to technological investments. This moderating effect bears high implications on policy focus whereby it is essential to focus on the most strained segments of MSMEs.

**P4:** manufacturing MSMEs produce more strongly positive associations between environmental and social performance and green manufacturing practices compared to economic performance because of the extended payback regions of the environmental investments.

Justification: According to the reviewed literature, the TBL returns have different timescales: the economic returns of automation appear to be immediate, whereas the environmental and social returns might be either long term (Rodrigues et al., 2016; Kiel et al., 2017). This hypothesis has significant

implications on the frameworks of making investment decisions in MSMEs.

**P5:** Policy-level enablers, such as financial incentives, investment in digital infrastructure and programmes to develop skills, mediate the relationship between financial/technical barriers and Industry 4.0 adoption, such that well-supplied MSMEs are higher levels of industry 4.0-adoption than structural endowments would suggest.

**Justification:** The theoretical foundation of the policy implications of this research (Section 7.3) is based on the moderating effect of institutional support to facilitating the process of breaking the structural barriers. This argument codifies that logic and offers an empirically falsifiable source of policy assessment (Muller et al., 2018; Ghobakhloo, 2020).

**Table 2. Industry 4.0 Technologies and Their Sustainability Applications**

<b>Technology</b>	<b>Application in Manufacturing</b>	<b>Sustainability Benefit</b>	<b>Key References</b>
<b>Internet of Things (IoT)</b>	Real-time monitoring of machines and production systems; predictive maintenance	Energy efficiency; reduced resource consumption; early fault detection	Frank et al. (2019); Ghobakhloo (2020); Jena et al. (2020)
<b>Big Data Analytics</b>	Data-driven production planning; quality optimisation; demand forecasting	Reduced material waste; improved yield; lower rework rates	Zhong et al. (2015); Dalenogare et al. (2018)
<b>Cyber-Physical Systems (CPS)</b>	Integration of digital control with physical production assets	Automated resource optimisation; reduced idle energy use	Liao et al. (2017); Brettel et al. (2016)
<b>Smart Manufacturing</b>	Autonomous scheduling;	Higher productivity with	Büchi et al. (2020); Kamble et al. (2018)

<b>Technology</b>	<b>Application in Manufacturing</b>	<b>Sustainability Benefit</b>	<b>Key References</b>
<b>/ AI</b>	intelligent quality control	lower resource intensity; reduced scrap	
<b>Cloud Computing</b>	Centralised data storage; collaborative manufacturing networks	Reduced infrastructure footprint; improved supply-chain coordination	Frank et al. (2019); Ghobakhloo (2020)
<b>Digital Supply Chain Systems</b>	End-to-end logistics visibility; supplier integration platforms	Reduced transport-related emissions; circular material flows	Dev et al. (2020); Tirabeni et al. (2019)
<b>Energy Monitoring Systems</b>	Real-time industrial energy consumption tracking and optimisation	Reduced carbon emissions; regulatory compliance; improved environmental KPIs	Fysikopoulos et al. (2014); Stock & Seliger (2016)
<b>Digital Twin Technology</b>	Virtual replication of physical assets for simulation and predictive testing	Reduced prototyping waste; optimised maintenance cycles; extended asset life	Beier et al. (2017); Kiel et al. (2017)
<b>Additive Manufacturing (3D Printing)</b>	On-demand, layer-by-layer production with minimal tooling	Near-zero material waste; localised production	Gebler et al. (2014); Müller et al. (2018)

Technology	Application in Manufacturing	Sustainability Benefit	Key References
		reducing logistics emissions	

## 6. DISCUSSION

**6.1 Digital Greens Digital Nexus: Three Mechanisms.** The research findings have developed strong evidence base related to the digital-green nexus within manufacturing MSMEs, which works in three heavily interconnected processes. The mechanism of operational visibility: IoT-based survival offers real-time production intuition that makes it possible to identify and remove production wastage and materials inefficiency at the operational level, the cornerstone of starting green manufacturing (Ghobakhloo, 2020; Frank et al., 2019). Can it be optimised predictively this way: with the help of big data analytics and CPS, it becomes possible to manage production proactively, minimizing the number of cases of unplanned downtimes, defects, and associated resources waste due to the predictive control of the process (Zhong et al., 2015; Dalenogare et al., 2018). The concept of the circular integration: digital supply chains and IoT-based reverse logistics provide the technical framework of the closed-loop flows of materials, allowing MSMEs to transform the linear model of production into a circular one with important consequences on materials cost reduction and regulatory compliance (Dev et al., 2020; Jensen and Remmen, 2017).

