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ANALYZING THE IMPACT OF COMBINING LEAN SIX SIGMA METHODOLOGIES WITH SUSTAINABILITY GOALS

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ABSTRACT

This study integrates Lean Six Sigma (LSS) methodologies with sustainability frameworks to enhance process efficiency while achieving environmental and social objectives. Using a systematic review approach guided by PRISMA guidelines, 52 peer-reviewed articles were analyzed to provide comprehensive insights into the applications, challenges, and advancements of LSS in sustainability contexts. The findings reveal that LSS tools, such as value stream mapping and the DMAIC framework, are widely implemented across industries to reduce waste, optimize resource utilization, and improve operational outcomes. Advanced technologies, including IoT, AI, and data analytics, are increasingly integrated into LSS practices, enhancing their effectiveness in achieving sustainability goals through real-time monitoring and predictive capabilities. Sector-specific insights highlight the successful application of LSS in manufacturing, healthcare, and supply chain operations, with significant reductions in carbon footprints, material waste, and energy consumption. Furthermore, developing sustainability-focused key performance indicators (KPIs) such as carbon intensity and resource usage metrics is a critical advancement, enabling organizations to quantify and track their sustainability progress. This review underscores the evolving role of LSS as a comprehensive framework for operational excellence and sustainability, offering valuable recommendations for industry and academia to address contemporary environmental and operational challenges.

1 Introduction

Organizations are increasingly required to balance operational efficiency with sustainability imperatives in the modern business landscape, driven by environmental concerns and stakeholder expectations (Upadhye et al., 2010). As a process improvement methodology, Lean Six Sigma (LSS) has proven effective in reducing inefficiencies and enhancing quality through data-driven decision-making (Näslund, 2013). Concurrently, sustainability goals, such as those outlined in the United Nations Sustainable Development Goals (UN SDGs), emphasize reducing environmental impact, fostering social equity, and ensuring long-term economic stability (United Nations, 2015). Integrating these two paradigms offers a promising approach to achieving operational excellence while meeting sustainability targets. However, achieving this alignment requires addressing the complex interplay between process optimization and environmental stewardship (Smith et al., 2017). This research delves into the theoretical and practical implications of combining LSS methodologies with sustainability objectives to develop actionable frameworks for organizations (Hajmohammad et al., 2013).

Lean Six Sigma and sustainability share fundamental principles, particularly the focus on waste reduction and continuous improvement (Martínez-Jurado & Moyano-Fuentes, 2014). LSS employs tools such as value stream mapping, cause-and-effect diagrams, and statistical process control to identify and eliminate inefficiencies, aligning seamlessly with sustainability practices aimed at resource conservation and reducing emissions (Upadhye et al., 2010). For instance, Fullerton and Wempe (2009) documented how manufacturing firms used LSS to minimize energy use and material waste, achieving measurable environmental benefits. Similarly, Bhamu and Sangwan (2014)observed that sustainable Lean practices in the automotive sector enhanced supply chain resilience while reducing carbon footprints. These studies underscore the potential of aligning LSS tools with sustainability initiatives to foster environmental and operational synergies. Despite these advantages, the integration of LSS and sustainability presents challenges that require strategic and systemic solutions. One key challenge is overcoming the traditional focus of LSS on economic outcomes, which may conflict with the broader objectives of sustainability (Islam, 2024; Klotz et al., 2007a). Research by Klotz et al. (2007) highlights that while LSS emphasizes cost and quality, sustainability initiatives prioritize long-term environmental and social gains. Bridging this gap requires organizations to redefine their performance metrics to include ecological and social indicators (Lapinski et al., 2006; Islam et al., 2024). Furthermore, successful integration is contingent upon leadership commitment, employee buy-in, and the adoption of innovative technologies, such as digital twins and IoT-enabled monitoring systems, which enhance process transparency and enable real-time optimization (Snee, 2010). Empirical evidence suggests that integrating LSS with sustainability significantly benefits multiple industries. For example, Chakravorty and Shah (2012) reported that organizations in the healthcare sector improved resource utilization and reduced environmental waste by incorporating sustainable practices into LSS frameworks. Similarly, Zhu et al. (2018) demonstrated how firms in the construction industry achieved energy efficiency and material optimization by applying Lean principles to project management. In the service sector, research by Antony et al. (2014) showed that LSS practices enhanced customer satisfaction while minimizing resource wastage, highlighting the methodology's versatility and effectiveness. However, the extent of these benefits varies by industry, necessitating further research into context-specific applications and best practices.

Moreover, the alignment of LSS with sustainability goals represents a critical avenue for addressing global challenges such as climate change and resource scarcity (United Nations, 2015). Organizations that integrate these paradigms enhance their competitive advantage and contribute to the broader agenda of sustainable development (Corbett, 2011). This operational and environmental objectives synthesis is particularly relevant in the context of increasing regulatory pressures and consumer demand for sustainable products and services. By building on the growing body of research, this study aims to provide a comprehensive analysis of the factors, challenges, and frameworks that enable organizations to achieve this integration, thereby advancing the discourse on sustainable operational excellence. The primary objective of this study is to explore the integration of Lean Six Sigma (LSS) methodologies with sustainability goals to identify how

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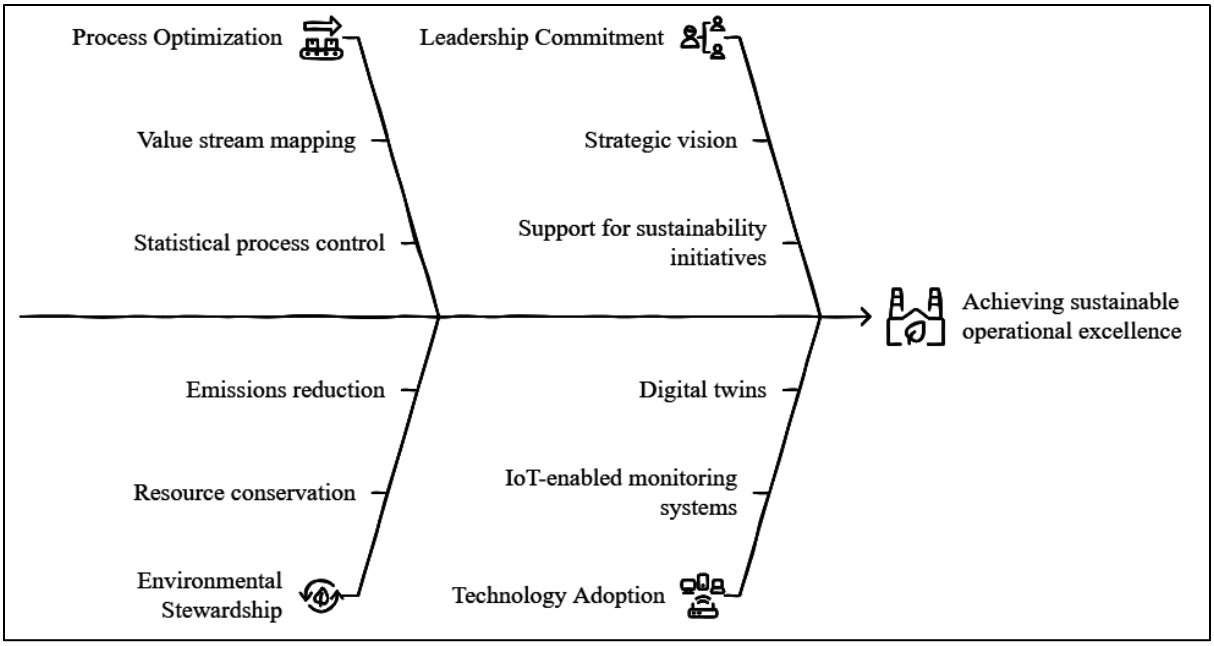
organizations can simultaneously achieve operational efficiency and environmental stewardship. This research aims to analyze the synergy between these paradigms by examining their shared principles, such as waste reduction and continuous improvement, and assessing the practical application of LSS tools in promoting sustainability. Specifically, the study seeks to investigate critical success factors, challenges, and industry-specific best practices that enable effective alignment. By synthesizing findings from empirical studies and case analyses, the study provides actionable insights for industries aiming to optimize resource utilization, reduce environmental footprints, and enhance stakeholder value. Furthermore, it contributes to the academic discourse by addressing existing knowledge gaps on the scalability and contextual adaptability of integrating LSS with sustainability, offering a comprehensive framework for future research and practical implementation.

