

Integrating Lean Six Sigma, Digital Transformation, and Sustainability in Operations: Evidence, Gaps, and Research Directions

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Abstract

Lean Six Sigma, digital transformation, and sustainability are now becoming a key strategy to create and deliver operational excellence and concurrently tackle environmental, economic and social aspects. However, there is a lack of a comprehensive body of research, which is scattered across LSS, Industry 4.0, digitalization and sustainable operations. The aim of this study is to perform a systematic literature review and to carry out a bibliometric and thematic synthesis analysis to look at how these three domains converge. The systematic screening of literature published from 2016 to 2026 resulted in 50 publications being used in the final evidence synthesis. The review looked at publications, technology for LSS and DMAIC, multidimensional operational and sustainability results, barriers and enablers to implementation, and gaps in evidence. The results show a high level of research activity from a high level, especially since 2022, and a growing focus on Lean Six Sigma 4.0 and digitally supported 'Sustainable Operations'. The different DMAIC stages were identified with important digital enablers, namely IoT, AI, ML, big-data analytics, digital twins, process mining, predictive analytics, and automation. Reported benefits are productivity, quality, resource efficiency, waste reduction, energy performance and cost efficiency, but social sustainability outcomes are relatively underdeveloped. The technological limitations, lack of skills, organizational resistance, investment needs, and lack of data capabilities are significant obstacles. These results are then combined in an integrative framework and priorities for future research are suggested.

Keywords: Lean Six Sigma; Digital Transformation; Sustainability; Industry 4.0; LSS 4.0; DMAIC; Operational Excellence; Sustainable Operations

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Introduction

The modern operations setting is dynamic and complex, and involves the joint achievement of goals that were previously dealt with individually by management efforts. Organizations are expected to increase productivity and quality, decrease costs and process variation, increase resilience, embrace data-driven technologies and meet steadily growing requirements for environmental and social sustainability. Therefore, operational excellence cannot be measured only in terms of cost, throughput, quality or productivity, but also on resource consumption, environmental impacts, employment related outcomes and long-term resilience. The management of operations is thus turning towards synergic solutions that prioritize process improvement, digitalization and sustainability in mutually reinforcing ways (de Freitas et al., 2017; Marques et al., 2025).

Lean Six Sigma (LSS) is one of the key methodologies of operational excellence and continuous improvement. It integrates Lean's principles of minimizing non-value-adding activities and enhancing process flow with Six Sigma principles of minimizing

the variability, defects, and process instability from data-driven decision making (Cherrafi et al., 2016; Kumar et al., 2023). The DMAIC (Define–Measure–Analyze–Improve–Control) approach it uses gives a structured process to identify process problems, then find their root causes, make improvements and maintain performance. Studies show that LSS can enhance product quality, productivity, cost effectiveness, process performance and/or organizational sustainability in various contexts, such as manufacturing (de Freitas et al., 2017; Kumar et al., 2023). But as operations grow more complex and data more intensive, conventional LSS have been found to be challenged in its application without the digital skills needed.

The opportunities for extending LSS beyond the traditional realm of improvement have increased as a result of Industry 4.0 and other aspects of digital transformation. Digital transformation is the process of incorporating digital technologies into the value creation, capabilities, decisions, and processes of an organization. The Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Big Data

analytics, Digital twins, Augmented Reality (AR) and Robotics technologies create an abundance of operational information (OI) with higher granularity (Citybabu & Yamini, 2023; Endrigo Sordan et al., 2024). Their incorporation into LSS has led to the development of new concepts such as Lean Six Sigma 4.0 and Digital Lean Six Sigma which represent more continuous and connected systems of improvement, with a predictive and data-driven approach (Alsadi et al., 2025; Skalli et al., 2023; Skalli et al., 2025).

One of the critical relationships is between digital technologies and DMAIC. Real-time data collection can enhance the Measure phase of the quadruple phase of the DOTM process with IoT, and Analyze (with the help of Big Data analytics and machine learning) can identify patterns, anomalies, and potential root causes. Digital twins and simulation can aid Improve as they allow for testing of alternative process configuration in a virtual environment, while connected monitoring and predictive analytics can assist Control by monitoring performance constantly (Endrigo Sordan et al., 2024; Mojumder, 2025). Digital transformation could thus accelerate the rate, accuracy, scalability and predictability of LSS. The organizational ability, skills and training of employees, leadership, and technological readiness and implementation conditions are also essential for successful digitalization (Alsadi et al., 2025).

Sustainability has also shifted from being a mostly environmental issue to being a major focus of operations management, taking place concurrently. Organizations must strive to balance environmental, social and economic aspects when operating their business in a sustainable way. The environmental goals are to minimize material usage, waste, energy consumption, and emissions; the economic goals are to focus on productivity, cost efficiency, quality, and long-term viability; and the social goals are to focus on employee health and safety, and workforce development. This has led to such strategies as Green Lean, Sustainable Lean Six Sigma (SLSS), and Green Lean Six Sigma (GLSS), which combine continuous-improvement processes with sustainability concerns (Cherrafi et al., 2016; Ghasemibojd et al., 2025; Walter et al., 2021; Yadav et al., 2023).

The relationship between LSS and sustainability is gaining traction, but varied outcomes emerge depending on the form of waste being dealt with, indicators used, context of organizations, and depth of integration of environmental and social goals into improvement projects. Previous studies showed the potential role of LSS in organizational sustainability (de Freitas et al., 2017) and later studies indicated that Green Lean Six Sigma and Sustainable Lean Six Sigma were two emerging research streams (Ghasemibojd et al., 2025; Walter et al., 2021; Yadav

et al., 2023). Recent studies have tied Lean, Green, Sustainability, and Industry 4.0, suggesting that digital technologies can offer further capabilities for operational improvement with sustainability aspects (Vilaça et al., 2026).

The intersection of these fields is a new field in the operations research area. Conceptually, LSS is the methodology for process improvement and the discipline of continuous improvement, digital transformation is about connectivity, real-time visibility, advanced analytics, prediction and automation, and sustainability is about the new type of performance orientation, which includes economic, environmental and social outcomes. Their integration can then help to move towards digitized sustainable operational excellence (Alsadi et al., 2025; Citybabu & Yamini, 2023; Skalli et al., 2023; Yadav et al., 2023). However, there is a lack of coherence on the literature. LSS and operational excellence is a relatively developed research area, and LSS–sustainability and LSS–Industry 4.0 have grown as distinct areas (Kumar et al., 2023; Skalli et al., 2023). While the convergence of Lean, Green, Sustainability and Industry 4.0 is being established by Vilaça et al. (2026), a more specific study of Lean and Green Sustainability is needed, as Six Sigma offers some unique statistical process control, variation reduction, data analysis, and DMAIC capabilities. However, recent findings also suggest that there are unanswered questions regarding the LSS digitalization, organizational readiness, skills of the labor force and implementation needs (Alsadi et al., 2025).

One particular research gap is the lack of synthesis of types of digital technologies and their interaction with LSS practices or DMAIC stages to produce multidimensional sustainability outcomes. The consistency of measurement is also inconsistent, as studies tend to focus on one of the outcomes (operational, environmental, economic, or social) with little attention to the others. There is thus a lack of clarity about whether digitalized LSS creates integrated sustainability benefits or provides mainly improvements in selected aspects of the operational performance. Furthermore, there is a need to synthesize the findings across studies in terms of organizational and human factors (such as leadership, digital readiness, employee skills and competencies, training, culture, technological compatibility, and data capacities) (Alsadi et al., 2025; Ghasemibojd et al., 2025; Skalli et al., 2023).

The need for synthesis is reinforced by methodological and contextual gaps. Conceptual frameworks, case studies and literature reviews have been common methods already used in existing studies and the studies are mostly centred around manufacturing environments. More comparative evidence would be

beneficial for industries, sizes of organisations, geographical locations, digital maturity, especially in SMEs and service operations under varying technological, financial and human-resource constraints. Accordingly, this study conducts a systematic literature review with bibliometric and thematic analysis of the intersection of LSS, digital transformation, and sustainability in operations. It examines research evolution, digital technologies associated with LSS and DMAIC, operational and sustainability outcomes, implementation barriers and enablers, and unresolved theoretical, methodological, technological, and contextual issues. Based on this synthesis, an integrative conceptual framework is developed linking LSS capabilities, digital transformation technologies, organizational conditions, and multidimensional sustainability performance. The study therefore seeks to complement existing reviews of LSS 4.0, Green Lean Six Sigma, and broader Lean–Green–Sustainability 4.0 research while establishing a focused evidence base and future research agenda for integrated sustainable digital operations.