These mechanisms explain the theoretical rationale of P2 of the DGT framework: digital technology builds the conditions of operation under which the implementation of green manufacturing is possible and implemented under scalable conditions, and not necessarily results in TBL performance improvements in the absence of these conditions. The mediation is structural but not incidental.

**6.2 Barriers and Enabling Conditions to MSME Adoptions.** The review of the literature on adoption barrier collides on the same range of structural constraints that proportionately weigh down on manufacturing MSMEs (Table 4). Financial and human barriers are especially acute in Tamil Nadu where the MSME sector is composed of micro-enterprises or firms with less than ten workers and annual turnover of less than 50,000 in India rupees. Nevertheless, the clustering nature of the industrial environment of Tamil Nadu provides meaningful opportunities in terms of collective adoption strategies that alleviate individual firm limitations. The investments in digital infrastructure at a cluster level, common technology platforms, and joint skill-development initiatives can significantly lower the per-firm adoption costs and speed up the process of cultural acquisition of green manufacturing technologies.

**Table 3. Barriers to Industry 4.0 Adoption and Recommended Interventions**

<b>Barrier Category</b>	<b>Specific Barriers</b>	<b>Recommended Interventions</b>
<b>Financial</b>	High upfront capital costs; limited access to credit; low profit margins; inability to absorb investment risk	Subsidised technology-leasing schemes; MSME digital-transformation credit lines at concessional rates; GST concessions on qualifying I4.0 equipment; government co-investment in shared technology platforms at cluster level
<b>Technical / Infrastructural</b>	Inadequate digital infrastructure; unreliable connectivity; legacy equipment incompatibility; absence of interoperability standards	State-level IoT-ready broadband rollout to MSME industrial clusters; modular retrofit IoT kits for legacy equipment; open-standard industrial data platforms; common manufacturing technology centres in major clusters
<b>Human Capital</b>	Digital skill deficit in workforce; low management awareness of I4.0 benefits; resistance to operational change; absence of in-house innovation capability	Structured Industry 4.0 and green manufacturing competency programmes via ITIs and polytechnics; MSME development institute awareness campaigns; change management coaching for MSME leaders; MSME–university innovation partnerships
<b>Organisational</b>	Short-term planning horizons; weak data governance; limited inter-firm	Integration of digital-green roadmaps into MSME business planning frameworks; cluster-level data-sharing platforms; industry association-led knowledge exchanges and peer learning networks; green manufacturing

Barrier Category	Specific Barriers	Recommended Interventions
	collaboration; absence of sustainability strategy	certification pathways
<b>Regulatory / Policy</b>	Fragmented policy ecosystem; absence of green manufacturing incentives; limited technology transfer mechanisms; weak enforcement of environmental standards	Dedicated state-level Digital–Green MSME policy framework; incentivised green certification linked to preferential procurement and export facilitation; public–private technology transfer hubs; progressive environmental compliance roadmap for MSMEs

**6.3 SDG Alignment and Global Relevance**

Table 5 shows that the DGT framework and its policy implications correspond to five UN Sustainable Development Goals. Industry 4.0 supporting productivity is utilized in SDG 8 (Decent Work and Economic Growth) to maintain the competitiveness of MSMEs and their employment. The SDG 9 (Industry, Innovation and Infrastructure) is achieved concerning the digitalization of manufacturing infrastructure of MSME. SDG 12 (Responsible Consumption and Production) works in terms of green manufacturing, especially waste minimisation and the incorporation of the circular economy. SDG 13 (Climate Action) gets developed with the help of the IoT-based monitoring of carbon emissions and energy optimisation. The multi-partnership policy framework suggested in Section 7.3 was based on SDG 17 (Partnerships for the Goals).