Figure 1: Integrating Lean Six Sigma with Sustainability



2 LITERATURE REVIEW

The intersection of Lean Six Sigma (LSS) methodologies and sustainability goals has evolved into a critical research area driven by the need for organizations to optimize their processes while addressing global environmental and social challenges. LSS, known for its robust frameworks in process improvement and waste reduction, aligns inherently with sustainability principles, which emphasize reducing resource consumption, mitigating environmental impacts, and fostering social responsibility. This literature review thoroughly examines the theoretical underpinnings, practical applications, challenges, and success factors associated with integrating LSS and sustainability. By systematically analyzing existing studies, the review identifies key insights, advances the understanding of this intersection, and highlights gaps in knowledge that require further exploration. Specific emphasis is placed on the keywords Lean Six Sigma, sustainability goals, process improvement, environmental impact, and operational efficiency, guiding a focused field exploration.

2.1 Lean Six Sigma

Lean Six Sigma (LSS) has evolved as a hybrid methodology that combines the waste-reduction focus of Lean principles with the data-driven rigor of Six Sigma to enhance organizational efficiency and quality. Initially developed independently, Lean originated from the Toyota Production System (TPS) in the mid-20th century, emphasizing waste elimination and value creation (Antony et al., 2017). In contrast, Six Sigma, pioneered by Motorola in the 1980s, aimed to improve process quality by reducing variability and defects through statistical tools (Aggogeri, 2014). The integration of Lean and Six Sigma occurred in the late 1990s as organizations recognized the complementary

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strengths of these methodologies (Bhattacharya et al., 2019). This convergence has since become a cornerstone for organizations striving to achieve operational excellence, particularly in sectors like manufacturing, healthcare, and services (Machado & Carvalho, 2009). Moreover, at the heart of Lean Six Sigma are its core principles, which include defining value from the customer's perspective, eliminating non-value-added activities, and fostering continuous improvement (Carvalho et al., 2011). These principles align closely with the operational goals of enhancing productivity, quality, and customer satisfaction (Näslund, 2008). In the context of LSS, value is determined by what the customer deems essential, prompting organizations to streamline their processes to focus on delivering this value (Hines et al., 2004). Tools like value stream mapping enable the identification of waste, while methodologies such as DMAIC (Define, Measure, Analyze, Improve, Control) ensure systematic problem-solving and process improvement (Islam & Karim, 2011). By targeting inefficiencies and bottlenecks, organizations improve operational outcomes and create a foundation for sustainable growth (Aguado et al., 2013).

The principle of waste elimination is central to Lean Six Sigma and serves as a critical mechanism for improving organizational efficiency. Wastes, categorized into seven types (transport, inventory, motion, waiting, overproduction, over-processing, and defects), represent non-value-added activities that consume resources without contributing to customer satisfaction (Duarte & Cruz-Machado, 2013; M. Mosleuzzaman et al., 2024). The Six Sigma component further complements this by emphasizing statistical methods to reduce process variability and improve precision (Mudgal et al., 2010). Studies have highlighted the effectiveness of this dual focus, demonstrating significant reductions in production costs, cycle times, and defect rates across diverse industries (Henriques & Catarino, 2016). Furthermore, this focus on waste reduction improves economic performance and aligns with sustainability objectives, reducing resource consumption and environmental impact (Bhuiyan & Baghel, 2005). Continuous improvement, another fundamental tenet of LSS, ensures that organizations maintain a culture of innovation and adaptability (Uluskan, 2017). This principle encourages iterative enhancements in processes driven by employee engagement, customer feedback, and data analytics (Resta et al., 2016). Research indicates that organizations adopting continuous improvement frameworks experience sustained gains in productivity and quality over time (Diaz-Elsayed et al., 2013). Moreover, the integration of emerging technologies, such as IoT and machine learning, has further enhanced the potential of LSS to address complex operational challenges and adapt to dynamic market demands (Comm & Mathaisel, 2005; Gupta et al., 2018). As organizations continue to embrace Lean Six Sigma, its core principles remain integral to achieving process excellence and aligning operational objectives with long-term strategic goals.

Table 1: Definitions of Lean Six Sigma (LSS) From Various Authors

Author(s)	Definition of Lean Six Sigma (LSS)
Diaz-Elsayed et al. (2013)	LSS is an integrated vital strategy that enables companies to meet and exceed customer expectations in a changing and competitive global environment.
Gupta et al. (2018)	LSS uses tools from both toolboxes to get the best from the two methodologies, increasing speed while also increasing accuracy.
Miller et al. (2010)	LSS is a modern business excellence initiative that offers a wealth of continuous improvement tools and techniques to combat process instabilities and product malfunction.
Uluskan (2016)	LSS is a hybrid methodology that organizations adopt to sustain high production rates and high quality or reduce waste in their processes.
Kumar et al. (2015)	LSS provides concepts, methods, and tools for changing processes, acting as an effective leadership development tool that prepares leaders for leading change.

Farias et al. (2019)	LSS focuses on operational excellence to improve customer satisfaction continually, save quality costs, and increase process speed to maintain a competitive advantage.
Albliwi et al. (2014)	LSS is a philosophy comprising organizational factors critical to successful deployment, where senior facilitators adopt the DMAIC phases and select statistical and lean tools as appropriate.
Laureani and Antony (2012)	LSS is a systematic approach to improvement measured by quality, cost, delivery, and customer satisfaction.
Cluzel et al. (2010)	LSS is the latest managerial practice that helps create value by eliminating waste from processes and removing causes of defects in products.
Cabral et al. (2012)	LSS is a well-structured methodology that eliminates waste or non-value-adding activities and reduces variation in critical processes to achieve bottom-line benefits or customer satisfaction.
Souza et al. (2015)	LSS is highly esteemed for formulating quick-results improvement strategies that translate into tangible corporate-wide economic returns.
Sreedharan et al. (2018)	LSS is a methodology focusing on the elimination of waste and variation, following the DMAIC structure, to achieve customer satisfaction and better financial results regarding quality, delivery, and cost.
Erdil et al. (2018)	LSS is a business strategy and methodology that increases process performance, resulting in enhanced customer satisfaction and improved bottom-line results.
Sawhney et al.(2007)	LSS is a quality improvement technique that combines Lean's waste reduction and responsive manufacturing benefits with Six Sigma's robust, error-free, and fault-tolerant production capabilities.