The study addresses the following research questions:

RQ1. How has research at the intersection of Lean Six Sigma, digital transformation, and sustainability in operations evolved over time, and what are its dominant thematic clusters?

RQ2. Which digital technologies are most frequently associated with Lean Six Sigma practices and different stages of the DMAIC framework, and what roles do they perform?

RQ3. What operational, economic, environmental, and social outcomes have been reported from the integration of Lean Six Sigma, digital transformation, and sustainability, and how are these outcomes measured?

RQ4. What organizational, technological, and human factors act as barriers or enablers to the successful integration of Lean Six Sigma, digital transformation, and sustainability?

RQ5. What theoretical, methodological, contextual, and empirical gaps remain, and what research directions can be derived from the existing evidence?

The study contributes with three main contributions. Firstly, it adds to the theoretical advancement of operations-management research, introducing the LSS, digital transformation, and sustainability views in the same analytical framework and acknowledging the organizational and technological context that might impact how they interact. Second, it adds to the literature by systematically mapping and synthesizing the evidence, which is spread across the research streams LSS 4.0, Sustainable/Green Lean Six Sigma and digital sustainability. Thirdly, it offers operational and research-based implications by highlighting the

technologies, capabilities, outcomes, barriers, and contextual factors that are important for organizations when pursuing a combination of operational excellence and digitalization and sustainability. The study outlines a framework for research to support the next generation of digitally enabled sustainable operational excellence.

2. Research Methodology

2.1 Research Design

The current study used a Systematic Literature Review (SLR) approach to explore the relationship among Lean Six Sigma (LSS), Digital Transformation (DT) and Sustainability in operations. The purpose of the review was to systematically identify, appraise and synthesize the literature available in scholarly form, and not to pick and choose publications in a narrative fashion. To achieve both quantitative and qualitative aspects on the research domain, the SLR was supplemented with bibliometric analysis and thematic synthesis. The development and the intellectual structure of the field were explored with the bibliometric component, the collaboration patterns were explored, and the thematic evolution was conducted, and thematic synthesis was conducted to identify substantive relationships between LSS practices, digital technologies, sustainability dimensions, implementation factors and operational outcomes. The literature selection process is reported according to the PRISMA 2020.

2.2 Literature Search Strategy

The literature search was undertaken via the Scopus database and PUBMED database as it was chosen for its broad coverage of operations management, manufacturing, quality management, sustainability and digital transformation research, thus offering a multidisciplinary approach. The search methodology was designed according to the main concepts studied: Lean Six Sigma, digital transformation and sustainability. Synonyms and closely related terms were added to capture the different ways terms are used in various research streams.

The search was conducted within the TITLE-ABS-KEY fields of Scopus. The Lean Six Sigma component included terms such as “Lean Six Sigma,” “Six Sigma,” “Lean manufacturing,” “Lean management,” “Lean production,” “DMAIC,” “LSS 4.0,” and “Digital Lean Six Sigma.” The digital transformation component included “digital transformation,” “Industry 4.0,” “smart manufacturing,” “Internet of Things,” “artificial intelligence,” “machine learning,” “big data,” “digital twin,” “process mining,” “cyber-physical systems,” robotics, and automation. The sustainability component incorporated terms including “sustainab*,” “sustainable operations,” “sustainable manufacturing,” “Green Lean,” “Green Lean Six Sigma,” “Sustainable Lean Six Sigma,” “circular

economy,” “environmental performance,” “resource efficiency,” and “social sustainability.”

The resulting Boolean search expression was structured as follows:

