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Effect of lean six sigma and recent technologies on environmentally sustainable manufacturing and financial management practices

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Abstract

Lean Six Sigma (LSS) is being used by manufacturing industries to improve operations, competitiveness and sustainability in a competitive industry. There is a demand for a study to investigate the impact of recent technologies (RT) and LSS techniques on environmentally sustainable (ES) manufacturing and financial management practices in Saudi manufacturing industries. The study intends to examine the influence of LSS and RT on the management of the Saudi manufacturing industries. A set of hypotheses is developed to address the study's objectives. A survey methodology was followed to investigate the effect of LSS and RT on ES practices in Saudi manufacturing industries. The questionnaire content was prepared and validated with the assistance of seven experts. The author applies exploratory factor analysis (EFA), confirmatory factor analysis (CFA) and structural equation modeling (SEM) to validate the responses. The author invited 277 food and chemical manufacturing employees across Saudi Arabia. A total of 205 responses were received from the participants with a response rate of 74.00%. The regression analysis found that the variables obtained were LSS ($R^2 = 0.73$), RT ($R^2 = 0.58$) and ES ($R^2 = 0.63$). The findings confirm the significant relationship between LSS, RT and ES. The integration of LSS methodology with cutting-edge technology offers a comprehensive strategy for enhancing ES and financial management in manufacturing sectors through waste reduction, efficiency improvement and adopting new practices. In addition, the study outcomes can assist the researchers in extending their innovative ideas for implementing LSS in industrial sectors.

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1. Introduction

There has been an improvement in quality of life and a negative impact on the environment due to the rapid growth of manufacturing industries worldwide (Gaikwad & Sunnapwar, 2020). A significant quantity of air pollutants are released by manufacturing firms which harms the environment and the well-being of life forms (Vashishth, Chakraborty, & Antony, 2019). There has been increasing demand for industries to reduce environmental harm and improve safety from the government and non-profit organizations. Organizations may lessen their ecological impact by sustaining processes (Yadav, Gahlot, Kaswan, Rathi, & Singh, 2022). Several companies have altered production methods and products to be more sustainable. On the other hand, it is anticipated that there will be a variety of technological challenges associated with modifying existing operations following the redesigning procedures (Gholami et al., 2021). According to the triple bottom line's

(3BL) viewpoint, redesigning the production process is insufficient to ensure sustainability. Sustainable manufacturing procedures and products may decrease emissions and toxic gases, reducing environmental effects, waste and energy consumption (Farrukh, Mathrani, & Taskin, 2020). Consequently, feasible solutions for sustainable development should be developed and the manufacturing process's sustainability needs to be evaluated.

LSS improves operations, reduces waste and optimizes the utilization of resources for ES (Farrukh et al., 2020). LSS and environmental responsibility may assist industries in strengthening operations and the environment. It reduces waste by eliminating non-value-added operations. Waste minimization boosts efficiency, conserves resources, saves energy and reduces environmental impact (Taddei, Sassanelli, Rosa, & Terzi, 2022). LSS programs optimize operations by reducing energy consumption. Streamlining processes and reducing procedures may reduce energy use and carbon impact (Jamwal, Agrawal, Sharma, & Giallanza, 2021). Improved performance is achieved through LSS process analysis and optimization. This may decrease material consumption, maximize resource efficiency and improve the sustainability of manufacturing and service delivery. Six Sigma commonly assesses and improves the complete product life cycle. This encompasses product impact on the environment from raw material extraction to disposal. Organizations may improve sustainability by addressing environmental issues at each level. LSS emphasizes efficiently achieving customer demands (Kushwaha, Kar, & Dwivedi, 2021). LSS-based sustainability may boost customer satisfaction and loyalty as a greater number of customers prioritize environmental sustainability. Minimizing legal risks and promoting appropriate ecological management can be aided by ensuring compliance.