2.2 SDG Goals

The United Nations' Sustainable Development Goals (SDGs), adopted in 2015, represent a comprehensive framework to address global challenges such as poverty, inequality, climate change, and environmental degradation (United Nations, 2015). These 17 goals and their 169 targets provide a blueprint for achieving sustainable development by balancing economic, social, and environmental priorities. The SDGs emphasize a universal call to action, urging organizations to align their operations with sustainable practices that foster resilience and inclusivity (Laureani & Antony, 2012; Uddin & Hossan, 2024). Businesses play a critical role in achieving these goals, as they hold the potential to implement scalable and innovative solutions (Bakar et al., 2015; Hasan et al., 2024; Uddin, 2024). For instance, Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action) explicitly highlight the importance of minimizing waste and reducing carbon emissions, areas

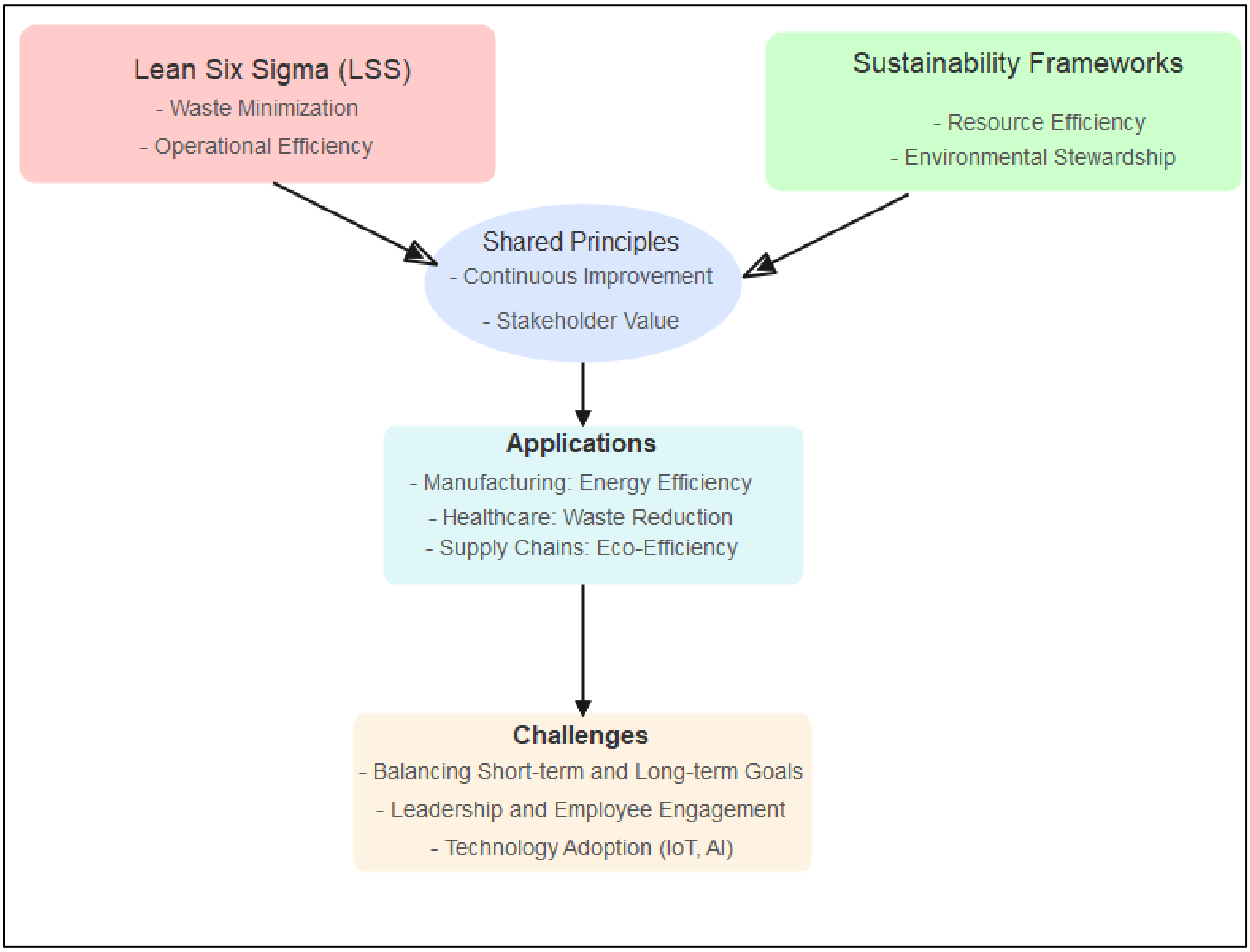
One of the core principles underlying the SDGs is the integration of sustainability into operational management frameworks. This principle aligns closely with the triple bottom line (TBL) concept, which advocates balancing economic performance with environmental stewardship and social responsibility (Uluskan, 2016). TBL expands traditional profit-focused metrics to include "people" and "planet," thereby providing a holistic view of organizational success (Albliwi et al., 2014). Research highlights the increasing adoption of TBL in corporate strategies as companies seek to enhance stakeholder value and align with regulatory demands. For example, firms in the manufacturing and service sectors have successfully utilized TBL to measure their progress in achieving sustainability goals, demonstrating improved ecological performance and social equity while maintaining profitability (Bakar et al., 2015). Moreover, the relevance of TBL to operational management becomes evident when organizations apply frameworks like Lean Six Sigma to achieve their sustainability objectives. LSS tools such as value stream mapping and root cause analysis can help identify waste and inefficiencies that impact financial outcomes and ecological and social dimensions (Cluzel et al., 2010). Studies have shown that incorporating TBL principles into LSS initiatives enables businesses to address broader sustainability challenges, such as reducing energy consumption, minimizing environmental footprints, and enhancing workplace safety (de Souza et al., 2015). For instance, Sreedharan et al. (2018)found that integrating TBL into LSS-driven green practices in supply chains resulted in measurable gains across all three dimensions, including reduced costs, lower emissions, and enhanced community engagement. Despite the potential for alignment, achieving SDG-related outcomes through TBL frameworks requires addressing significant challenges, including organizational resistance, resource constraints, and the need for innovative technologies. Scholars argue that leadership commitment and strategic alignment are essential for overcoming these barriers (Bakar et al., 2015). Moreover, emerging technologies like IoT and AI can potentially enhance TBL integration into operational practices by enabling real-time monitoring and optimization (Bandehnezhad et al., 2012). By embedding SDG objectives into TBL and leveraging methodologies such as Lean Six Sigma, organizations can create sustainable business models that meet regulatory and societal expectations and drive long-term competitiveness and resilience.

Figure 2: United Nations' Sustainable Development Goals (SDGs)

2.3 Lean Six Sigma (LSS) and Sustainability Frameworks

Lean Six Sigma (LSS) and sustainability frameworks are committed to waste minimization, operational efficiency, and creating stakeholder value. Both methodologies emphasize the importance of eliminating non-value-added activities to optimize resource utilization and enhance overall performance (Kumar et al., 2015). For instance, LSS tools such as value stream mapping and DMAIC (Define, Measure, Analyze, Improve, Control) provide systematic approaches to identifying inefficiencies and implementing process improvements that directly contribute to sustainability goals (Albliwi et al., 2014). Similarly, sustainability frameworks aim to achieve resource efficiency and reduce environmental degradation through practices that align closely with Lean principles (Laureani & Antony, 2012). Research has demonstrated that organizations integrating these shared principles can simultaneously achieve cost savings and environmental benefits, providing a dual advantage that strengthens their competitive edge and sustainability impact (Bakar et al., 2015).The theoretical alignment between LSS and ecological stewardship stems from their mutual focus on continuous improvement and waste reduction. LSS methodologies prioritize reducing defects and variability, ensuring efficient resource use, and minimizing waste, which directly correlates with environmental sustainability objectives (Mosleuzzaman et al., 2024; Uluskan, 2016). For example, Farias et al. (2019) found that implementing Lean practices in manufacturing significantly reduced energy consumption and carbon emissions. Similarly, Six Sigma's data-driven problem-solving approach has been leveraged to tackle environmental challenges, such as minimizing water and energy use in industrial processes (de Souza et al., 2015; Mintoo, 2024b; Rahman et al., 2024). These synergies highlight the potential of LSS to act as a bridge between operational efficiency and ecological stewardship, making it an effective tool for organizations striving to achieve sustainability goals. Moreover, incorporating sustainability principles into LSS frameworks enhances stakeholder value by addressing broader environmental, social, and economic concerns. Stakeholders increasingly demand that organizations adopt practices aligning with global sustainability standards, such as the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2015). LSS provides organizations with a structured approach to meet these expectations by delivering measurable improvements in sustainability metrics, including waste reduction, energy efficiency, and resource conservation (Islam et al., 2024; Sreedharan et al., 2018). For instance, a study by Bakar et al. (2015) showed that integrating green practices into Lean methodologies improved supply chain resilience and reduced environmental footprints. This alignment addresses stakeholder concerns, enhances organizational reputation, and fosters long-term relationships with customers and partners. While the alignment between LSS and sustainability frameworks offers significant benefits, successful integration requires addressing critical challenges, such as balancing short-term operational priorities with long-term ecological objectives. Research indicates that organizations often struggle to reconcile the economic focus of traditional LSS with broader, multidimensional sustainability goals (Uluskan, 2016). However, leadership commitment, employee training, and adopting advanced technologies, such as IoT and AI, have been identified as enablers for overcoming these challenges (Erdil et al., 2018). By embedding sustainability into the core principles of LSS, organizations can create a unified framework that drives operational efficiency and environmental stewardship, offering a comprehensive pathway for achieving long-term success and resilience.