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TITLE-ABS-KEY(  
("lean six sigma" OR "six sigma" OR "lean  
manufacturing" OR  
"lean management" OR "lean production" OR  
DMAIC OR "LSS 4.0"  
OR "digital lean six sigma")  
AND  
("digital transformation" OR "industry 4.0" OR  
"smart manufacturing" OR "internet of things" OR IoT  
OR  
"artificial intelligence" OR "machine learning" OR  
"big data" OR "digital twin" OR "process mining" OR  
"cyber-physical systems" OR robotics OR automation)  
AND  
(sustainab* OR "sustainable operations" OR  
"sustainable manufacturing" OR "green lean" OR  
"green lean six sigma" OR "sustainable lean six sigma"  
OR  
"circular economy" OR "environmental performance"  
OR  
"resource efficiency" OR "social sustainability")  
)
```

A search strategy was tried before the final retrieval to determine if the search terms collected literature that was relevant to the research question while minimizing literature that was irrelevant to the research question. The final search date, search filters, retrieved records and exported bibliographic dataset were recorded to facilitate the possibility of reproducing the results.

2.3 Inclusion and Exclusion Criteria

A screening process was preceded by the development of eligibility criteria. Accepted publications included peer-reviewed and English-language research/review articles listed in Scopus, and that had a substantive connection with Lean Six Sigma or related Lean/Six Sigma approaches as well as with digital transformation, Industry 4.0, digital technologies, sustainability or sustainable operations. The studies also had to be rich enough in bibliographic and substantive information so they could be systemically extracted and analyzed. Editorials, letters, notes, conference abstracts, book chapters, and non-relevant publications were excluded. Research articles that only used the key concepts as a terminology, without explicitly examining them in relation to operational improvement, digitalization or sustainability were excluded.

2.4 Screening and Study Selection

The bibliographic records were retrieved from Scopus and then exported for screening and reference management. Pre-eligibility check for the presence of

duplicate records and removal of the duplicate records. Titles and abstracts of the other publications were initially used to screen the publications. Those articles that were apparently relevant were then given full-text analysis. Studies were excluded at this stage if they failed to meet the pre-established eligibility criteria or the information in the study was not relevant to the research questions. The reasons for exclusion at the full-text stage were documented to ensure transparency of selection.

The entire selection process was presented in a PRISMA 2020 flow chart, showing the number of records identified, the number of duplicates removed, the number of records screened, the number of records excluded, the number of full text publications assessed, the number of articles excluded with reasons and the number of studies that were included for the final synthesis. The numbers in the PRISMA diagram were directly obtained from the search and screening process in Scopus, and not estimated.

2.5 Data Extraction and Coding

A data extraction matrix was created in a structured form to systematically document the features and results of the publications included. The bibliographic data (such as authorship, year of publication, journal, DOI, country, keywords, and citation information) was taken from the Scopus records. Full-text analysis was then performed to identify the context at which the research was conducted, the approach used, the LSS practices, the DMAIC stage (if any), the type of digital technologies studied, the sustainability dimensions focused on, the operational outcomes reported, the barriers to implementation, the enabling factors, the theoretical perspectives, the main findings, and the research limitations identified. The evidence identified was then synthesized in a standardized coding system for the four main dimensions of LSS characteristics, digital transformation characteristics, sustainability outcomes, and contextual/implementation factors. The focus was on the relationships between individual digital technologies and LSS activities to be captured, rather than a holistic approach to digital transformation. Likewise, sustainability outcomes were split into operational, economic, environmental and social categories to allow for comparison between studies.

2.6 Bibliometric Analysis

In order to analyze trends in publications per year, influential publications, leading journals, productive authors, countries contributing to the publications and institutional contributions, the descriptive bibliometric analysis was performed first. This analysis gave an overview of the development and distribution of research in the field. The literature was then analysed using network analysis in order to explore the intellectual and social structure of the literature. The

relationships between the most common research concepts were revealed by keyword co-occurrence analysis, and the presence of thematic clusters was detected. Collaborative patterns of research were investigated by co-authorship analysis and influential intellectual foundations were analyzed using co-citation analysis. A contemporary research cluster analysis was performed using bibliographic coupling to determine the research clusters in the similar references cited. Thematic development and evolution in the literature were also explored using the Bibliometrix/Biblioshiny. Thematic mapping and temporal analysis helped to identify the existing, emerging, declining, and developing research themes and to put the relationship between LSS, digital transformation, and sustainability research in time.

2.7 Thematic and Evidence Synthesis

The bibliometric results were supplemented by a qualitative process of thematic synthesis of the included publications. The full-text evidence was analyzed for how LSS practices were actually linked with digital technology in operational contexts, and what operational outcomes were reported, in addition to examining keywords.

The synthesis highlighted especially the link between digital technologies and the DMAIC improvement cycle, and identified evidence of the use of digital technologies such as IoT, artificial intelligence, machine learning, big-data analytics, digital twins, process mining, and automation for various improvement activities. It also analyzed if the applications mentioned were linked to any improvements in the operational performance, economic performance, environmental performance or social sustainability.

The literature was then reviewed for common organizational, technological and contextual factors that impact implementation. These encompassed leadership and management support, organizational culture, workforce capabilities, digital readiness, technological infrastructure, data quality, interoperability, legacy systems, investment requirements and resistance to organizational change.

2.8 Research Gap Analysis and Framework Development

The gaps in the literature were determined by synthesizing the results of the bibliometric analysis with the evidence from the thematic synthesis. Gaps were explored at the theoretical, methodological, technological, empirical and contextual level. Special emphasis was given to the areas that had been identified as having high literature activity but not much empirical evidence, inconsistent outcome measurement, little or no theoretical explanation, or little or no investigation across varying organizational and geographical contexts.

The last synthesis was employed to construct an integrative conceptual framework that depicts the relationships that are identified in the literature. The framework links the capabilities of Lean Six Sigma, the capabilities of Digital transformation, the mechanisms of Operational improvement, and the multiple sustainability outcomes. The framework is designed to be a representation of the available evidence and should not be interpreted as an empirically proven causal model.

2.9 Methodological Rigor and Reproducibility

The methodological rigor was ensured by the use of predefined search terms, explicit eligibility criteria, systematic screening, structured data extraction, and standardized bibliometric procedures. A search strategy and screening process were documented to facilitate reproducibility and the evidence-extraction framework ensured consistency in the classification of the selected studies. The methodological triangulation offered by the combination of bibliometric mapping and thematic synthesis also enabled for the examination of patterns found quantitatively within the publication data against the substantive findings which were reported in the primary literature.

3. Results

3.1 Literature Selection and Characteristics

Bibliographic databases, such as PubMed and Web of Science, were used for literature search. The search strategy aimed to find publications that examined the link between Lean Six Sigma (LSS) and the digital transformation and Industry 4.0 related technologies, as well as operational contexts and sustainability. Searches were conducted and records from both databases were retrieved and merged and duplicates were screened out. After the title and abstract screening and full-text eligibility assessment based on defined inclusion and exclusion criteria 50 publications were kept for final evidence synthesis. In the screening and full-text assessment phases, records that did not meet the eligibility criteria and records that were not considered to be substantive enough for integration of Lean Six Sigma, digital transformation and sustainability were excluded.

The study-selection process was done based on PRISMA 2020 protocol. The records that were identified via the database search were first evaluated for eligibility and then the titles and abstracts were screened, after which the full text of potentially relevant publications were assessed. The final set of 50 publications were the results of evidence synthesis and formed the evidence base for the thematic synthesis of Lean Six Sigma, digital transformation, and the integration of sustainability. The present review focused on PubMed and as such, the evidence base is therefore not comprehensive of the broader

multidisciplinary evidence on operations-management.

The publications covered in this book were published between 2016 and 2026, highlighting the relatively new nature of the research that looks at the convergence of operational excellence, digital transformation and sustainability. The evidence base included several methodological approaches, such as systematic and narrative literature reviews, bibliometric analyses, development of conceptual frameworks, empirical studies, case studies, and analytical modelling. The literature hence was at various stages of evidence maturation, from conceptual propositions and framework development to empirical investigation of integrated LSS, digital and sustainability practices.

Studies of different operational contexts. A significant research environment was manufacturing, covering sustainable manufacturing, automotive manufacturing, electronics manufacturing, implementation of Industry 4.0, digital twins and applications concerning circular economy. The evidence also covered companies in the healthcare, telecommunication, supply-chain, digital technology, academic research laboratory and small and medium businesses sectors. The spread of studies across sectors suggests that the topic of Lean Six Sigma and digital transformation and sustainability is being explored outside of traditional manufacturing contexts, but is not equally present.