LSS approaches and RT is essential in financial management across all industry sectors to optimize supply chain finance operations, reduce costs, increase efficiency, manage risks, ensure compliance and improve data-driven decision-making (Kushwaha et al., 2021). These strategies may help industries become more financially stable, resilient and competitive in today's volatile business environment. Financial data may be better understood as a result of RT including, business intelligence tools and data analytics which allow companies to make decisions based on data and improve their financial performance. Organizations may benefit from advanced analytics methods, including machine learning and predictive analytics by better predicting financial patterns, identifying risks and opportunities and optimizing investment plans (Wang, Xu, Zhang, & Zhong, 2022).

Industry 4.0 and RT led to enhanced data availability in product or process design, quality control and condition monitoring (Wang et al., 2022). Industry 4.0 prioritizes rapid market response and consumer satisfaction; sustainability enhancement is gaining attention. The closed loop of the product life cycle is carefully recognized while resource efficiency is examined holistically throughout the process. RT may promote a circular economy by decreasing overproduction, energy consumption and waste leading to increased sustainable manufacturing. It is necessary to provide historical data that covers the behavior of components and processes to detect issues and start the quality improvement approach.

Saudi Arabian industries should improve environmental sustainability to meet global standards and manage environmental challenges (Ur Rehman, Usmani, Umer, & Alkahtani, 2020). The ecological effect of manufacturing processes remains a source of concern even though the area is growing economically and industrially. The issue is inefficient utilization of resources, waste generation and a lack of systematic mitigation of environmental impact (Al-Atiyat, Ojo, & Soh, 2021).

Manufacturing typically wastes energy, water and raw materials. This lack of efficiency leads to higher operating expenses and a more significant environmental impact (Abualfaraa et al., 2022; Albliwi & Al-Harbi, 2020; Mabrouk, Ibrahim, & Eddaly, 2021). A major environmental threat is excessive waste production, including solid waste and emissions. Environmental degradation and ecological damage may result from poor waste management. The manufacturing industry has a substantial role in generating greenhouse gas emissions (Abualfaraa et al., 2022).

Non-compliance with regulations and setbacks in sustainability efforts could result from a lack of systematic actions to lessen the carbon footprint. Incorporating environmental sustainability strategies into industrial operations is not well-defined or standardized (Stankalla, Koval, & Chromjakova, 2018). It is difficult to assess, track and enhance sustainability measures in the absence of a systematic strategy. These limitations have motivated the author to investigate the effect of integrating LSS, RT and ES in Saudi Arabian industries.

The author formulated the following research questions (RQs) based on the knowledge gap in the existing literature:

RQ1: What is the significance of recent technologies in monitoring environmental sustainability?

RQ2: What is the relationship between LSS, RT and ES?

The remaining part of this study is structured as follows: Section 2 describes the development of hypotheses for addressing RQs. The methodology of the proposed study is presented in section 3. Section 4 highlights the analysis outcomes.

The significance of the findings is presented in section 5. Finally, the study's contributions are listed in section 6.

2. Literature Review

RT has great promise for improving ES and suggests further studies to investigate current theories and approaches (Kamble, Gunasekaran, & Dhone, 2020). However, little empirical research has shown a relationship between RT and ES. In addition, the understanding that can be gained from these investigations is restricted. Kamble et al. (2020) examined the impact of industry 4.0 technologies like RT, IoT and additive manufacturing on sustainable performance in lean manufacturing systems (Kamble et al., 2020). Cheng and Liu (2018) evaluated ES using public databases whereas Dubey et al. (2019) examined the impact of RT on ES with flexible and control orientation as a moderating variable. These investigations indicated that RT had a beneficial effect on the ES despite moderating factors. However, these studies focused on data analysis as a general strategic tool rather than specific capabilities. It is necessary to conduct multiple studies to aid entities in developing successful data analysis strategies to improve ES.

The term "Industry 4.0" describes a technical, economic, social and strategic shift that is part of the larger shift towards a more linear economic model (Arcidiacono & Pieroni, 2018). The sophisticated technologies of Industry 4.0 enable the rapid and efficient gathering, storage, analysis and sharing of large amounts of data between humans and machines (Angreani, Vijaya, & Wicaksono, 2020). Industry 4.0 facilitates the development of intelligent goods and services that possess attributes such as an enhanced understanding of consumer demands, improved customer interaction and real-time monitoring to enhance performance (Gallab, Bouloiz, Kebe, & Tkiouat, 2021).