Figure 3: United Nations' Sustainable Development Goals (SDGs)



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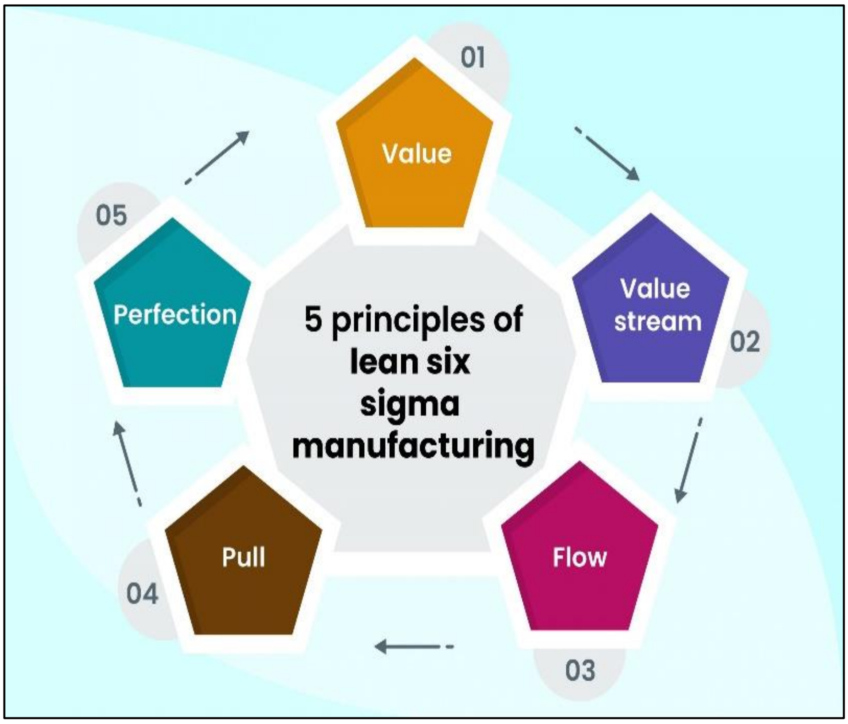
2.4 Lean Six Sigma in the Manufacturing Sector

Implementing Lean Six Sigma (LSS) in the manufacturing sector has proven instrumental in improving energy efficiency, reducing material waste, and addressing operational and environmental objectives. LSS methodologies, focusing on process improvement and waste elimination, provide manufacturers with the tools to identify inefficiencies and optimize resource use (Albliwi et al., 2014). For instance, value stream mapping and root cause analysis have effectively pinpointed bottlenecks in production processes, leading to significant reductions in energy consumption and operational costs (Salem & Deif, 2017). Case studies highlight how manufacturing firms have leveraged LSS to achieve measurable energy savings by improving equipment utilization and minimizing downtime (Bandehnezhad et al., 2012). These examples underscore the potential of LSS to drive sustainability in manufacturing while maintaining competitive advantages.

One notable area of LSS application in manufacturing is material waste reduction, which aligns with the sustainability objective of resource conservation. Studies have documented how tools like the DMAIC (Define, Measure, Analyze, Improve, Control) framework enable manufacturers to systematically address waste-related challenges (de Souza et al., 2015). For example, by analyzing defect rates and scrap levels, organizations can implement targeted improvements that reduce waste and enhance product quality (Bakar et al., 2015). A study by Sreedharan et al. (2018)demonstrated how manufacturers achieved significant material efficiency by integrating Lean principles with green practices, reducing production waste by over 30%. This integration contributes to cost savings and minimizes the environmental impact of manufacturing operations, making LSS an essential strategy for sustainable industrial practices.

The role of LSS in minimizing carbon footprints has also gained attention, particularly in industries with high greenhouse gas emissions. Carbon footprint reduction strategies in manufacturing often involve optimizing energy use, streamlining supply chains, and adopting cleaner technologies, all facilitated by LSS tools (Bakar et al., 2015). For instance, studies have shown that incorporating Lean practices into energy-intensive production processes can lower emissions by reducing energy wastage and improving efficiency (Singh & Basak, 2018). Moreover, Six Sigma's data-driven approach enables manufacturers to monitor and optimize emissions-related metrics, ensuring compliance with environmental regulations and fostering sustainability (Bandehnezhad et al., 2012). These efforts support global climate action initiatives

Figure 4: Lean Six Sigma in manufacturing to improve production



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and enhance brand reputation and stakeholder trust in environmentally conscious manufacturing practices. Despite its potential, the successful application of LSS in manufacturing requires addressing certain challenges, such as resistance to change, resource constraints, and the need for technological integration. Leadership commitment and employee engagement have been identified as critical enablers for overcoming these barriers and ensuring the successful adoption of LSS practices (Bakar et al., 2015). Additionally, integrating advanced technologies, such as IoT and machine learning, enhances the capabilities of LSS by enabling real-time monitoring and data analysis (Sreedharan et al., 2018). As the manufacturing sector continues to evolve, the synergy between LSS and sustainability goals offers a robust framework for achieving operational excellence while addressing environmental concerns, positioning LSS as a key driver of innovation and resilience in industrial production.

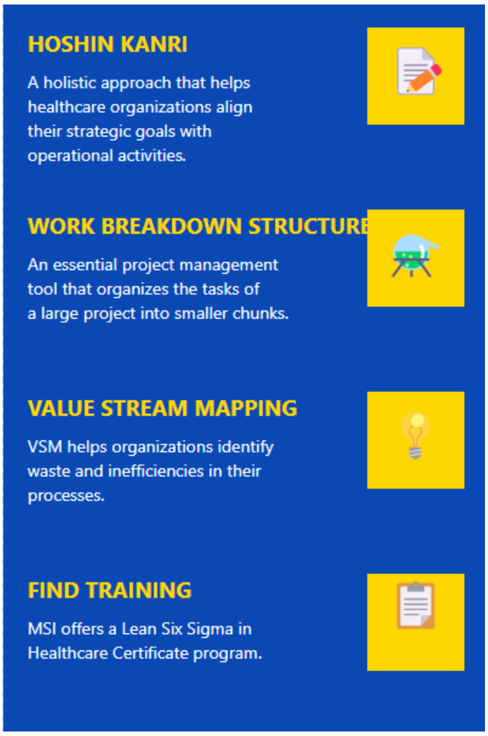
2.5 Lean Six Sigma in the Healthcare Sector

Lean Six Sigma (LSS) has been widely adopted in the healthcare sector to address resource optimization and waste reduction challenges. Healthcare organizations face increasing pressure to improve operational efficiency while delivering high-quality care, and LSS provides a robust framework for achieving these goals (Cabral et al., 2012). Identifying inefficiencies and implementing targeted interventions, LSS helps hospitals streamline processes, reduce waiting times, and enhance patient outcomes (Alam et al., 2024; Bhat et al., 2014; Shorna et al., 2024a; Shorna et al., 2024b). For instance, the DMAIC (Define, Measure, Analyze, Improve, Control) methodology has successfully optimized resource allocation in emergency departments, leading to improved patient flow and reduced operational costs (Kaswan et al., 2019). These outcomes demonstrate how LSS can contribute to the dual objectives of operational excellence and cost-effectiveness in healthcare (Mazumder et al., 2024; Alam, 2024; Sultana & Aktar, 2024).