The geographical dimension of the literature included was international. The studies were from countries and regions such as Italy, India, Pakistan, Brazil, Taiwan, Moroccan, Egypt, and Indonesia, and others. Specifically, a significant portion of the research in the evidence base concerned sustainable implementation of Lean Six Sigma, critical success factors, manufacturing and integration of Industry 4.0, particularly for the Indian context. In addition, there were a number of studies that did not focus on a specific geographical context, but rather covered a wider international and/or literature-based approach, with European and other Asian contexts also represented.

The characteristics of the literature included suggest a gradual shift from studies addressing mainly the Lean/Six Sigma and Sustainability linkage to more comprehensive studies that involve the incorporation of Industry 4.0, Digital Transformation, Artificial Intelligence, Digital Twins, Data Analytics and other digital technologies. It is therefore informative to review the individual evolution of these research streams, and also the degree of integration between the various streams into a holistic framework of 'digitally enabled sustainable operational excellence'.

3.2 Bibliometric and Thematic Structure

The literature reviewed shows that the research interest in the convergence of LSS, Digital Transformation and Sustainability is continuously increasing. The earliest of the selected evidence base dates back to 2016, when Cherrafi et al. studied the integration of lean manufacturing and Six Sigma and sustainability and called for an integrated model that combines operational improvement and sustainability goals. Later during the late 2010s, the major focus of the research was on the integration of sustainability concepts in Lean and Six Sigma, and the research articles included studies on the green effects and sustainability integration in LSS projects (Chugani et al., 2017; Erdil et al., 2018). Through this early stage, sustainability became more than just an operational goal – it was an extension of operational excellence. In the literature, digital technologies and Industry 4.0 became more and more part of the research stream of LSS from 2020 onwards. Swarnakar et al. (2020) reviewed the critical success factors for the implementation of sustainable LSS in manufacturing companies, and Chiarini and Kumar (2020) analyzed the integration of LSS and Industry 4.0 for operational excellence in Italian manufacturing companies. In the same time period, research into sustainable production frameworks and implementation models was also being developed, suggesting that at the start of the research period, researching digitalisation and sustainability emerged as two separate yet partly overlapping research streams (Parmar & Desai, 2020; Tiwari et al., 2020).

Literature since 2021 shows a greater linkage between LSS, Digital Transformation and sustainability. Walter et al. (2021) summarized the evolution of sustainable LSS frameworks and Prakash et al. (2021) performed a bibliometric analysis of the general evolution of LSS research. Later studies focused increasingly on the consideration of Industry 4.0 technologies, digitalization and digitally enabled LSS. The volume of studies published from 2023 to 2025 focused on the notion of 'Lean Six Sigma 4.0 (LSS4.0)' and how Industry 4.0 technologies were combined with DMAIC, along with the creation of structured frameworks for digitally enabled operational excellence (Citybabu & Yamini, 2023a, 2023b; Pongboonchai-Empl et al., 2024; Skalli et al., 2024; Alsadi et al., 2025).

The literature included in the study has been synthesized in a thematic way that reveals three research streams that are closely related. The first relates to Sustainable Lean Six Sigma and Green Lean Six Sigma in which environmental and sustainability goals are integrated into traditional Lean and Six Sigma improvement processes. This stream addresses issues related to sustainable LSS frameworks, critical success and failure factors, green impacts, and

sustainability and LSS integration (Walter et al., 2021; Marques et al., 2025; Chugani et al., 2017; Ghasemibojd et al., 2025). More recent research has continued this line towards Green Lean Six Sigma and sustainable development, suggesting a gradual focus on the systematic incorporation of environmental performance into operational improvement.

The second stream is dedicated to Lean Six Sigma and Industry 4.0/digital transformation. The literature here explores how digital technologies can enhance the data driven and structured problem-solving attributes of LSS. The research covers Industry 4.0 integration frameworks, Digital transformation of LSS practices, Digital twin applications and Digital technologies across DMAIC methodology (Chiarini & Kumar, 2020; Citybabu & Yamini, 2023b; Maheshwari & Devi, 2024; Pongboonchai-Empl et al., 2024; Alsadi et al., 2025). LSS4.0 is a new conceptual stream, which points to a transition from digital technologies being seen as standalone improvement technologies to a view of digitalization as an enabler of the overall transformation of LSS.

The third stream refers to the intersection of LSS, digital transformation and overall sustainability goals. Recent research and studies have started to consider these aspects at the same time, for example, in relation to sustainable manufacturing, a circular economy, energy efficiency, Industry 5.0, and digital sustainability. For instance, Ibrahim and Kumar (2025) explored critical success factors of an LSS–Industry 4.0 framework geared towards sustainable manufacturing, and Shrivastava and Mishra (2025) analyzed the relationship between LSS, Industry 4.0, and the development of the circular economy. Santos et al. (2025) also expanded this integration towards sustainable energy improvement, following a Lean Six Sigma 4.0 agenda. The same trend of integrating various aspects of operations and industry into a single analytical approach is reflected in the recent research focused on Green Lean Six Sigma and Industry 5.0 (Boumsisse et al., 2025; Ghasemibojd et al., 2025; Beloor et al., 2026).

In these streams, there are some common ideas holding the intellectual development of the field. The concepts of Lean Six Sigma, DMAIC, Industry 4.0, digital transformation, sustainability, operational excellence, digital twin, data-driven decision-making, Green Lean Six Sigma, and circular economy were recurring conceptual anchors in the literature reviewed. These concepts—digital twin, artificial intelligence, data analytics, and Industry 4.0—are now becoming more common in the more recently published papers, which signify a shift from traditional process improvement methods to digitally supported improvement systems. Meanwhile, sustainability concepts have moved beyond the dimension of waste

reduction in the environment to the dimension of resource efficiency, the circular economy, sustainable manufacturing, and sustainability performance in general.

In terms of the publication trend, a conceptual development from LSS and sustainability integration, to LSS and Industry 4.0 integration, and finally to the more recent combination of LSS, digital transformation and sustainability is illustrated. This evolution can also be seen in the recent studies on the use of terms like LSS4.0, digital Lean Six Sigma, sustainable digital operations, circular economy, and digitally enabled sustainable manufacturing by several authors (Citybabu & Yamini, 2023b; Skalli et al., 2024; Santos et al., 2025; Wankhede & Agrawal, 2025). Lean Six Sigma is no longer considered as three distinct areas of research but is instead becoming the frame for process improvement, the technology and analysis that enable it, and the multiple dimensions of performance that are the goal of the process.

Evidence from the bibliometric analysis and thematic analysis then suggests that the field is evolving toward an integrated approach of digitally supported sustainable operational excellence, but with varying empirical integration. There is still a considerable amount of literature that concentrates on the two-dimensional linkage between LSS and sustainability or LSS and Industry 4.0, whilst relatively less work has examined the triple-twin relationship between the three dimensions in an empirical study of a single operational context. The pattern serves as a foundation for the study of how specific digital technologies are being adopted into LSS practices and how the adoption of the technologies impacts on the operational, economic, environmental, and social results.

Table 1. Characteristics and Thematic Structure of the Evidence Base

Category	Findings from the reviewed literature
Evidence base	50 publications, 2016–2026
Research evolution	Early emphasis on LSS–sustainability; increasing LSS–Industry 4.0 integration from 2020; stronger LSS4.0 and three-way LSS–digital–sustainability integration during 2023–2026

Dominant sector	Manufacturing
Other sectors	Healthcare, telecommunications, supply chain, digital technology, academic research laboratories and SMEs
Major geographical contexts	India, Italy, Pakistan, Brazil, Taiwan, Morocco, Egypt, Indonesia and international/literature-based studies
Major methodological approaches	Literature/systematic reviews, bibliometric studies, conceptual frameworks, empirical studies, case studies and analytical modelling
Theme 1	Sustainable/Green Lean Six Sigma: sustainability integration, environmental performance, waste reduction and resource efficiency
Theme 2	LSS and Digital Transformation/Industry 4.0: IoT, AI/ML, Big Data, digital twins, automation and DMAIC integration
Theme 3	Integrated LSS–Digital–Sustainability: sustainable manufacturing, circular economy, energy efficiency, Industry 5.0 and digitally enabled sustainable operations

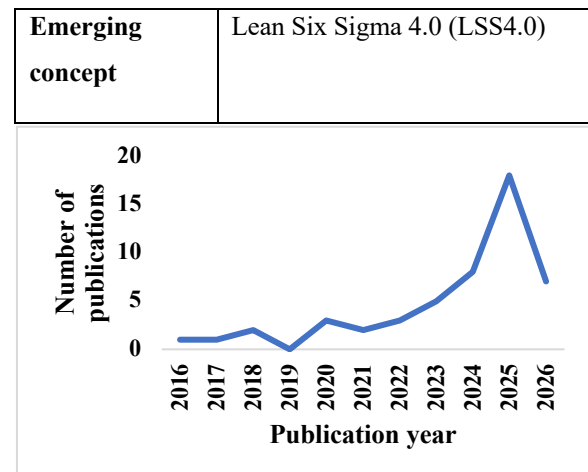


Figure 1. Publication trend of studies included in the systematic literature review, 2016–2026

3.3 Integration of Lean Six Sigma and Digital Transformation

The literature reviewed shows a continuous incorporation of the digital transformation technologies into LSS, especially under the paradigm of Industry 4.0. The integration has been gradually moving away from the traditional, data-driven improvement process and towards a digitally facilitated process with real-time data collection, sophisticated analytics, automation, simulation, and intelligent decision-making. This convergence has been described by recent studies as Lean Six Sigma 4.0 (LSS4.0) that digital technologies are systematically integrated into LSS instead of them being treated as standalone technological interventions (Citybabu & Yamini, 2023a, 2023b; Skalli et al., 2024; Alsadi et al., 2025).

3.3.1 Digital Technologies Associated with Lean Six Sigma

There have been a number of Industry 4.0 and digital technologies that have been linked to LSS implementation. IoT, AI, ML, Big Data analytics, digital twins, data mining, robotic process automation (RPA), and other connected digital technologies. The use of these technologies reinforces the data driven basis for LSS by facilitating data collection, processing, interpretation and leveraging of process data (Chiarini & Kumar, 2020; Citybabu & Yamini, 2023a; Pongboonchai-Empl et al., 2024).