Industry 4.0 includes several technologies such as the IoT, AI, big data analytics, cloud computing and cyber-physical systems. The fundamental tenets of Industry 4.0 are interconnection, information openness, technical support and decentralized decision-making. The integration of IoT devices into machinery, equipment and goods facilitates the instantaneous gathering and transmission of data (Song, Du, & Zhu, 2017). Sensors are used to monitor several characteristics, including temperature, pressure and performance metrics (Song et al., 2017). This allows for a better understanding of the operating state of equipment and processes. Big data analytics tools are used to evaluate and extract insightful information from the vast quantities of data collected by IoT devices. This data analysis is beneficial for tasks such as predictive maintenance, quality control, demand forecasting and decision-making. AI technologies such as machine learning algorithms and predictive analytics are used to automate jobs, improve processes and facilitate data-driven decision-making. AI facilitates predictive maintenance by evaluating data from equipment to forecast maintenance requirements resulting in less downtime and improved resource efficiency. Cyber-physical systems combine computer algorithms with physical processes to provide real-time monitoring, control and automation (Song, Fisher, Wang, & Cui, 2018). Cyber-physical systems enable dynamic and flexible production processes allowing machines to intercommunicate and alter their operations in response to evolving circumstances (Huang, Irfan, Fatima, & Shahid, 2023).

Many studies have examined the individual impacts of LSS and contemporary technologies on sustainability and financial management but few have examined their combined implementation (Belhadi, Kamble, Gunasekaran, Zkik, & Touriki, 2023; Belhadi, Kamble, Zkik, Cherrafi, & Touriki, 2020; Karadayi-Usta, 2019). Additional investigation is required to examine the successful integration of LSS approaches with new technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics to create synergistic impacts on sustainability and financial performance. Numerous studies provide qualitative or anecdotal proof of the beneficial impacts of LSS and contemporary technologies on sustainability and financial management. Nevertheless, further quantitative study is required to evaluate the extent of these impacts and their consequences for industrial processes. Quantitative analysis aids in identifying crucial performance criteria, measuring enhancements in efficiency, reduction of waste and financial results and furnishing factual data to bolster decision-making (Sony & Naik, 2020).

The majority of current research on LSS and RT is conducted using cross-sectional methods or relies on short-term case studies. Longitudinal studies are necessary to investigate the long-term viability and financial consequences of implementing LSS and embracing modern technology in industrial environments. Longitudinal studies provide valuable insights into the long-term sustainability of improvements and the lasting financial advantages produced by LSS and RT by monitoring changes over time.

The influence of LSS and contemporary technologies on sustainability and financial management might differ across various manufacturing sectors and industries. Additional study is required to investigate the individual problems, possibilities and most effective methods for implementing LSS and embracing modern technology within different sectors. An examination focused on individual sectors may assist in identifying industry-specific elements that drive, impede or contribute to the achievement of sustainability and financial objectives.

The majority of previous studies on LSS and modern manufacturing technologies have mostly focused on huge organizations, neglecting small and medium-sized firms (SMEs). SMEs frequently experience distinct obstacles and limitations in terms of resources which might hinder their capacity to apply LSS methodologies and embrace cutting-edge technology. Additional study is required to investigate the practicality, efficiency and expandability of LSS and contemporary technologies in SMEs and determine methods for overcoming obstacles to implementation.

3. Hypotheses Development

Industry 4.0 and digitalization enhance data availability in product or process design, quality control and condition monitoring (Gallab et al., 2021). Industry 4.0 prioritizes rapid market response and consumer satisfaction, sustainability enhancement is gaining attention. The closed loop of the product life cycle is carefully recognized while resource efficiency is examined holistically throughout the process. Industry 4.0 aims to enhance processes by using data-driven insights to identify improvement areas that align with LSS's focus on reducing waste. LSS's continuous improvement supports Industry 4.0's data-driven strategy (Song et al., 2017). Sustainability can be enhanced by the integration of lean concepts and Industry 4.0 technology which allow for targeted waste reduction. Organizations may increase energy efficiency, waste reduction and emissions management through data analytics. Industries can monitor, evaluate and improve sustainability operations with real-time data and intelligent technology (Song et al., 2018). RT may promote a circular economy by decreasing overproduction, energy consumption and waste leading to increased sustainable manufacturing. It is necessary to provide historical data that covers the behavior of components and processes to detect issues and start the quality improvement approach.