**Table 4. DGT Framework Alignment with UN Sustainable Development Goals**

<b>SDG</b>	<b>Goal Title</b>	<b>Linkage to Digital–Green Transformation</b>	<b>Specific Connection in This Study</b>
<b>SDG 8</b>	<b>Decent Work &amp; Economic Growth</b>	Industry 4.0 adoption improves MSME productivity, operational efficiency, and competitiveness, sustaining employment and economic growth in Tamil Nadu's industrial clusters	Economic performance dimension of DGT framework; Theme 1 (productivity gains); managerial implications for cost reduction
<b>SDG 9</b>	<b>Industry, Innovation &amp; Infrastructure</b>	Digital transformation modernises manufacturing infrastructure and fosters technological innovation in MSMEs, building resilient and sustainable industrial ecosystems	Core of DGT framework; entire Industry 4.0 technology adoption layer; policy recommendation for cluster-level digital infrastructure investment
<b>SDG 12</b>	<b>Responsible Consumption &amp; Production</b>	Green manufacturing practices — energy efficiency, waste reduction, circular economy integration — directly operationalise responsible production patterns in manufacturing MSMEs	Green manufacturing practices layer of DGT framework; Theme 2; circular economy enablement through I4.0 (Dev et al., 2020)
<b>SDG 13</b>	<b>Climate Action</b>	IoT-based energy monitoring, carbon emissions tracking, and resource optimisation reduce the carbon footprint of manufacturing operations	Environmental performance dimension of TBL; energy monitoring systems in Table 1; environmental KPI measurement (Rodrigues et al., 2016)
<b>SDG 17</b>	<b>Partnerships for the Goals</b>	Multi-stakeholder collaboration between policymakers, technology	Policy implications (Section 7.3); cluster-level public–private partnership



SDG	Goal Title	Linkage to Digital–Green Transformation	Specific Connection in This Study
		providers, industry associations, and academic institutions is essential to enable MSME digital–green transformation	recommendations; technology transfer mechanism design

This explicit SDG mapping has two functions: it shows the global topicality of research conducted in a regional environment of emerging economy, and it gives a systematic ground to orient MSME digital-green transformation programme aligned to Voluntary National Review engagements of India depending on the 2030 Agenda.

#### 6.4 Contribution to Theory

This paper contributes to the sustainability theory of manufacturing in three ways. To begin with, the DGT framework integrates the formerly divided literatures on Industry 4.0, green manufacturing, and TBL performance into an integrated theoretical framework, defining the mediating role of green manufacturing a causal specification found none previous frameworks (cf. Kamble et al., 2018; Bonilla et al., 2018). Second, the study expresses conceptual relationships in an empirically falsifiable manner by deriving five testable propositions, which puts the field beyond descriptive synthesis and on the road to theoretical development. Third, the framework is pegged against the particular institutional and industrial conditions of Tamil Nadu, which makes the study build on context-sensitive sustainability transition theory amid emerging economy manufacturing a body of research that is largely undertheorized when compared to the body of advanced economy manufacturing.

### 7. IMPLICATIONS

#### 7.1 Theoretical Implications

The framework of DGT presents a theoretically accurate and empirically testable framework which can be used to study the digital nexus in manufacturing M-SMEs toward the green nexus. Theoretical growth needs to be oriented on the following topics in future: determining the boundary conditions when each of the three mechanisms (operational visibility, predictive optimisation, circular integration) is most powerful; how the TBL performance improvements are sequenced as the featured MSMEs advance to later stages of digital maturity; and how generalisable the framework can be to the diverse emerging economy regional industrial ecosystems.