Opportunities exist with the use of IoT and connected sensing technologies to continuously monitor the process and acquire data in real time. Process data can be gathered periodically in a traditional LSS project, and digital systems can offer more detailed and frequent data on process conditions in connected systems. This helps in the early detection of process variation and helps in evidence-based decision making

during the improvement cycle (Citybabu & Yamini, 2023a; Pongboonchai-Empl et al., 2024).

AI and ML are playing a growing role in digital LSS. The technologies can be used for in-depth analysis of large-scale data, pattern recognition, prediction of process behaviour, and detection of abnormalities. The application of AI-related research methods in the field of LSS research also shows that AI's relevance extends beyond its use as an operational technology to understanding and enhancing LSS practices, as well (Madzik et al., 2025). With the rise of the use of AI, data analytics, and digitalization, LSS has been turning to more intelligent and predictive approaches to process improvement (Alsadi et al., 2025; Torno, 2026).

LSS can be further enhanced by the use of Big Data analytics and data-mining techniques. They are especially applicable in an application where the organizations are storing a large number of different process data. Organizations can leverage LSS statistical thinking and powerful data-analysis tools to uncover relationships and patterns within the processes that might not be apparent through traditional analytical methods alone (Pongboonchai-Empl et al., 2024; Wankhede et al., 2024).

A promising development to the integration of LSS and digital transformation is the concept of a digital twin. Digital Twins allow a virtual representation of a physical process or system and can be used for performance evaluation, simulation and improvement alternative assessment. Maheshwari and Devi (2024) studied the linkage between LSS performance strategies and digital twin modelling, and Mojumder (2025) discussed digital-twin based framework for the manufacturing efficiency evaluation. The aforementioned studies illustrate how digital twins can contribute to improving process understanding and informing decision making for improvement prior to or during implementation in physical processes.

RPA is a type of digital integration but is more oriented towards process automation than in-depth analytical modelling. In the healthcare sector, Huang et al. (2024) illustrated how RPA could be used in a healthcare context to support lean digital transformation. This suggests that digital LSS is not limited to manufacturing and can also be used in administrative and service processes, where repetitive processes, process delays are sources of inefficiencies.

3.3.2 Distribution Across DMAIC Stages

Digital technologies and LSS are tightly coupled with the DMAIC approach. The literature reviewed suggests that digital technologies can be used in various activities throughout the Define, Measure, Analyze, Improve and Control stages, but not the same ones at each stage. In a specific study, Pongboonchai-Empl et al. (2024) analysed the use of Industry 4.0

technologies in LSS DMAIC and found digitalization can improve the methodological competence of LSS.

Digital technologies can support problem identification, process visualization, identification of improvement requirements and setting of performance objectives during the Define phase. The evidence base is less specific in Define compared to the other DMAIC phases.

IoT and connected sensors, automated data collection and digital monitoring are significant advantages for the Measure phase. These technologies provide more information on the process and can enable more continuous monitoring of critical process parameters. Therefore, the traditional measurement function of LSS can be reinforced by real-time data collection and digitally connected (Chiarini & Kumar, 2020; Pongboonchai-Empl et al., 2024).

One of the most significant parts of digital integration is the Analyze phase. Advanced capabilities include identification of patterns, relationships and abnormalities, as well as possible causes of process variation using Big Data analytics, data mining, AI and ML. As a result, the implementation of Industry 4.0 technologies broadens the scope of the analytical tools that are usually linked to statistical analysis in Six Sigma (Pongboonchai-Empl et al., 2024; Wankhede et al., 2024).

Digital twins, simulation, automation and predictive technologies can be used to evaluate and optimise potential interventions during the Improve phase. Digital twin applications are significant as it allows to consider various process configurations or improvement scenarios in a virtual environment (Maheshwari & Devi, 2024; Mojumder, 2025).

Real-time monitoring, automated data collection and predictive analytics, and digitally-enabled process control can support the Control phase. The capabilities can help the organizations to detect deviations and act on the process changes. The literature also suggests that the empirical evidence of the fully integrated mechanisms of digital control is less advanced compared to the conceptual discussion about LSS4.0 (Skalli et al., 2024; Alsadi et al., 2025).

Table 2. Integration of Digital Technologies Across DMAIC and Their Operational Roles

Digital technology	Define	Measure	Analyze	Improve	Control	Principal role	Supporting references
IoT /	○	●	●	○	●	Real-time	Chiarini &

sensors						process data acquisition and continuous monitoring	Kumar (2020); Cityabu & Yami ni (2023); Pongboonchai-Empl et al. (2024); Wan khed e et al. (2024)
AI / Machine Learning	○	○	●	●	●	Prediction, pattern recognition, anomaly detection and decision	Cityabu & Yami ni (2023); Pongboonchai-Empl et al. (202

						ion supp ort	4); Madz ik et al. (202 5); Alsa di et al. (202 5)
Big Data / Data analy tics	●	●	●	●	●	Larg e- scale proce ss analy sis and data- drive n decis ion- maki ng	Cityb abu & Yami ni (202 3); Wan khed e et al. (202 4); Pong boon chai- Empl et al. (202 4); Alsa di et al. (202 5)

Digital twins	○	○	●	●	●	Virtual process representation, simulation and optimization	Mareshwari & Devi (2024); Mojunder (2025); Skalli et al. (2024)
Process mining / Data mining	●	●	●	●	○	Process discovery, pattern identification and root-cause analysis	Pongboonchai-Empl et al. (2024); Cityabu & Yami (2023)
RPA / Automation	○	●	○	●	●	Automation of repetitive activities	Huang et al. (2024); Alsaadi et

						and process improvement	al. (2025)
Predictive analytics	○	○	●	●	●	Prediction of process deviations and future performance	Chiarini & Kumar (2020); Pongboonchai-Empl et al. (2024); Wan Khedde et al. (2024)
Connected dashboards / monitoring	●	●	●	○	●	Process visualization, performance monitoring and	Chiarini & Kumar (2020); Wan Khedde et al. (202

						contr ol	4); Alsa di et al. (202 5)
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3.3.3 Evolution Toward Lean Six Sigma 4.0

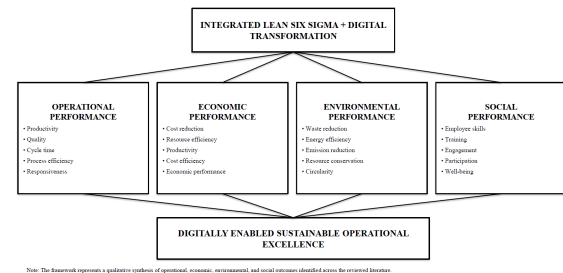
The literature reviewed reflects the evolution of traditional LSS to Lean Six Sigma 4.0. At first, Industry 4.0 technologies were mostly perceived as "complementary" technologies that can enhance certain LSS activities. Later, conceptual and operational frameworks that incorporate digital technologies into LSS methodology were developed (Chiarini & Kumar, 2020; Citybabu & Yamini, 2023a, 2023b).

Citybabu and Yamini (2023b) conceptualized LSS4.0 as an approach to adapting LSS practices with the digital era; another design-science-based framework to integrate LSS and Industry 4.0 was developed by Skalli et al. (2024). Recent research builds on this by looking at digitalization from the practitioners' and organizations' perspectives (Alsadi et al., 2025; Torno, 2026). Accordingly, the evolution is from technology-supported LSS to digitally connected LSS, involving the integration of connectivity, analytics, automation and intelligent technologies into systems of continuous improvement.

The integration is increasingly not only limited to Industry 4.0, but also to Industry 5.0 ideas. Boumsisse et al. (2025) explored the optimization of Green Lean Six Sigma using Industry 5.0 technologies, suggesting the development of a new generation in which the concept of digital transformation is introduced into the sustainability and human-centred approach. As a result, LSS4.0 is now seen more than just as a technological enhancement of LSS, but as a holistic solution for operational excellence, digital transformation and sustainability.

3.4 Sustainability and Operational Outcomes

The literature reviewed shows that 'Lean Six Sigma' plus sustainability moves beyond quality, cost and efficiency to sustainability issues related to the environment, the economy and society. The aim of sustainable LSS frameworks is to achieve waste minimisation, process efficiency, resource conservation and environmental performance, and the latest research has increasingly associated these goals with the implementation of digital transformation and Industry 4.0 technologies (Cherrafi et al., 2016; Chugani et al., 2017; Walter et al., 2021; Ghasemibojd et al., 2025).



Note: The framework represents a qualitative synthesis of operational, economic, environmental and social outcomes identified across the reviewed literature.

Figure 3. Multidimensional performance outcomes of integrated Lean Six Sigma and digital transformation.

3.4.1 Operational Outcomes

The result of LSS implementation that is consistently reported is operational performance. The analyzed studies link LSS to increased process efficiency, productivity, quality, waste reduction, process performance and operational excellence. The benefits have been demonstrated in different contexts, such as manufacturing, healthcare, logistics and more (Chiarini & Kumar, 2020; John & Kadadevaramath, 2020; Sordan et al., 2022; Muhammad et al., 2022).

By leveraging digital technologies, these operational outcomes can be further enhanced, with increased process visibility, data availability, analytical capability and responsiveness. Improved process monitoring and data-driven improvement are some of the factors that have been linked to operational excellence when integrating Industry 4.0 and LSS (Chiarini & Kumar, 2020). Likewise, empirical studies of LSS and Industry 4.0 have identified operational characteristics related to the integration of these two, and the significance of digital skills in process improvement systems is further highlighted by the fact that it is becoming increasingly important in the field of process improvement (Wankhede et al., 2024).

Based on the evidence presented above, it is concluded that operational excellence is still an integral part of the integrated LSS, and digital transformation offers more avenues for measuring, analyzing, and enhancing process performance.

3.4.2 Economic Outcomes

Operational improvements resulting from LSS are linked to the economic outcomes. These factors can contribute to improving economic performance of organizations, such as a reduction in process waste, better resource usage, higher productivity, better process efficiency and elimination of non-value adding activities (Cherrafi et al., 2016; Tiwari et al., 2020; Marques et al., 2025).