Recent technology, data analysis and environmental sustainability are crucial to addressing global environmental challenges and promoting sustainability. The collection of data through sensors, Internet of Things devices and various additional information sources has been made simpler by recent technological advancements. Data analysis is essential for gaining insights (Song et al., 2018). Data analytics helps firms understand resource management, energy efficiency, waste reduction and other environmental sustainability issues. IoT and other smart technologies allow data collection and real-time monitoring across multiple environmental sources (Belhadi et al., 2023). The incorporation of sensors into infrastructure, buildings and ecosystems achieves continuous data streams. Analyzing this data reveals trends, anomalies and sustainable intervention options. Machine learning and AI-powered predictive analytics help companies forecast equipment problems and plan maintenance (Belhadi et al., 2020). This strategy extends equipment lifetime which benefits the environment in addition to reducing downtime and preventing resource wastage. Using technologies such as satellite images, drones and remote sensing contributes to environmental monitoring and protection. Data analysis helps power systems integrate renewable energy. Organizations may maximize renewable energy usage by evaluating weather patterns, energy demand and production data, lowering non-renewable consumption and encouraging sustainability (Karadayi-Usta, 2019).

Data is the backbone of LSS initiatives (Sony & Naik, 2020). Gathering and analyzing massive volumes of data from various functional units is essential due to the critical nature of decision-making. Consequently, data analysis (DA) skills can potentially benefit LSS strategies. Although few instances exist, DA capabilities have been shown to considerably boost the effect of LSS in improving operations and addressing the growing significance and availability of data. The research suggests that integrating LSS efforts with DA capabilities enhances decision-making efficiency.

According to the studies Ren et al. (2019), Feroz, Zo, and Chiravuri (2021), Kaswan, Rathi, and Khanduja (2020), Yadav et al. (2021) and Letchumanan et al. (2022) RT enhances root cause analysis reliability and speed decreasing LSS program implementation costs in an iron foundry case study. The literature review provides enough evidence to support the idea that organizations can boost ES by instituting a continuous improvement framework that encourages natural conception through RT and mechanical implementation of these ideas through LSS despite a lack of research on the combined effects of RT and LSS on ES. The author develops the following hypotheses in perspective with the existing literature:

Hypothesis 1 (H_1): LSS positively influences the application of RT.

Hypothesis 2 (H_2): LSS positively affects ES. LSS mediates the relationship between RT and ES.

Hypothesis 3 (H_3): RT positively influences ES.

Figure 1 visualizes the proposed research framework.

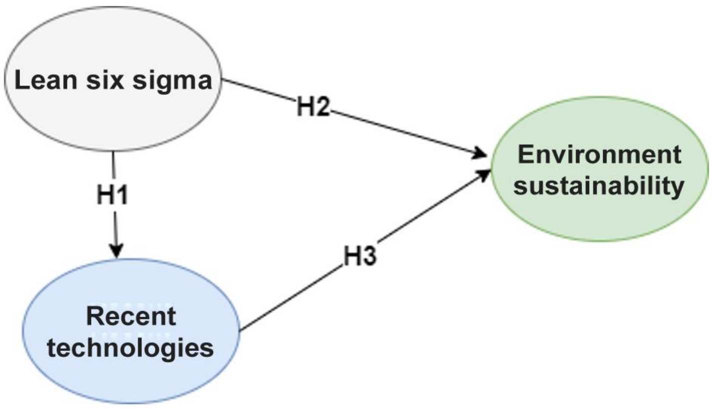

Figure 1. Research framework.

4. Methodology

In this study, the author employs widely applied survey methodology to address the RQs. EFA assists in developing hypotheses regarding hidden factors influencing observable variables. It offers valuable insights into the interconnections between variables and aids in developing theoretical frameworks. It enables researchers to analyze data relationships and trends without imposing a fixed model structure. It is especially beneficial for complicated datasets with unclear variable relationships. CFA is used to assess the extent to which the proposed factor structure aligns with the actual data. Researchers validate the provided theoretical framework using CFA to evaluate the model's alignment with the empirical data. Theoretical or research-based hypotheses can be tested using CFA.