#### 7.2 Managerial Implications

The DGT framework gives states a structured investment prioritisation logic to the MSME managers



in Tamil Nadu. The scheme presupposes a progression-based implementation plan based on financial and technical capabilities: Phase 1 -IoT-based energy monitoring (high attention, rather inexpensive; fulfills regulatory mandate and energy-saving directly); Phase 2 -predictive maintenance analytics (moderate-cost; offers simultaneous operational cost reduction and waste minimisation); Phase 3 - cloud-based production management and digital supply chain integration (more investment; allows full TBL performance adjustment and the ability to reduce energy costs and waste). At every stage, a TBL business case should be built by its managers that would measure returns of every aspect of economic, environmental, and social dimension, not solely a cost-saving in operations.

### **7.3 Policy Implications**

The Tamil Nadu state and national policymakers are to establish a multi-layer Digital -Green MSME Policy Framework that includes five intervention domains coordinated to be summarised in Table 4. Interventions aimed at financial accessibility (subsidised technology-leasing models, dedicated credit facilities at concessional interest rates, GST concessions on qualifying Industry 4.0 equipment, co-investment of the government in shared cluster-level digital platforms) could be applied. The priority of infrastructure interventions should be the installed IoT-ready broadband network in the key MSME industrial belts and modular retrofit IoT kits to old equipment. Structured Industry 4.0 and green manufacturing competency programmes should be provided via ITIs, polytechnics and MSME development institutes through human capital interventions. Green manufacturing certification should also be connected with preferential public procurement and ease of export provision which should form positive incentives to adoption voluntarily. Lastly, the channels of partnership, namely the public-private technology transfer hubs in Coimbatore, Tiruppur, Chennai, and Ambur-Ranipet shall assist the propagation of the digital-green technologies to MSME end-users at mass scale by the technology providers. Many of these interventions already have an institutional structure in the MSME policy ecosystem in place in Tamil Nadu; the necessary intervention is specific investment and coordination and not institutional creation.

### **8. LIMITATIONS**

There are a number of limitations to this study which are imposed by the SLR methodology. First, the use of secondary data implies that the latest unpublished changes in the practices of digital transformation of MSMEs are not reflected. Second, the locality of the contextual discourse, which is the Tamil Nadu, might hinder the direct externalisation of the policy recommendations to industrial ecosystems elsewhere, but the DGT framework itself has more generalisable theoretical breadth. Third, the time frame (2015-2024) indicates the existence of the current level of research on Industry 4.0, which is still dynamic. Fourth, since this is a single-author review, it was not completely ruled out that the selection bias might not be present, even though systematic documentation of screening decisions has been kept throughout. Fifth, the conceptual character of the DGT framework implies



that mediating and moderating relationships between the variables are not empirically validated yet, this is purposeful, as the definition of a theoretical architecture is the precondition to conducting empirical tests.

## **8.1 CONCLUSIONS**

This was a systematic literature review which explored the connections between the digital transformation, green manufacturing practices and sustainable performance in manufacturing of MSMEs in Tamil Nadu, India. The 33 studies identified using thematic synthesis found three themes which reinforced each other in their role, namely the transformative potential of Industry 4.0 technologies in manufacturing systems; structural enablers of green manufacturing through operational visibility, predictive optimisation, and circular integration; and improvements in triple-bottom-line performance.

The research hypothesized Digital Green Transformation (DGT) conceptual framework, indicating the mediated effect of the green manufacturing practices on the trajectory between Industry 4.0 technology adoption and TBL sustainable performance in manufacturing MSMEs. The five research propositions based on the framework are testable, and this offers a systematic basis on which future empirical studies can be conducted. The contributions of the framework were aligned with UN SDGs 8, 9, 12, 13, and 17, and, therefore, its global irrelevance and policy congruency were determined. Recommended interventions related to the managerial and policy levels were synthesised with barriers to adoption, including financial, technical, human capital, organisational, and regulatory, as well as the recommended interventions.