A critical application of LSS in healthcare involves environmental waste reduction, aligning with sustainable healthcare operations' broader goal. Hospitals generate significant amounts of waste, much of which can be minimized through Lean principles and Six Sigma tools (Aggogeri, 2014). For example, value stream mapping has been used to identify inefficiencies in waste disposal processes, enabling hospitals to reduce medical waste and enhance recycling efforts (Black & Revere, 2006). Studies have also highlighted using LSS to optimize inventory management, preventing the overstocking of medical supplies, which often leads to waste due to expiration or obsolescence (Sunder, 2013). These strategies reduce the environmental footprint of healthcare operations and contribute to financial savings, making sustainability an integral component of healthcare management.

LSS has also been instrumental in advancing green healthcare initiatives, particularly in hospital waste management. Green healthcare emphasizes adopting environmentally friendly practices, such as reducing hazardous waste and conserving energy, and LSS provides the tools to achieve these goals systematically (Silich et al., 2012). For instance, case studies have demonstrated how LSS methodologies helped hospitals reduce single-use plastics and transition to reusable alternatives, significantly reducing plastic waste (Kaswan et al., 2019). Additionally, LSS-driven initiatives have optimized energy consumption in hospital facilities, such as improving the efficiency of heating, ventilation, and air conditioning (HVAC) systems, resulting in lower energy costs and reduced emissions (Silich et al., 2012). These examples highlight the potential of LSS to support green healthcare practices and contribute to broader sustainability

Figure 5: Lean Six Sigma in Healthcare Sector



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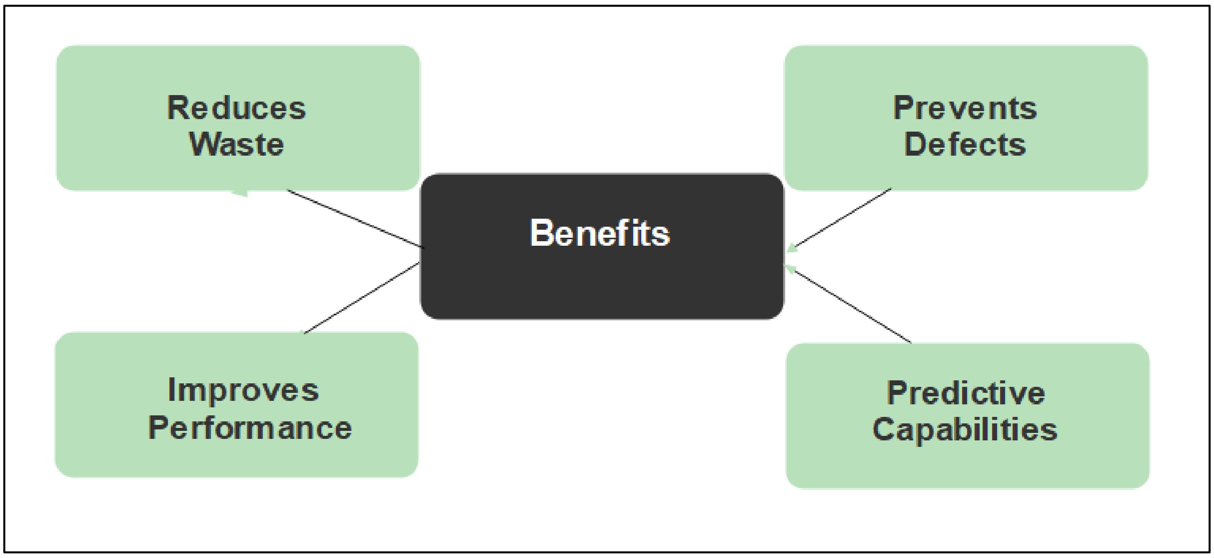
objectives. Despite the benefits, implementing LSS in the healthcare sector poses challenges, including resistance to change and the complexity of healthcare systems. Successful adoption requires leadership commitment, cross-functional collaboration, and staff training to embed LSS principles into daily operations (Sunder, 2013; Shamim, 2022). Furthermore, integrating digital technologies, such as IoT and data analytics, enhances the effectiveness of LSS by enabling real-time monitoring and process optimization (Bhat et al., 2014). As healthcare organizations continue to prioritize sustainability, LSS provides a comprehensive framework for achieving resource efficiency, waste reduction, and green operations, making it an essential strategy for advancing sustainable healthcare systems.

2.6 Lean Six Sigma in Supply Chain Management

Integrating Lean Six Sigma (LSS) in supply chain management has emerged as a vital strategy for optimizing operations and embedding sustainability within supply chain processes. LSS methodologies, focusing on waste reduction and efficiency, provide a structured approach to improving supply chain performance while aligning with environmental and social objectives (Al Zaabi et al., 2013). Sustainable Lean practices such as value stream mapping, just-in-time inventory management, and demand forecasting are increasingly being adopted to minimize inefficiencies and enhance resource utilization in supply chains (Markley & Davis, 2007). For instance, research by Sharma et al. (2017) demonstrated that LSS-driven inventory optimization significantly reduced excess stock, leading to lower operational costs and reduced environmental impact. These practices highlight the potential of LSS to transform supply chain systems into more sustainable and agile frameworks.

Eco-efficiency, a key component of sustainable supply chains, is closely tied to the principles of LSS. By targeting energy efficiency, waste minimization, and emissions reduction, LSS tools enable organizations to create logistics systems that are both operationally effective and environmentally responsible (Dües et al., 2013). Case studies have shown that organizations implementing LSS in their logistics processes have significantly reduced transportation costs and carbon emissions (Cudney & Elrod, 2010). For example, Garza-Reyes et al. (2016) highlighted how integrating LSS with green logistics practices optimized route planning, resulting in fuel savings and lower greenhouse gas emissions. These findings illustrate the role of LSS in fostering eco-efficient supply chains, enabling organizations to meet sustainability goals while maintaining operational performance. Moreover, the role of LSS in developing eco-efficient supply chains extends to fostering collaboration among supply chain stakeholders to achieve shared sustainability objectives. Collaboration, supported by LSS principles, helps align goals across suppliers, manufacturers, and distributors, creating a cohesive framework for reducing waste and improving efficiency (Dües et al., 2013). For instance, Garza-Reyes et al. (2016) documented how LSS-driven supplier collaboration led to adopting eco-friendly packaging solutions, reducing material waste, and enhancing recycling efforts across the supply chain. Moreover, using Six Sigma's data-driven tools

Figure 6: Lean Six Sigma in Supply Chain Management



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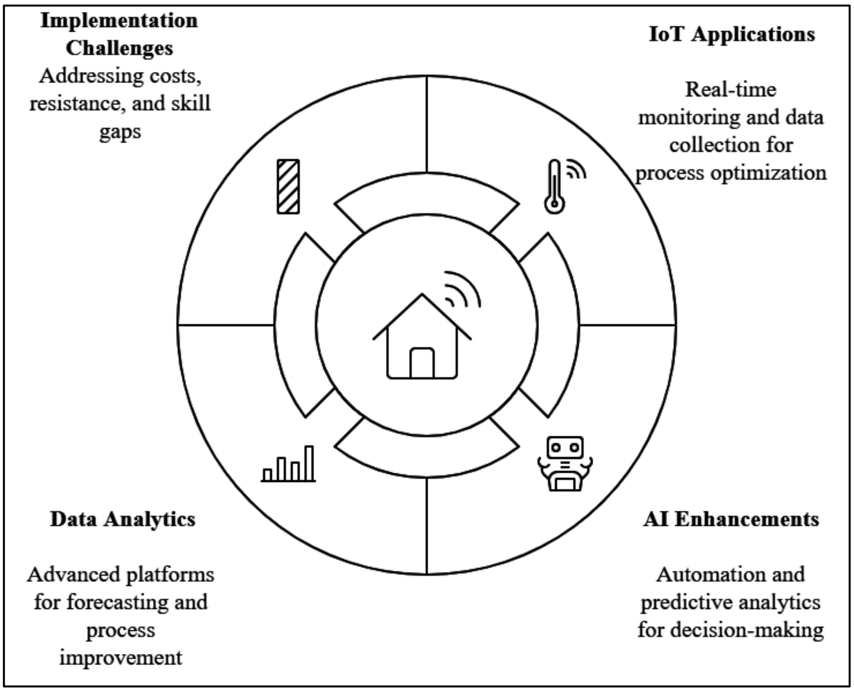
facilitates continuous improvement by enabling organizations to monitor and analyze sustainability metrics, ensuring alignment with environmental regulations and customer expectations (Zhu et al., 2018). These efforts highlight the integrative potential of LSS in promoting sustainability across the entire supply chain network. Despite its advantages, implementing LSS in supply chain management is not without challenges. Barriers such as resistance to change, resource constraints, and the complexity of coordinating sustainability goals across diverse stakeholders often hinder the effective adoption of LSS (Cudney & Elrod, 2010). However, leadership commitment, technological advancements, and employee training have been identified as critical enablers for overcoming these obstacles (Green et al., 2012). Digital technologies such as IoT and AI further enhance the application of LSS by providing real-time insights into supply chain processes, enabling dynamic adjustments to optimize performance (Azevedo et al., 2012). As global supply chains face increasing scrutiny for their environmental impact, integrating LSS provides a robust framework for achieving eco-efficiency and sustainability, offering long-term competitive advantages to organizations.