SEM enables the investigation of mediating and moderating effects by providing a holistic framework. Researchers may examine the indirect impacts of factors and test how particular associations are enhanced or decreased. For longitudinal research, SEM may explore data from various time points. It facilitates the analysis of temporal variations in variables and improves comprehension of their dynamic interconnections. EFA, CFA and SEM are performed to test the convergent and discriminant validity of the questionnaire.

4.1. Data Collection

The author employs a survey instrument to test the hypotheses. A draft version of the questionnaire was prepared and validated in two phases. The author developed the questionnaire based on the existing studies. A total of 26 items were included in the questionnaire. In addition, the authors presented optional items to obtain the demographic data. A five-point Likert scale ranging from strongly agree (1) to strongly disagree (5). The RT variable covers eight questions that were extracted from the studies. A total of 9 questions were included in the LSS variable.

Finally, the ES variable covers 9 questions based on the studies. In the final phase, the author invited seven experts to validate the questionnaire content. Four professionals are ES experts, the remaining are Industry 4.0 and data science experts. The author revised the questionnaire based on the experts' insights. The target population of the proposed study includes analysts, engineers and managers working in the food and chemical manufacturing industries across the Kingdom of Saudi Arabia. The author requested that they provide their perceptions to ensure the participants' awareness of the RT, LSS, and ES. According to Belhadi et al. (2023) and Mabrouk et al. (2021), the sample size for the study is determined. The author distributed the invitations to 277 participants through their email addresses. The author forwarded the Google Forms link to the participants after receiving confirmation. A total of 198 completed questionnaires were received resulting in a response rate of 71.4%.

The authors sent a reminder email to the participants to increase the response rate. Finally, seven participants responded to the questionnaire. Thus, the author obtained a sum of 205 responses with a response rate of 74%.

4.2. Data Analysis

EFA is a statistical method used to analyze a group of variables and reveal the hidden patterns and relationships within them. It aims to discover latent factors that account for the observed correlations between the variables.

The importance of EFA resides in its capacity to reveal latent patterns or dimensions within the data which may provide valuable insights into the fundamental structures or ideas being assessed. EFA assists researchers in simplifying complex datasets and constructing theoretical frameworks for further study by discovering shared components among observed variables.

CFA is a statistical method that assesses the accuracy of a proposed component structure by analyzing the extent to which observed variables align with their anticipated underlying factors. The importance of CFA rests in its capacity to systematically examine theoretical models and determine the degree of agreement between observed data and pre-existing assumptions.

The CFA assists researchers in validating or improving theoretical conceptions and measurement models through the use of empirical data.

SEM is a robust statistical method used to examine intricate connections between unobservable variables and observable variables within a unified framework. SEM integrates components of factor analysis and regression analysis to investigate causal pathways, mediating effects and both direct and indirect correlations between variables. The importance of SEM resides in its capacity to assess intricate theoretical models and investigate the underlying processes that accelerate actual occurrences.

IBM SPSS version 27 and IBM SPSS Amos 27 (Windows 10) are extensively used to analyze the responses. The primary SPSS statistics module focuses on descriptive statistics and bivariate and multivariate analyses. In contrast, the IBM SPSS Amos module is exclusively dedicated to SEM which includes EFA and CFA. IBM SPSS offers a user-friendly graphical interface that enables researchers and analysts to construct, estimate and evaluate complex statistical models rapidly. This is particularly advantageous for users who may lack advanced programming expertise.

SPSS Amos is a component of the SPSS software package for SEM. It provides various specialized tools and capabilities for SEM making it a valuable option for academics interested in EFA, CFA and SEM.

5. Results

In this section, the author presents the outcome of the data analysis. Table 1 reveals the demographic profile of the participants. Initially, the EFA analysis was used for the data preparation. It shows the data patterns, correlations and sample adequacy. The author applied principal component analysis for the factor analysis, communalities, factor loadings and Eigen values were computed. The findings indicated that there is a significant correlation between the observed variables. In addition, the Kaiser-Meyer-Olkin (KMO) and Barlett's sphericity tests were performed to evaluate the sample's adequacy. A KMO value of 0.87 shows that the samples were adequate.