Digital technologies' integration into the business process could still positively affect economic performance by providing increased process intelligence, decreasing manual processes, and

enabling more efficient resources allocation. But digital transformation comes with its own set of implementation considerations such as technology investments, the need to train employees, build infrastructure and adapt to the changes. Therefore, the economic value of integrated LSS and digital transformation should be viewed in terms of expected efficiencies and implementation considerations (Ibrahim & Kumar, 2025; Alsadi et al., 2025).

The latest research is increasingly focused on the assessment of LSS projects from a wider range of performance perspectives, rather than solely based on the direct cost cutting. Thus, sustainable LSS frameworks try to reconcile economic performance and environmental and operational goals (Walter et al., 2021; Marques et al., 2025).

3.4.3 Environmental Outcomes

One of the most widely analyzed aspects of sustainability found in the literature reviewed is environmental performance. Lean, Six Sigma and sustainability have been found to be integrated to provide waste reduction, resource efficiency, energy improvements and environmental impact reductions (Cherrafi et al., 2016; Chugani et al., 2017; Erdil et al., 2018).

Huang et al. (2023) studied the correlation between the principles of LSS and data-driven decision making and sustainable manufacturing environmental performance. This shows an example of how analytical and improvement skills of LSS can play a role in achieving environmental goals, if sustainability indicators are included in the decision-making process.

The environmental dimension has also evolved to Green Lean Six Sigma. In recent reviews and frameworks, the incorporation of environmental goals into the conventional LSS approaches has been highlighted such as waste reduction, resource efficiency, and sustainable manufacturing (Ghasemibojd et al., 2025; Javed, 2025). Alanezi and Franchetti (2025) also put forward an integrated framework for LSS and sustainable manufacturing to enhance efficiency and environmental protection.

More recent publications link the concepts of LSS and Industry 4.0 to the goals of circular economy. Shrivastava and Mishra (2025) explored the synergy between LSS and Industry 4.0 in fostering the development of circular economy, and Santos et al. (2025) emphasized the potential of LSS4.0 for sustainable enhancement of energy. These changes are pointing to a shift in environmental outcomes from waste reduction to more comprehensive resource efficiency, circularity and sustainable energy management.

3.4.4 Social Outcomes

Social sustainability is less well described in the literature when compared to the other operational and environmental outcomes. However, the studies highlight workforce capabilities, employee involvement, organizational preparedness, training, leadership and change management as key elements in the achievement of sustainable LSS implementation (Swarnakar et al., 2020a, 2020b; Zala et al., 2020).

The human dimension is also critical as digital technologies are becoming more and more integrated, and employees need to acquire the right technical and analytical skills to ensure that digital LSS are implemented effectively. Alsadi et al. (2025) pointed out practitioner and organizational views on digitalization of LSS, and Torno (2026) explained some qualitative research on LSS practitioners in the Industry 4.0 environment.

Social and human-centred dimension continues to be further bolstered with the arrival of Industry 5.0. Boumsisse et al. (2025) studied Green Lean Six Sigma with the application of Industry 5.0 technologies, proposing future trends involving the integration of technologies with human and sustainability goals. There is, however, comparatively less pre-standardized quantitative evidence of social outcomes, including employee well-being, workforce inclusion and job quality, and long-term organizational development.

3.4.5 Sustainability Measurement Approaches

The reviewed studies are based on a wide variety of sustainability indicators. Measurement of the environment is mainly based on energy consumption, waste generation, emissions, resource usage, and environmental performance metrics (Chugani et al., 2017; Huang et al., 2023; Ghasemibojd et al., 2025). Typically, the operational assessment is done on productivity, quality, process efficiency, cycle time, delays and operational performance (John & Kadadevaramath, 2020; Sordan et al., 2022).

The indicators used to measure the economic sustainability of a system range from cost to productivity, resource efficiency, and organizational performance and vary according to research (Tiwari et al., 2020; Marques et al., 2025). Social sustainability has been more commonly captured by qualitative or organizational metrics like employee participation, employee training, employee leadership, organizational readiness, and employee capabilities (Swarnakar et al., 2020a; Swarnakar et al., 2020b; Alsadi et al., 2025).

One of the key conclusions from the literature reviewed is that sustainability measurement is not consistently implemented throughout LSS. In this context, Cherrafi et al. (2016) emphasized the need for systematic incorporation of sustainability into LSS, and subsequent reviews further indicated that

systematic development of sustainable-oriented LSS frameworks is an important research field (Walter et al., 2021; Ghasemibojd et al., 2025; Rana & Jani, 2026). However, the literature shows that there is greater and more consistent focus on environmental and operational sustainability indicators than on social sustainability indicators.

In general, the evidence shows that integrated LSS, digital transformation and sustainability can contribute to an overarching notion of organizational performance in which operational excellence is included in the mix of economic efficiency and environmental responsibility. However, the social dimension is comparatively underdeveloped and some of the discrepancies in the measurement approach make it hard to compare between studies. Focusing on sustainability, future research on LSS should therefore be enhanced by multi-dimensional measurement approaches, which consider not only operational and economic aspects but also social and environmental aspects.

Table 3. Multidimensional Outcomes and Sustainability Indicators

Performance dimension	Major outcomes identified	Common measurement indicators	Evidence strength / pattern	Supporting references
Operational	Productivity, quality improvement, process efficiency, waste reduction, cycle-time improvement,	Productivity, defect rate, cycle time, delays, throughput, process efficiency, waste	Strong and consistently reported	Cherrefi et al. (2016) ; Chugani et al. (2017) ; Tiwari et al. (2020) ; Huang

	responsiveness and operational excellence			et al. (2023)
Economic	Cost reduction, improved productivity, resource efficiency, process efficiency and economic performance	Operating cost, cost efficiency, productivity, resource utilization, financial /process performance	Frequently reported	Cherrefi et al. (2016) ; Tiwari et al. (2020) ; Walter et al. (2021) ; Marques et al. (2025)
Environmental	Waste minimization, energy efficiency, resource conservation, emission	Waste generation, energy consumption, emission, material consumption, resource	Strong and increasingly integrated	Chugani et al. (2017) ; Huang et al. (2023) ; Ghase miboj

	n reducti on, sustain able manufa cturing and circular ity	utilizatio n, environ mental performa nce		d et al. (2025) ; Marqu es et al. (2025)
Social	Employ ee particip ation, workfo rce capabili ty, training , leaders hip, organiz ational readine ss and employ ee- related outcom es	Training, employee e engagem ent, workforc e capabilit y, participa tion, occupati onal well- being, organizat ional readiness	Relati vely limited and less standa rdized	Walter et al. (2021) ; Swarn akar et al. (2020) ; Alsadi et al. (2025)
Integra ted sustain ability	Combi ned operati onal, econom	Multidi mension al sustainab ility	Emerg ing; measu rement remain	Cherra fi et al. (2016) ; Walter

	ic, environ mental and social perfor mance within sustain able operati ons	indicator s combin ing operatio nal, economi c, environ mental and social measures	s inconsi stent	et al. (2021) ; Ghase miboj d et al. (2025) ; Rana & Jani (2026)
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3.5 Barriers and Enablers of Integration

A mix of human, financial, tech, organizational and context conditions is involved in LSS, DT and sustainability integration. The literature analyzed shows that technology adoption is not enough to achieve successful integration. Instead, a blend of strategic orientation, leadership backing, technological systems, staff skills, readiness and sufficient resources are needed in organizations. The evidence also shows that barriers and enablers are mutually dependent and that a lack of one can affect the effectiveness of the other (Swarnakar et al., 2020a, 2020b; Citybabu & Yamini, 2023b; Ibrahim & Kumar, 2025).

3.5.1 Organizational Factors

Organizational factors are an important factor that determines the implementation of integrated LSS-DT-sustainability. Leadership commitment, strategic alignment, organizational readiness and organizational change management are mentioned as key enabling conditions over and over again. For an integrated approach, LSS, digital transformation, and sustainability goals should be interwoven with organizational strategy and not stand alone as separate programs, projects, or initiatives (Swarnakar et al., 2020a; Skalli et al., 2024).

Leadership is even more critical given that change is needed to existing processes, decision making structures and organizational practices in order to integrate. If management is not committed, digital initiatives can be thought of as putting all the technology in place but not integrated into ongoing systems for continuous improvement. Likewise, sustainability goals can only be of a secondary nature if they are not integrated into operational performance goals (Swarnakar et al., 2020b; Marques et al., 2025).

The organization's culture and readiness for change also affects implementation. According to the literature, organizational resistance to change can hinder the introduction of new technologies and improvement processes, while employee engagement and organizational readiness to implement new processes contribute to the success of change (Abdul Hamid, 2023; Zala et al., 2020). As structured LSS4.0 frameworks develop, the need for organizational integration rather than isolated technological implementation has become apparent (Citybabu & Yamini, 2023b; Skalli et al., 2024).

3.5.2 Technological Factors

Technology infrastructure is a significant precondition of the digital LSS. A number of different technologies are seen as key to the effective application of IoT, AI, Big Data analytics, digital twins, automation, and others associated with Industry 4.0, which require the appropriate digital infrastructure, availability of data, interoperability of systems, and data quality (Chiarini & Kumar, 2020; Pongboonchai-Empl et al., 2024; Wankhede et al., 2024).