## **8.2 Future Research Directions**

The future studies should give priority to empirical validation of the DGT framework based on the following avenues. The mediation and moderation roles of green manufacturing practices (P1 and P2) and the financial/human capital barriers (P3) should be statistically tested in quantitative survey studies by differentiating Tamil Nadu MSME clusters. Longitudinal designs would allow looking at the process of improving TBL performance over the stages of digital maturity (P4). Industry cluster case studies - especially Coimbatore engineering case study, Tiruppur knitwear cluster and Ambur leather cluster case studies would provide case study contexts on differentiated adoption pathways within a sector. Causal identification of policy moderation effects could be empowered through Natural experiment designs that make use of policy variation e.g. by introducing subsidised technology programmes on certain clusters (P5). Lastly, comparative studies across Indian States (Tamil Nadu, Maharashtra, Gujarat) and emerging economies (India, Vietnam, Bangladesh, Mexico) would put the overall generalisability of the DGT framework to the verified regional foundations to the test.



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The authors declare that they have no conflict of interest.

**REFERENCES**

- Beier, G., Niehoff, S., Ziems, T., & Xue, B. (2017). Sustainability aspects of a digitalized industry: A comparative study from China and Germany. *International Journal of Precision Engineering and Manufacturing – Green Technology*, 4(2), 227–234. <https://doi.org/10.1007/s40684-017-0027-1>
- Bonilla, S. H., Silva, H. R. O., Terra da Silva, M., Gonçalves, R. F., & Sacomano, J. B. (2018). Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges. *Sustainability*, 10(10), 3740. <https://doi.org/10.3390/su10103740>
- Brettel, M., Klein, M., & Friederichsen, N. (2016). The relevance of manufacturing flexibility in the context of Industry 4.0. *Procedia CIRP*, 41, 105–110. <https://doi.org/10.1016/j.procir.2015.12.021>
- Büchi, G., Cugno, M., & Castagnoli, R. (2020). Smart factory performance and Industry 4.0. *Technological Forecasting and Social Change*, 150, 119790. <https://doi.org/10.1016/j.techfore.2019.119790>
- Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, 204, 383–394. <https://doi.org/10.1016/j.ijpe.2018.08.019>
- Deloitte. (2025). India economic outlook: MSME distribution across states. Deloitte Insights.
- Dev, N. K., Shankar, R., & Qaiser, F. H. (2020). Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resources, Conservation & Recycling*, 153, 104583. <https://doi.org/10.1016/j.resconrec.2019.104583>
- Elkington, J. (1998). Partnerships from cannibals with forks: The triple bottom line of 21st-century business. *Environmental Quality Management*, 8(1), 37–51. <https://doi.org/10.1002/tqem.3310080106>
- Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, 210, 15–26. <https://doi.org/10.1016/j.ijpe.2019.01.004>
- Fysikopoulos, A., Pastras, G., Alexopoulos, T., & Chryssolouris, G. (2014). On a generalized approach to manufacturing energy efficiency. *International Journal of Advanced Manufacturing Technology*, 73, 1437–1452. <https://doi.org/10.1007/s00170-014-5818-3>
- Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, 74, 158–167. <https://doi.org/10.1016/j.enpol.2014.08.033>
- Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of*