Table 1. Demographic data analysis.

Categories		Responses	Response rate (%)
Industries			
	Food	123	60
	Chemical	82	40
Industry size			
	Large	57	27.8
	Medium	75	36.5
	Small	73	35.7
Designation			
	Manager	49	23.9
	Analysts	75	36.5
	Engineer	81	39.6

The outcomes of correlation and discriminant validity analysis are described in Table 2. The factor loadings of the constructs are greater than 0.50. In addition, Table 2 shows the variables' average variance extracted (AVE). There are no discriminant validity issues in the responses.

Table 2. Correlation and discriminant validity.

	LSS	RT	ES	AVE
LSS	0.819			0.716
RT	0.429	0.862		0.728
ES	0.689	0.712	0.872	0.599

Furthermore, the convergent validity analysis found that the model fit without convergent validity issues. The findings of the CFA model analysis are presented in Table 3.

Table 3. CFA model analysis outcomes.

	Chi-square	The goodness of fit (GFI)	Adjusted GFI	Comparative fit index (CFI)	Root mean square error of approximation (RMSEA)
Values	1796.42	0.931	0.907	0.869	0.049
Threshold values	--	> 0.7	> 0.7	> 0.81	> 0.04

The findings of the SEM analysis show the influence of LSS on applications of RT (β = 0.87), ES (β = 0.73) and full mediation of RT and ES (β = 0.81). On the other hand, RT positively influences ES (β = 0.77). Figure 2 presents the outcome of SEM analysis. The results indicated a significant relationship between RT, LSS and ES.

In addition, the explanatory power was measured for the constructs using the regression of determinations (R^2).

Table 4 shows the regression analysis and hypothesis results.

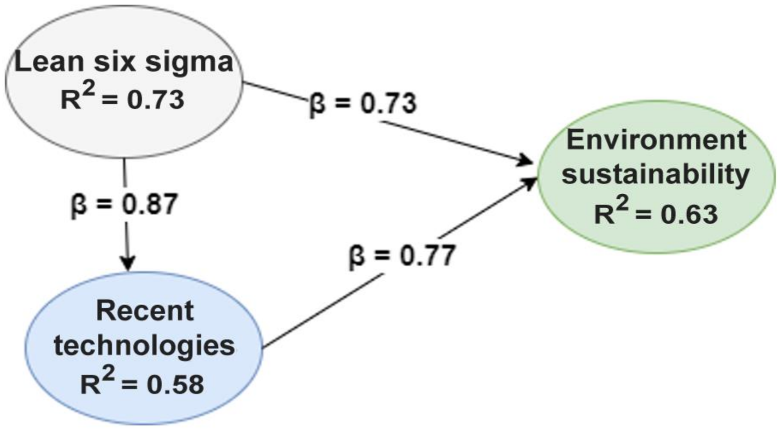

Figure 2. SEM analysis outcomes.

Table 4. Regression analysis outcome.

Hypotheses	Standardized estimates	Results
H1	0.73	Supported
H2	0.58	Supported
H3	0.63	Supported

6. Discussion

The study's findings align with those of other studies such as Mabrouk et al. (2021), Albliwi and Al-Harbi (2020), Abualfaraa et al. (2022), Stankalla et al. (2018), Kamble et al. (2020) and Cheng and Liu (2018) highlighting the significance of data-driven decision-making and LSS in promoting sustainable manufacturing processes. In addition, the research findings align with previous studies that have emphasized the importance of employee motivation and decision-making skills in promoting ES. The results contribute to the expanding body of research that has been conducted on the significance of LSS, data-driven decision-making and organizational culture in the process of fostering sustainable manufacturing practices. Understanding these components' interrelationships helps firms improve their environmental performance and achieve sustainability objectives. Incorporating environmental measurements into lean and Six Sigma initiatives is crucial for achieving ES. Without RT, ES measures become unmanageably complicated. The analysis indicates that RT may boost ES by catalysing LSS techniques. Additionally, the research found that LSS fully mediates the relationship between RT and ES. According to Ren et al. (2019) RT may be used to develop algorithms for optimizing different phases of a product's or process's lifecycle and to analyze the product's or ES processes. LSS tends to be extremely effective for gaining ES.