One of the significant technology challenges is the adoption of new digital technologies into the current organizational structure. There could be old information and OT systems that weren't built to communicate with more modern digital systems. This can, therefore, limit the real-time transmission and analysis of process information (Skalli et al., 2024; Alsadi et al., 2025).

Another crucial factor is data quality. But without the ability to track processes with reliable information, Six Sigma is limited in its value and application of digital transformation analysis. This growth of AI and advanced analytics, in turn, generates a parallel demand for data architecture that is stable and the right governance (Wankhede et al., 2024; Madzik et al., 2025).

In addition, as organizations become more digitally connected, cybersecurity, interoperability, and technological complexity also are important considerations. Hence, technological readiness should not just be applied to the acquisition of technology, but to the capacity to integrate, maintain, govern and effectively use the digital technology in the organization.

3.5.3 Human and Workforce Factors

The human dimension is very relevant, as within an integrated LSS and digital transformation, changes in the roles and skills of employees and how they work are required. Some of the literature highlights the challenges of lacking technical skills, training, and adapting to the workforce or resistance to change (Swarnakar et al., 2020b; Alsadi et al., 2025; Torno, 2026).

The employees implementing the LSS4.0 can be required to have a combination of knowledge in process improvement, statistical analysis, digital technologies and data interpretation. Thus, traditional LSS training might not be adequate in the context of the application of advanced digital technologies in organizations. Therefore, training and technical qualification have turned out to be relevant enabling factors for the implementation of digital LSS (Citybabu & Yamini, 2023b; Alsadi et al., 2025).

Change management is also applicable since the responsibilities and processes can be changed during digital transformation. Transformations that have been found to be successful in the healthcare and other organizational fields suggest that both process redesigns and organizational changes must be taken into account (Huang et al., 2024; Lunardi et al., 2025). Therefore, human enablers of importance are employee engagement, digital literacy, continuous learning and change-management.

3.5.4 Financial and Contextual Factors

Another significant factor is the financial limitations that arise, especially for small- and medium-sized enterprises. The process of digital transformation can involve investments in sensors, software, data infrastructure, automation, training employees, integrating systems, and maintaining them. These requirements can pose more challenges for the implementation by SMEs and resource poor organizations (Zala et al., 2020; Ibrahim & Kumar, 2025).

Implementation outcomes are also dependent on context. As shown in the literature, the applications of integrated LSS-DT approaches depend on the different organizational environments, including manufacturing, healthcare, telecommunications, supply chains, digital technology companies, and more (Sordan et al., 2022; Huang et al., 2024; Said El Shenawy et al., 2025). The feasibility and effectiveness of integration may result in differences, therefore, based on the size of the organizations, their level of technological maturity, sectoral needs, resources, and institutional conditions.

Resource constraints should not be considered as financial constraints only, as evidenced. Lack of infrastructure, inadequate technical staffing, insufficient training capacity and lack of organizational expertise can also be part of these. The contexts can be all of a piece in influencing the possibility of transitioning from conceptual LSS4.0 frameworks to implementation.

3.5.5 Major Barriers Versus Enabling Conditions

The overall evidence shows the main challenges to integration are resource constraints, implementation costs, organizational change resistance, inadequate digital infrastructure, inadequate skills of staff, lack of

data capabilities, and integration challenges with technology. On the other hand, key enabling factors are leadership commitment, strategic alignment, organizational readiness, employee engagement, technical training, reliable data infrastructure, technological capability, and effective change management (Swarnakar et al., 2020a, 2020b; Skalli et al., 2024; Alsadi et al., 2025).

It is not just a contrast between the technological and organizational barriers, however. It is necessary to develop technological and organizational capabilities at the same time in order to implement it successfully. Digital technologies are the enablers of better process visibility and analysis; LSS is the structured methodology for process improvement and sustainability is the broader performance goals (Citybabu & Yamini, 2023b; Marques et al., 2025).

3.6 Evidence Gaps and Emerging Research Themes
Although LSS, digital transformation and sustainability have gained more interest in academia both in volume and quality, the literature remains scattered. To date, there has been significant research on individual or two-way connections, such as LSS and sustainability, LSS and Industry 4.0, or digital transformation and sustainability. But research that focuses on the simultaneous integration of all three dimensions is still rather scarce. This division is an important one for future operations-management research.

3.6.1 Theoretical Gaps

A big theoretical divide involves the lack of a suitably integrated theory of the relationship between LSS and digital transformation with sustainability. Existing studies tend to create individual frameworks for sustainable LSS or LSS4.0, with less research examining how digital skills can impact LSS activities and how these activities, in turn, can contribute to sustainability outcomes (Cherrafi et al., 2016; Walter et al., 2021; Skalli et al., 2024).

The literature thus needs to be better theoretically explained around the causal links between digital capabilities, process-improvement practices, and sustainability performance. Specifically, future research should go beyond just describing the technological applications and understand the impact and conditions under which digital LSS can achieve better results in terms of sustainability.

3.6.2 Methodological Gaps

The methodological evidence is marked by the extensive application of conceptual frameworks, literature review, case study, cross-sectional study and exploratory methods. While they are useful in theory development and initial exploration, there is comparatively less evidence in the form of longitudinal studies that can assess sustainability of

improvement over time (Citybabu & Yamini, 2023a; Skalli et al., 2024; Ghasemibojd et al., 2025).

Another gap is the gap between creating the framework, and applying it in an actual situation. There are multiple studies that suggest integrated models, however none of which have been implemented and tested in multiple organizational contexts. It is therefore recommended that future research designs validate the present findings with the use of more empirical approach such as longitudinal, comparative, mixed methods, and quantitative research designs.

3.6.3 Technology Gaps

The rise of AI, digital twins, IoT, Big Data analytics, automation and Industry 5.0 technologies has ushered in new research opportunities. The literature, however, is not consistent when it comes to individual technologies and their linkage to the whole LSS methodology (Pongboonchai-Empl et al., 2024; Alsadi et al., 2025).

Digital twins and advanced analytics are gaining in popularity; yet more empirical proof is needed to substantiate the impacts on ongoing operational and sustainability outcomes. Likewise, there are other areas that are becoming important and are still in the nascent stages of study, such as AI-based LSS and autonomous or predictive improvement systems (Maheshwari & Devi, 2024; Madzik et al., 2025).

3.6.4 Contextual Gaps

There is an uneven geographic and sectoral evidence base. The manufacturing sector and selected Asian and European contexts are well represented in research, and other geographical regions and sectors are less represented. Furthermore, the literature lacks in the comparison in evidence from SMEs and resource-constrained organizations (Zala et al., 2020; Ibrahim & Kumar, 2025).

Other services, such as those not in the health or telecommunications industry, are relatively under-explored as well. The principles and mechanisms of integrated LSS-DT-sustainability should therefore be investigated in other service sectors such as healthcare, finance, education, public administration and logistics in the future.

3.6.5 Sustainability and Measurement Gaps

One of the key areas that needs improvement is sustainability measurement. While social sustainability outcomes are less apparent in the literature, environmental outcomes like waste, energy use, emissions, and resource efficiency are much more visible. Economic and operational measures are also commonly mentioned, but there was no consistency between studies in the indicators used (Chugani et al., 2017; Huang et al., 2023; Ghasemibojd et al., 2025).

Social sustainability is still relatively little developed, including in the context of human-centred digital

transformation, employee participation, job quality, workforce development, and the well-being of employees. This imbalance highlights the need for multi-dimensional sustainability measurement frameworks, which combine to a common evaluation structure, environmental, economic, operational, and social indicators (Walter et al., 2021; Rana & Jani, 2026).

3.6.6 Under-Researched Areas

The synthesis uncovers several areas with limited research: longitudinal assessment of integrated initiatives, implementation in service companies other than healthcare and telecommunication; applications in other service sectors than the above mentioned; emerging-economy contexts; social sustainability; human centred digital transformation; standardized sustainability metrics; and empirical validation of proposed LSS4.0 frameworks.

Transition from descriptive digitalisation towards intelligent and adaptive improvement systems is another important emerging theme. The practical implementation of AI, digital twins, Industry 5.0 and data-driven LSS in order to continuously optimize sustainability performance is still not well understood (Boumsisse et al., 2025; Torno, 2026).

3.7 Integrative Framework and Future Research Directions

The evidence analyzed indicates that Lean Six Sigma, digital transformation, operational improvement, and sustainability connect in an integrative way. These dimensions are not individual managerial tasks, but rather they can be viewed as related parts of a more comprehensive system of operational excellence that is sustainable.

3.7.1 LSS–Digital Transformation–Operational Improvement–Sustainability Pathway

The suggested journey starts with Lean Six Sigma as a platform for process improvement. LSS offers a framework for problem solving (DMAIC), waste reduction, variation reduction, process standardization, and continuous improvement. Digital transformation then further reinforces this base through connectivity, real time data, advanced analytics, automation and simulation (Chiarini & Kumar, 2020; Citybabu & Yamini, 2023b; Pongboonchai-Empl et al., 2024).