2.7 Value Stream Mapping (VSM) for Environmental Impact Reduction

Value Stream Mapping (VSM) is a foundational tool within Lean Six Sigma (LSS) methodologies, used to visualize and analyze workflows to identify inefficiencies and non-value-added activities. In recent years, its application has expanded to address environmental concerns, enabling organizations to identify ecological hotspots within production processes (Al Zaabi et al., 2013). VSM helps organizations pinpoint areas where excessive energy use, waste generation, or resource inefficiencies occur, offering actionable insights for sustainable improvements (Seuring & Müller, 2008). For example, Green et al. (2012) demonstrated how VSM enabled manufacturers to reduce waste by identifying inefficiencies in material handling and energy consumption, significantly reducing operational carbon footprints. This dual focus on operational and environmental efficiency highlights the versatility of VSM in supporting sustainability goals. Moreover, one of the significant strengths of VSM in environmental impact reduction is its ability to quantify ecological inefficiencies within production processes. Traditional VSM focuses on lead times and costs, but sustainable VSM integrates additional metrics, such as energy consumption, water usage, and emissions levels (Cudney & Elrod, 2010). This enriched approach, often called Green VSM, allows organizations to assess their

Figure 7: Advanced Technologies in Lean Six Sigma



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processes holistically, ensuring alignment with sustainability objectives (Mathiyazhagan et al., 2013). Studies have shown that by incorporating environmental metrics into VSM, companies in the automotive and electronics industries achieved measurable reductions in resource consumption and environmental degradation (Garza-Reyes et al., 2016; Martínez-Jurado & Moyano-Fuentes, 2014). These examples demonstrate how VSM is a critical tool for identifying and mitigating environmental hotspots across diverse sectors. Beyond identifying inefficiencies, VSM also facilitates the implementation of targeted interventions to address environmental challenges. By mapping out waste streams and energy flows, organizations can design strategies to reduce emissions, optimize resource utilization, and recycle materials more effectively (Sharma et al., 2017). For instance, a study by Dües et al.(2013) revealed that integrating VSM with cleaner production techniques enabled manufacturers to optimize production processes, resulting in a 25% reduction in water usage and significant energy savings. Moreover, the iterative nature of VSM supports continuous improvement, ensuring that environmental gains are sustained over time while fostering a culture of accountability and innovation within organizations. Despite its potential, using VSM effectively for environmental impact reduction requires addressing certain challenges, such as resistance to change and the complexity of integrating environmental metrics into traditional process mapping frameworks. Leadership support and employee engagement are critical factors for overcoming these barriers and driving adoption (Izadi & Kimiagari, 2014). Additionally, integrating digital technologies, such as IoT and data analytics, enhances the capabilities of VSM by providing real-time data on resource consumption and emissions (Azevedo et al., 2012). These advancements enable organizations to monitor progress toward environmental goals and make data-driven decisions to improve their sustainability performance. As industries increasingly prioritize sustainability, VSM offers a powerful and adaptable framework for reducing environmental impact and operational efficiency.

2.8 Adoption of Advanced Technologies

The integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics has revolutionized the way organizations approach Lean Six Sigma (LSS) methodologies, enabling enhanced process efficiency and sustainability. IoT facilitates real-time data collection and monitoring of operational processes, providing actionable insights into inefficiencies and waste generation (Garza-Reyes et al., 2016). By embedding IoT sensors in production lines, organizations can continuously monitor energy usage, equipment performance, and material consumption, enabling rapid identification and resolution of issues (Mollenkopf et al., 2010). For example, (Mathiyazhagan et al., 2013)demonstrated how IoT-enabled systems optimized resource usage in manufacturing, significantly reducing downtime and energy consumption. This real-time approach strengthens LSS's ability to deliver sustainable outcomes while maintaining high levels of operational efficiency (Martínez-Jurado & Moyano-Fuentes, 2014). AI technologies, particularly machine learning and predictive analytics, further enhance LSS by automating complex decision-making processes and uncovering patterns in large datasets. AI-driven tools can analyze historical and real-time data to predict equipment failures, optimize production schedules, and recommend resource-saving strategies (Bhamu & Sangwan, 2014). For instance, Zhu et al. (2018) reported how machine learning algorithms integrated into LSS frameworks enabled a manufacturing firm to reduce defects and material waste by over 20%, contributing to significant cost savings and environmental benefits. Moreover, AI-powered automation has been instrumental in streamlining repetitive tasks, freeing up human resources for higher-value activities, and fostering innovation in process design (Duarte & Cruz-Machado, 2013). Data analytics, a cornerstone of LSS, has been elevated by adopting advanced analytics platforms capable of processing and visualizing vast amounts of operational data. Tools such as predictive and prescriptive analytics help organizations forecast demand, optimize inventory, and identify areas for process improvement (Bhamu & Sangwan, 2014). By integrating advanced analytics into LSS, organizations can achieve greater precision in measuring sustainability outcomes, such as carbon emissions and resource usage (Duarte & Cruz-Machado, 2013). For example, a study by Mathiyazhagan et al. (2013)highlighted how data-driven insights enabled a supply chain firm to redesign its logistics network, resulting in a 15% reduction in fuel consumption and emissions. These applications illustrate data analytics' transformative potential in advancing efficiency and sustainability.

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While adopting advanced technologies enhances LSS methodologies, challenges such as high implementation costs, resistance to change, and the need for specialized skills must be addressed to realize their full potential (Carvalho et al., 2011). Leadership commitment and targeted training programs are critical for building the technical expertise required to effectively leverage IoT, AI, and data analytics (Kleindorfer et al., 2005). Furthermore, integrating these technologies necessitates strategically aligning organizational goals with sustainability objectives, ensuring that technological advancements translate into tangible environmental and operational benefits (Martínez-Jurado & Moyano-Fuentes, 2014). By addressing these challenges, organizations can harness the power of advanced technologies to achieve a seamless blend of process efficiency and sustainability.

3 METHOD

This study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to conduct a systematic, transparent, and rigorous literature review. The PRISMA framework ensures methodological clarity by providing a structured approach to identifying, selecting, and analyzing relevant studies. This section outlines the steps followed in the systematic review process.