The author found that organizations can benefit from a holistic approach that integrates LSS principles with data-driven decision-making, employee motivation and a strong company culture. This study's findings follow the existing studies (Feroz et al., 2021; Kaswan et al., 2020; Letchumanan et al., 2022; Yadav et al., 2021). Industries can improve their operational efficiency, raise customer loyalty and increase profitability by concentrating on these crucial areas which allows them to encourage sustainable manufacturing techniques. The proposed study highlights the significance of continual improvement and continuing assessment to pursue sustainable manufacturing processes. It is in line with the existing research studies (Ganjavi & Fazlollahtabar, 2021; Nagadi, 2022; Shokri, Antony, & Garza-Reyes, 2022; Shokri & Li, 2020). Organizations may improve their methods and create more sustainable, environmentally friendly operations that benefit their bottom line and the globe through increased research and experimentation.

The current literature on LSS emphasizes its efficacy in minimizing waste, raising process efficiency and improving quality. Multiple studies have shown that LSS has a beneficial effect on environmental sustainability by detecting and removing causes of waste and inefficiency in industrial processes. RT provides continuous monitoring of data, the analysis of information and the optimization of resources resulting in a decrease in the environmental footprint. Kaswan et al. (2020) discovered that the deployment of LSS resulted in noteworthy decreases in energy consumption, material utilization and greenhouse gas emissions across different sectors. Yadav et al. (2021) emphasized the potential of IoT and AI to enhance energy efficiency, decrease emissions and enhance environmental sustainability in industrial processes. Similarly, the proposed study highlighted the significant role of LSS in the manufacturing industry. Letchumanan et al. (2022) and Shokri et al. (2022) emphasized the capacity of AI and big data analytics to enhance financial efficiency, minimize expenses and enhance overall financial performance. The current literature on LSS and RT mostly examines their effects on sustainability and financial management through the use of case studies, surveys and theoretical frameworks (Ganjavi & Fazlollahtabar, 2021; Nagadi, 2022; Raval, Kant, & Shankar, 2019; Shamsi & Alam, 2018; Shokri & Li, 2020; Sreedharan & Sunder, 2018; Trakulsunti, Antony, & Douglas, 2020; Wahba, Kamil, Nassar, & Abdelsalam, 2019). On the other hand, the proposed study employed quantitative analysis to investigate how the combination of LSS with modern technology affects manufacturing in real-world situations. The proposed research presented a thorough analysis by assessing the combined effect of LSS and contemporary technologies, building upon the rich insights provided by prior studies on their separate effects. In addition, the proposed study highlighted the effects of LSS integration with new technology on financial performance and sustainability as well as the processes behind these effects and interactions.

The proposed study has effectively addressed a number of knowledge gaps highlighted in the current literature. The main objective is to thoroughly investigate the combined implementation of LSS techniques with advanced technologies like IoT, AI, and big data analytics. The research addresses a significant gap in the literature by examining how the combination of these techniques may successfully enhance sustainability and financial performance. It focuses on the integrated use of LSS and modern technologies in manufacturing to produce synergistic benefits. The study used quantitative research methodologies to evaluate the influence of LSS and RT on environmentally friendly manufacturing and financial management practices. The research gathers and examines quantitative data including performance measures, financial indicators and environmental impact evaluations to provide empirical proof of the extent to which LSS and contemporary technologies affect sustainability and financial results. Furthermore, it encompasses environmental impact assessments to examine the ecological effect of LSS deployment and the integration of cutting-edge technology in industrial activities. The research assesses the environmental effect of LSS and contemporary technologies providing insights on how to enhance sustainability practices and make more eco-friendly production decisions.