- Cleaner Production, 252, 119869. <https://doi.org/10.1016/j.jclepro.2019.119869>
- Giret, A., Trentesaux, D., & Prabhu, V. (2015). Sustainability in manufacturing operations scheduling: A state-of-the-art review. *Journal of Manufacturing Systems*, 37, 126–140. <https://doi.org/10.1016/j.jmsy.2015.08.002>
- Godrej Capital. (2025). MSME sector in Tamil Nadu: Economic contribution and opportunities. <https://www.godrejcapital.com>
- Government of Tamil Nadu. (2024). Policy notes 2024–2025: Micro, Small and Medium Enterprises Department. Government of Tamil Nadu.
- Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and SMEs have equal opportunities? *Technological Forecasting and Social Change*, 146, 119–132. <https://doi.org/10.1016/j.techfore.2019.05.021>
- Jena, M. C., Mishra, S. K., & Moharana, H. S. (2020). Application of Industry 4.0 to enhance sustainable manufacturing. *Environmental Progress & Sustainable Energy*, 39(1), e13360. <https://doi.org/10.1002/ep.13360>
- Jensen, J. P., & Remmen, A. (2017). Enabling circular economy through product stewardship. *Procedia Manufacturing*, 8, 377–384. <https://doi.org/10.1016/j.promfg.2017.02.048>
- Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection*, 117, 408–425. <https://doi.org/10.1016/j.psep.2018.05.009>
- Kiel, D., Müller, J. M., Arnold, C., & Voigt, K.-I. (2017). Sustainable industrial value creation: Benefits and challenges of Industry 4.0. *International Journal of Innovation Management*, 21(8), 1740015. <https://doi.org/10.1142/S1363919617400151>
- Kinara Capital. (2024). MSMEs in Tamil Nadu: Growth and economic contribution. <https://kinaracapital.com>
- Liao, Y., Deschamps, F., Loures, E. D. F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0: A systematic literature review and research agenda proposal. *International Journal of Production Research*, 55(12), 3609–3629. <https://doi.org/10.1080/00207543.2017.1308576>
- Markley, M. J., & Davis, L. (2007). Exploring future competitive advantage through sustainable supply chains. *International Journal of Physical Distribution & Logistics Management*, 37(9), 763–774. <https://doi.org/10.1108/09600030710840859>
- Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., & Barbaray, R. (2018). The industrial management of SMEs in the era of Industry 4.0. *International Journal of Production Research*, 56(3), 1118–1136. <https://doi.org/10.1080/00207543.2017.1372647>
- Morelli, J. (2011). Environmental sustainability: A definition for environmental professionals. *Journal of Environmental Sustainability*, 1(1), 1–9. <https://doi.org/10.14448/jes.01.0002>
- MSME Development Institute Chennai. (2024). Annual report 2023–2024. Ministry of Micro, Small and Medium Enterprises, Government of India.



- Müller, J. M., Kiel, D., & Voigt, K.-I. (2018). What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability*, 10(1), 247. <https://doi.org/10.3390/su10010247>
- Norman, W., & MacDonald, C. (2004). Getting to the bottom of 'Triple Bottom Line'. *Business Ethics Quarterly*, 14(2), 243–262. <https://doi.org/10.5840/beq200414211>
- Peukert, B., Benecke, S., Clavell, J., Neugebauer, S., Nissen, N. F., Uhlmann, E., & Finkbeiner, M. (2015). Addressing sustainability and flexibility in manufacturing via smart modular machine tool frames. *Procedia CIRP*, 29, 514–519. <https://doi.org/10.1016/j.procir.2015.02.013>
- Prause, G. (2015). Sustainable business models and structures for Industry 4.0. *Journal of Security and Sustainability Issues*, 5(2), 159–169. [https://doi.org/10.9770/jssi.2015.5.2\(3\)](https://doi.org/10.9770/jssi.2015.5.2(3))
- Rodrigues, V. P., Pigosso, D. C. A., & McAloone, T. C. (2016). Process-related key performance indicators for measuring sustainability performance of ecodesign implementation into product development. *Journal of Cleaner Production*, 139, 991–1001. <https://doi.org/10.1016/j.jclepro.2016.08.126>
- Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in Industry 4.0. *Procedia CIRP*, 40, 536–541. <https://doi.org/10.1016/j.procir.2016.01.129>
- Tirabeni, L., De Bernardi, P., Forliano, C., & Franco, M. (2019). How can organisations and business models lead to a more sustainable society? A framework from a systematic review of the Industry 4.0. *Sustainability*, 11(22), 6363. <https://doi.org/10.3390/su11226363>
- Zhong, R. Y., Huang, G. Q., Lan, S., Dai, Q. Y., Chen, X., & Zhang, T. (2015). A big data approach for logistics trajectory discovery from RFID-enabled production data. *International Journal of Production Economics*, 165, 260–272. <https://doi.org/10.1016/j.ijpe.2015.02.014>