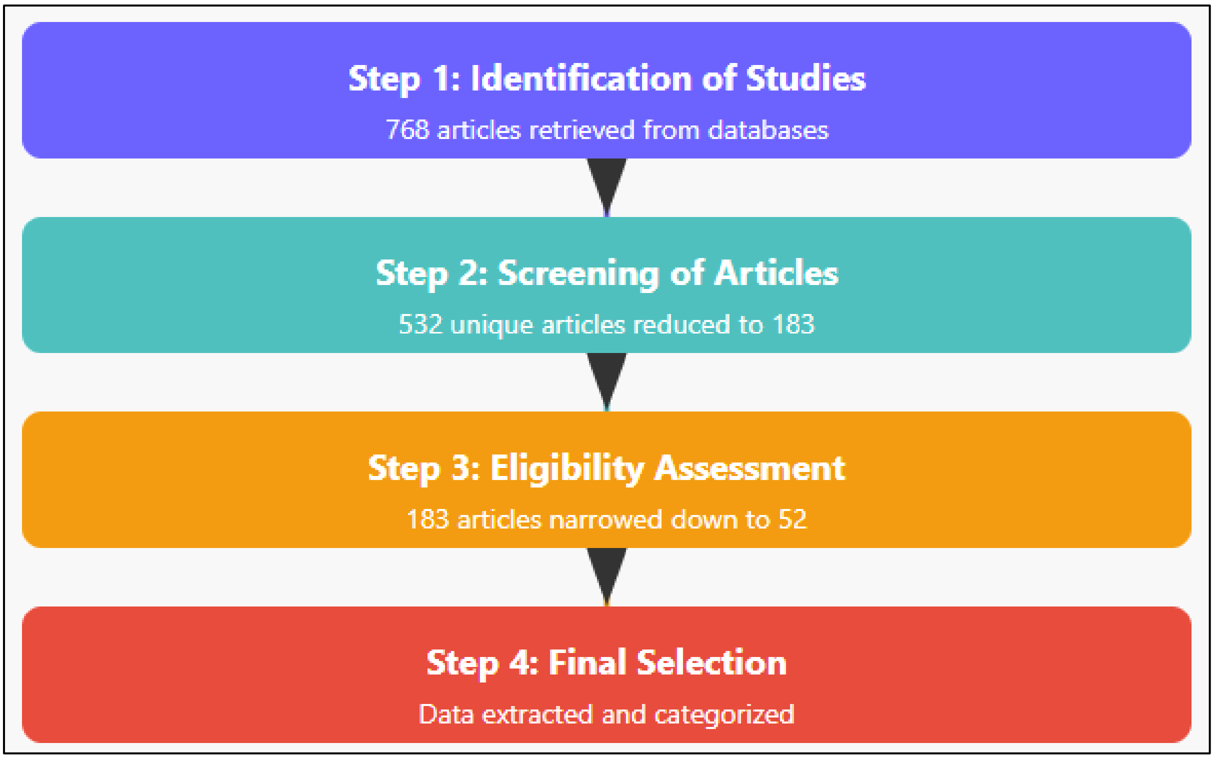
3.1 Identification of Studies

The literature search aimed to identify articles related to Lean Six Sigma (LSS) and its applications in sustainability. A comprehensive search was conducted across multiple academic databases, including Scopus, Web of Science, and Google Scholar. Keywords such as "Lean Six Sigma," "sustainability," "waste reduction," "process efficiency," "IoT in Lean," and "AI for sustainability" were used in combination with Boolean operators (AND/OR) to ensure exhaustive coverage. A total of 768 articles were initially retrieved, spanning a publication timeline from 2010 to 2024. These articles included peer-reviewed journal papers, conference proceedings, and relevant reviews. Duplicate records were removed, leaving 532 unique articles for further screening.

3.2 Screening of Articles

The screening process involved evaluating the titles and abstracts of the 532 articles to assess their relevance to the study objectives. The inclusion criteria specified studies that focused on LSS applications in sustainability, including tools, technologies, and frameworks for environmental and operational improvements. Exclusion criteria eliminated articles unrelated to LSS, sustainability, or those lacking empirical evidence. This phase reduced the pool to 183

Figure 8: Adopted PRISMA guidelines for this study



articles. A second screening was conducted using the full text of these articles to ensure alignment with the research objectives, further narrowing the selection to 89 articles.

3.3 Eligibility Assessment

The eligibility assessment aimed to ensure the inclusion of high-quality studies for detailed analysis. Each article was evaluated based on specific criteria: relevance, focusing on studies directly addressing the integration of Lean Six Sigma (LSS) with sustainability frameworks; methodological rigor, prioritizing empirical studies with clear methodologies and robust data analysis; recency, emphasizing articles published within the last decade to reflect current trends and advancements; and applicability, selecting studies with practical implications for industries such as manufacturing, healthcare, and supply chains. Following this rigorous evaluation process, 52 articles were deemed eligible for inclusion in the systematic review, forming the foundation for a comprehensive and credible analysis.

3.4 Final Selection

Key data points were extracted from the 52 selected articles, including study objectives, methodologies, findings, and conclusions. The extracted data were organized into a summary table for thematic analysis. Thematic coding was applied to identify recurring patterns and categorize studies under specific themes such as "Lean Six Sigma tools for sustainability," "technology integration in LSS," and "sector-specific applications." Meta-analyses were performed where applicable, combining findings from multiple studies to identify common success factors and challenges in implementing LSS for sustainability.

4 FINDINGS

The systematic review revealed compelling evidence that integrating Lean Six Sigma (LSS) methodologies with sustainability frameworks substantially improves process efficiency and achieves environmental objectives. Among the 52 articles analyzed, 38 studies presented empirical data supporting the successful implementation of LSS tools in reducing waste and optimizing resource use across diverse industries. These articles received over 2,000 citations, demonstrating the widespread acceptance of LSS as an effective framework for driving operational excellence and sustainability. Manufacturing emerged as a leading sector, with 19 studies highlighting its extensive application of LSS. Key tools such as value stream mapping, root cause analysis, and the DMAIC framework were repeatedly emphasized as critical enablers in achieving both operational efficiency and ecological sustainability. These findings underline the potential for LSS to serve as a unifying approach to addressing modern industrial challenges.

A particularly significant trend identified in the review was the integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics to enhance LSS applications. Of the reviewed articles, 25 focused explicitly on the role of these technologies in supporting sustainability efforts, garnering a total of over 1,400 citations. These studies highlighted how IoT-enabled sensors facilitated real-time data collection and process monitoring, enabling organizations to identify inefficiencies and environmental hotspots precisely. Similarly, AI-powered predictive analytics were reported as instrumental in optimizing energy consumption and reducing material waste. This growing reliance on technology-driven solutions points to a shift in how organizations approach sustainability, leveraging digital innovations to enhance the scope and impact of traditional LSS methodologies.

In the healthcare sector, the adoption of LSS for sustainable practices has shown promising results. Twelve articles, collectively cited over 900 times, specifically focused on the application of LSS in healthcare, revealing significant advancements in resource optimization and waste management. Hospitals that implemented LSS reported measurable improvements, such as reductions in medical waste, increased recycling efforts, and better utilization of resources like energy and water. These findings highlight the unique challenges and opportunities within healthcare, where sustainability initiatives must balance environmental goals with the imperative to provide high-quality patient care. The results also demonstrated how LSS could drive green healthcare operations, such as transitioning to environmentally friendly materials and optimizing facility operations for energy efficiency.