The superior digital-LSS system provides operational improvements such as better quality, productivity, process efficiency, resource utilization and responsiveness. These operational benefits then can lead to sustainability benefits such as waste reduction, energy efficiency, resource conservation, reduced emissions, and sustainable operational performance (Chugani et al., 2017; Huang et al., 2023; Marques et al., 2025).

The pathway can therefore be expressed as:

Lean Six Sigma → Digital Transformation → Operational Improvement → Sustainability

The relationship must not be assumed to be one-to-one. Sustainability goals are also considered in the selection of LSS projects and digital technologies, and sustainability performance data can be used as feedback during the Measure, Analyze, Improve, and Control steps of DMAIC. Likewise, better operational performance can create organisation resources to facilitate additional investments in digital and sustainability initiatives.

3.7.2 Proposed Conceptual Framework

The conceptual framework that has been proposed is based on the synthesis and is made up of four interrelated parts. First is LSS capability, which consists of DMAIC, Continuous Improvement, Waste reduction, Variation reduction and Process discipline. The second is digital transformation capability, which is the new technology that relies on digitalization, including the Internet of Things, artificial intelligence and machine learning, Big Data, digital twins, process analytics, and automation. The third one is operational performance which includes all the elements of quality, productivity, efficiency, process responsiveness and cost performance. The fourth is sustainability performance which can be expressed through environmental, economic and social outcomes.

The framework is moderated or enabled by organizational, technological, human, and contextual factors. The effectiveness of digital LSS capabilities in operational and sustainability gains depends on the leadership, organizational readiness, workforce capabilities, technological infrastructure, data quality, and resource availability (Swarnakar et al., 2020a, 2020b; Ibrahim & Kumar, 2025; Alsadi et al., 2025). The concept of integrated performance is therefore not defined through the use of a specific technology or management methodology, but through the interaction of the four capabilities of methodology, digital, organization and sustainability orientation.

3.7.3 Research Propositions and Emerging Research Themes

The synthesis yields a number of research hypotheses that can be used for further empirical study:

Proposition 1: Greater integration of digital technologies with LSS practices is expected to lead to improvements in operational performance, which include better visibility of processes, availability of data, analytical capability, and decision-making.

Proposition 2: Digital LSS is likely to influence the sustainability performance through operational improvements like waste reduction, resource efficiency, productivity and process optimization.

Proposition 3: Organizational readiness, leadership commitment and strategic alignment are expected to

be correlated with the relation between LSS-DT integration and operational performance.

Proposition 4: Successful implementation of digitally enabled LSS should build workforce digital competence and employee engagement.

Proposition 5: Effective application of AI, analytics, IoT, digital twins within LSS will require data quality and technological infrastructure to be in place as background conditions.

Proposition 6: Sustainability advantages of integrated LSS-DT can be assumed to be higher when the environmental, economic and social performance indicators are included in the improvement process as well as evaluated afterwards.

These propositions are not statements of causal relationships proposed in the existing literature, but rather are statements of research agenda based on the reviewed evidence. It is consistent with methodological and theoretical gaps were identified throughout the evidence base (Skalli et al., 2024; Ghasemibojd et al., 2025; Rana & Jani, 2026).

3.7.4 Prioritized Future Research Agenda

Evidence-based prioritised research agenda is established. First, future research should provide more robust evidence based on a longitudinal study and/or multiple sites to test for statistical evidence of whether LSS-DT-sustainability improvements will continue over time. Second, standardized multidimensional performance measures, that integrate operational, economic, environmental and social outcomes, should be designed and validated for researchers.

Third, stronger efforts could be put into SMEs and resource poor organizations where financial and technological restrictions may play a significant role on implementation. Fourth, LSS4.0 frameworks need to be transferred to the service sector and emerging-economy applications to assess the extent to which it is transferable to more traditional service-sector and emerging-economy contexts.

Fifth, future studies should explore how the implementation of ICTs is human-centred, such as digital skills, employee involvement, organizational learning, work adaptation and change management. Lastly, empirical studies need to analyze new technologies like AI, digital twins, Industry 5.0, and advanced analytics against specific DMAIC phases and measurable sustainability results (Alsadi et al., 2025; Boumsisse et al., 2025; Torno, 2026).

The combined directions suggest a shift in the process from framework development to empirical validation, from technology adoption to technology enabled transformation, and from isolated environmental indicators to integrated sustainability performance. This is an important next step in the research on sustainable digital operational excellence.

Table 4. Barriers, Enablers, Evidence Gaps and Future Research Priorities

Domain	Major barrier / evidence gap	Enabling condition	Priority research direction	Supporting references
Organizational	Resistance to change, weak strategic alignment, limited leadership commitment and organizational readiness	Leadership commitment, strategic alignment, organizational readiness and change management	Examine organizational readiness and leadership as moderators of LSS–digital transformation performance	Swarnakar et al. (2020a, 2020b); Skalli et al. (2024); Alsadi et al. (2025)
Technological	Legacy systems, poor interoperability, inadequate digital infrastructure	Reliable digital infrastructure, interoperability, data quality and	Empirically evaluate IoT, AI/ML, Big Data, digital twins and	Chiari ni & Kumar (2020); Pongboonchai-Empl et al.

	structure, data-quality limitations and technological complexity	data governance	automation across DMAIC stages	(2024) ; Wankhede et al. (2024) ; Alsadi et al. (2025)
Human/workforce	Skills gaps, inadequate training , limited digital literacy and resistance to technological change	Digital competence, training , employee engagement and continuous learning	Development and empirically test human-centred LSS4.0 implementation models	Swarnakar et al. (2020b); Cityba bu & Yamin i (2023b); Alsadi et al. (2025) ; Torno (2026)
Financial /contextual	High investment requirements, limited resources and implem	Scalable technologies, resource planning and context	Validation LSS4.0 approaches in SMEs and resour	Zala et al. (2020) ; Ibrahi m & Kumar (2025)

	entation constraints, particularly in SMEs	- specific implementation strategies	ce-constrained organizations	
Theoretical	Limited integrated explanation of the relationships among LSS, digital capabilities and sustainability	Integrative conceptual and theoretical models	Development and empirically test theories explaining the LSS–digital – sustainability relationship	Cherrafi et al. (2016) ; Walter et al. (2021) ; Skalli et al. (2024)
Methodological	Heavy reliance on reviews , conceptual frameworks, case studies and	Longitudinal, comparative and mixed-method research designs	Conduct longitudinal, multi-site and mixed-method investigations	Cityba bu & Yamin i (2023a) ; Skalli et al. (2024) ; Ghase miboj

	cross-sectional investigations		of integrated implementation	d et al. (2025)
Contextual	Manufacturing dominates the evidence base, while services, SMEs and emerging-economy contexts remain comparatively underrepresented	Cross-sector and cross-country research	Expanded empirical research to service industries, SMEs and emerging economies	Sordana et al. (2022) ; Said El Sheny et al. (2025) ; Ibrahim & Kumar (2025)
Sustainability measurement	Operational and environmental indicators	Standardized multidimensional sustainability	Development of operational, economic	Chugan et al. (2017) ; Walter et al.

	dominate, while social sustainability indicators remain less consistent	measurement	mic, environmental and social performance frameworks	(2021) ; Huang et al. (2023) ; Ghosemibojd et al. (2025)
Empirical validation	Many proposed LSS4.0 and sustainable-LSS frameworks have limited real-world validation	Multi-site implementation, longitudinal evaluation and empirical testing	Move from conceptual framework development toward rigorous empirical validation	Skalliet al. (2024) ; Alsadi et al. (2025) ; Rana & Jani (2026)

Conclusion

The integration of the three concepts – Lean Six Sigma, digital transformation and sustainability – is a growing trend in operations management, as shown from this systematic literature review. There is clear evidence that, while Lean and Six Sigma are still being used in traditional ways, digitally-enabled improvement systems are becoming more common and are enhancing the acquisition, analysis, prediction, optimization, and control of processes. The DMAIC methodology is complemented and enhanced by the use of other concepts and tools, such as IoT, Artificial

Intelligence, Machine Learning, Big Data Analytics, Digital Twins, Process Mining, Predictive Analytics and Automation as shown in the figure above, which are becoming more popular in the application of LSS 4.0. Meanwhile, sustainability has broadened the LSS performance goal from productivity, quality and cost to environmental resource efficiency, waste and emission reduction and, more expansively, organizational sustainability.

Despite this development, the literature is not uniformly good. There is far greater representation of operational and economic outcomes than of social sustainability outcomes, and furthermore the approaches used to measure outcomes differ from one study to another. Organizational resistance, poor digital infrastructure, interoperability and data-quality problems, lack of skills among the workforce, leadership needs, and financial constraints are also barriers to implementation, especially in organizations that face resource limitations. Overall, the evidence suggests that the conceptual frameworks for LSS4.0 are still not well supported by empirical studies. Longitudinal and comparative studies, cross-sector and cross-country studies, SME centric implementation models, standardized multidimensional sustainability metrics, and human-centred approaches to digital transformation should thus be favored for further research. In conclusion, the combination of LSS process discipline and digital capabilities and sustainability goals offers a promising avenue for digitally enabled sustainable operational excellence, which needs to be further substantiated empirically and be more context-sensitive in its implementation.

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