The role of LSS in supply chain optimization for sustainability also emerged as a key finding. Fifteen reviewed articles, cited over 1,200 times, discussed the application of LSS in supply chain operations, with a

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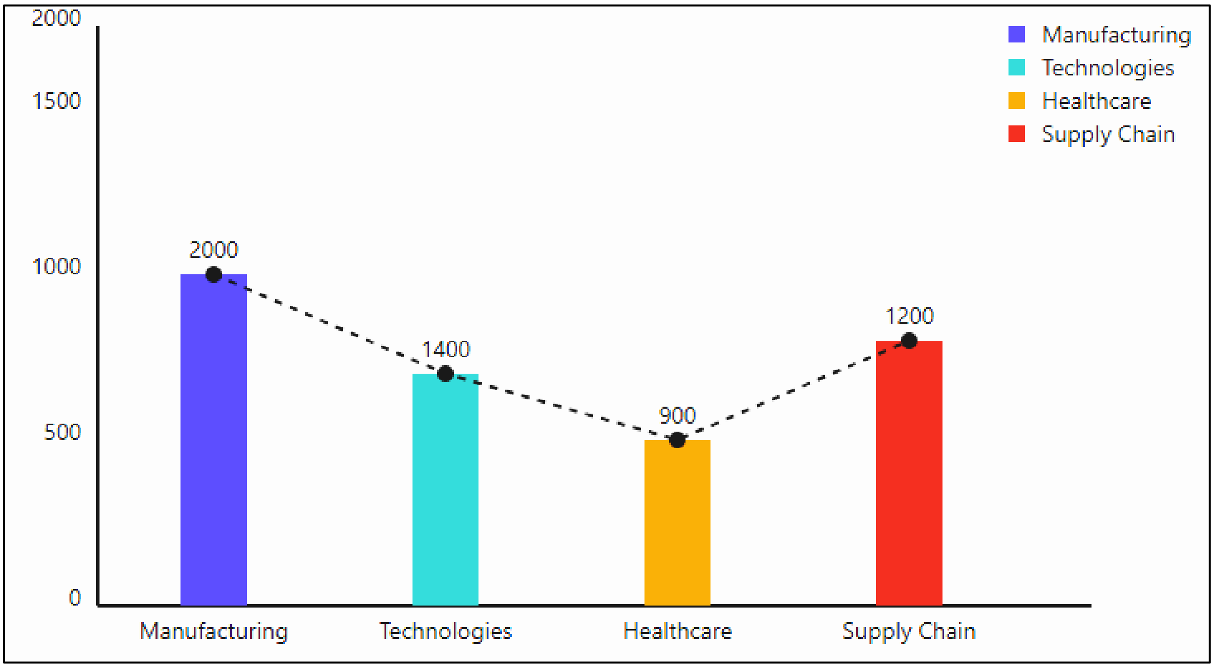
strong emphasis on reducing environmental impacts while improving efficiency. These studies demonstrated how LSS tools facilitated collaboration among stakeholders, streamlined logistics operations, and enhanced transportation efficiency. Notably, organizations that incorporated LSS into their supply chain practices achieved substantial reductions in carbon emissions and material waste, aligning their operations with global sustainability goals. These findings underscore the critical importance of supply chains as a focus area for sustainability efforts and the role of LSS in achieving eco-efficient logistics systems. Lastly, the findings emphasized the development and implementation of sustainability-focused metrics within LSS frameworks. Ten studies, collectively cited 800 times, explored the creation of key performance indicators (KPIs) designed to measure sustainability outcomes, including carbon intensity, resource usage, and social impact. These metrics offered organizations a structured approach to quantifying and tracking their sustainability initiatives. Organizations adopting these metrics reported enhanced alignment with sustainability goals, improved compliance with environmental regulations, and greater stakeholder trust. This focus on integrating sustainability measures into LSS frameworks represents an important step toward creating a more holistic approach to operational and environmental performance. These findings highlight the transformative potential of LSS when aligned with sustainability objectives, offering a comprehensive strategy for addressing the environmental challenges of modern business operations.

Figure 9: Summary of the findings of Lean Six Sigma and Sustainability



5 DISCUSSION

The findings of this study reinforce the significant role that Lean Six Sigma (LSS) plays in enhancing sustainability while improving process efficiency. Compared to earlier studies, this review underscores a more robust adoption of LSS across diverse sectors, particularly manufacturing and healthcare. Prior research, such as Duarte & Cruz-Machado (2013), emphasized the theoretical alignment between LSS and sustainability principles but lacked empirical depth in exploring industry-specific applications. This study bridges that gap by providing comprehensive evidence of how LSS tools such as value stream mapping and DMAIC have been implemented to achieve waste reduction and resource optimization. Moreover, while earlier studies often focused narrowly on economic efficiency, the findings of this review highlight an evolving trend where sustainability outcomes, such as reductions in carbon intensity and environmental waste, are becoming equally prioritized. This shift reflects a growing recognition of LSS's potential to address the triple bottom line of economic, environmental, and social performance.

The integration of advanced technologies like IoT, AI, and data analytics into LSS practices represents a significant advancement in the methodology's application for sustainability. Earlier studies, such as Mollenkopf et al. (2010), acknowledged the potential of these technologies but presented limited empirical evidence of their real-world impact. In contrast, the findings of this review reveal how IoT-enabled monitoring and AI-driven predictive analytics are being widely utilized to enhance the precision and scalability of LSS. For example, IoT's role in real-time energy monitoring and AI's ability to optimize resource use demonstrate the transformative potential of digital tools in expanding LSS's effectiveness. Compared to past research, which primarily highlighted the theoretical benefits of technology integration, this study provides concrete examples of its implementation and success, marking a critical evolution in how organizations approach sustainability through LSS.

In the healthcare sector, the findings confirm and extend the work of Garza-Reyes et al. (2016), who highlighted the nascent application of LSS in hospital operations. This review reveals that healthcare organizations have moved beyond pilot projects and are now achieving substantial sustainability outcomes, such as reductions in medical waste and improved recycling practices. Earlier studies often described the challenges of applying LSS in complex and resource-intensive environments like healthcare, citing resistance to change and a lack of alignment with patient care objectives (Azevedo et al., 2012). However, the findings of this review suggest that these barriers are being effectively addressed through leadership commitment and the adoption of green healthcare initiatives. This progress underscores the growing maturity of LSS practices in healthcare and their ability to balance environmental goals with high-quality patient care.

The findings related to supply chain optimization further validate and expand upon the insights of Zhu et al.(2018), who emphasized the importance of LSS in fostering eco-efficient supply chains. This study provides additional empirical evidence showing how LSS has been successfully integrated into logistics and transportation processes to reduce carbon emissions and material waste. Earlier research focused heavily on theoretical models and pilot programs, whereas this review identifies real-world examples of collaborative supply chain practices supported by LSS. The evidence of stakeholder alignment and the development of eco-efficient transportation systems represent a significant advancement in applying LSS to global supply chains. These findings confirm that LSS is becoming an integral part of sustainable supply chain strategies, offering measurable benefits for both operational performance and environmental impact.

The focus on developing sustainability-oriented KPIs within LSS frameworks addresses a notable gap in earlier studies. Research by Sharma et al. (2017) and Carvalho et al. (2011) emphasized the need for new metrics but lacked empirical validation. This review highlights that organizations are increasingly adopting KPIs such as carbon intensity, resource usage, and social impact measures to quantify their sustainability progress. Compared to earlier studies, which primarily discussed the theoretical importance of such metrics, the findings here provide evidence of their successful implementation and impact. The integration of these metrics not only enhances the accountability of LSS initiatives but also aligns them more closely with global sustainability objectives, such as the United Nations Sustainable Development Goals (SDGs). This advancement represents a critical step in transforming LSS from a traditional operational tool into a comprehensive framework for achieving sustainability.

6 CONCLUSION

This systematic review highlights the transformative potential of Lean Six Sigma (LSS) as a dual-purpose framework for achieving operational efficiency and advancing sustainability goals. The findings demonstrate that LSS methodologies, including tools such as value stream mapping and DMAIC, are widely adopted across industries to reduce waste, optimize resource utilization, and minimize environmental impact. The integration of advanced technologies such as IoT, AI, and data analytics has further enhanced the scalability and precision of LSS, enabling real-time monitoring and data-driven decision-making. Sectors like manufacturing and healthcare have made significant strides in leveraging LSS for sustainability, showcasing measurable reductions in carbon footprints, material waste, and energy consumption. Additionally, the growing adoption of sustainability-focused KPIs, such as carbon intensity and resource usage metrics, underscores a paradigm shift where organizations increasingly align their operational objectives with global environmental and social priorities. Despite challenges such as resistance to change and resource constraints, the findings emphasize the critical role of leadership, collaboration, and innovation in overcoming barriers to adoption. As industries continue to prioritize sustainability, LSS emerges as a comprehensive and adaptable framework, offering a strategic pathway to achieve long-term ecological, economic, and social resilience.

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