6.1. Practical Implications

Industry managers, policymakers and researchers can benefit significantly from the study's conclusions. The research underscores the significance of integrating LSS methodology, data-driven decision-making and cultivating a supportive organizational culture to improve environmental performance in the manufacturing sector. Managers should develop balanced scorecards, educate employees and foster a sustainable improving culture. Sustainable product and service choices may also be achieved by emphasizing customer relationship management. These measures may help industrial businesses enhance their environmental performance and remain competitive. Our approach establishes a framework for sustainability research by identifying critical characteristics that influence effectiveness. Policymakers may encourage firms to adopt more sustainable practices by offering incentives and resources and boosting manufacturing sustainability education and awareness. The findings indicate that sustainable manufacturing techniques help enterprises and the environment through cooperation and continual development.

A theoretical framework integrating LSS, RT and ES has numerous consequences. The integration of LSS with ES is consistent with the concept of systems thinking. Theoretical models that prioritize comprehensive perspectives of companies and supply chains are essential to comprehend the interdependence of activities and their effects on the environment. This integration requires a systems thinking approach to account for the intricate relationships between LSS, RT and ES objectives. Continual improvement is vital for operational excellence and environmental sustainability. Recognizing the revolutionary potential of the principles associated with Industry 4.0 is essential. Organizations should include these ideas in their models as technology develops ecologically friendly and digitally correlated industrial ecosystems. Theoretical frameworks should consider the interconnections between lean principles, circular economy theories and modern technology. Theoretically, businesses should build all-encompassing frameworks that include environmental sustainability measures and LSS by drawing on existing performance assessment ideas to understand how to optimize resource efficiency within sustainable manufacturing processes. The framework should include organizational learning theories since sustainable practices need ongoing learning and adaptation.

Organizations can effectively incorporate LSS principles, RT and ES to enhance operational efficiency and competitiveness. The integration positively impacts environmental stewardship and meets societal expectations for sustainable business practices. The practical implications include all facets of organizational functioning highlighting the need for a comprehensive and unified strategy to attain sustainable and effective operations. Utilizing technology such as IoT and data analytics allows for immediate monitoring, the identification of inefficiencies and the facilitation of predictive maintenance to minimize periods of inactivity.

Implementing lean principles maximizes the use of resources, including raw materials, energy and labor. Advanced technologies enhance resource optimization by using intelligent manufacturing processes, energy-conserving systems and exploiting sustainable energy sources. The primary objective of LSS techniques is to optimize product and process quality by minimizing defects and maximizing customer satisfaction. The use of AI-based automation improves accuracy, minimizes mistakes and adds to the production of consistently high-quality results. The integration of lean concepts with Industry 4.0 technology results in the implementation of smart manufacturing whereby networked systems facilitate decision-making based on data analysis.

6.2. Study Limitations

The organizational culture, managerial methods and regulatory environment in Saudi Arabian manufacturing enterprises may vary from those in other countries which might impact the implementation of

LSS and the acceptance of contemporary technology. The readiness of businesses to accept change and innovation may be influenced by cultural norms, hierarchical structures and decision-making procedures. The technology infrastructure and digital capabilities of Saudi Arabian manufacturing enterprises may vary in terms of availability and complexity depending on the locations and industries. The restricted availability of cutting-edge technologies, such as IoT, AI and big data analytics might impede the implementation and efficacy of technology-based solutions for sustainability and financial management. The manufacturing sector in Saudi Arabia encompasses a wide range of sectors such as petrochemicals, construction, automotive and food processing. Each industry has its distinct features and obstacles. It may be challenging to apply the results to other businesses, thus the suggested research should concentrate on certain areas to provide valuable insights. The legislative framework pertaining to environmental sustainability and financial management practices in Saudi Arabia may vary from those of other nations. Organizational behavior and performance assessment techniques may be influenced by compliance requirements, reporting standards and government efforts about sustainability and financial transparency.

6.3. Future Directions

The future direction of this study will examine emerging trends, potential areas of research and practice implications for further investigation. The author will examine the incorporation of sustainable energy technology such as solar and wind power into industrial operations to improve environmental sustainability and decrease reliance on fossil fuels. The practicality, cost-efficiency and ecological advantages of implementing renewable energy solutions with LSS processes and sophisticated technology will be evaluated. The author will analyze the impact of LSS methodologies and contemporary technological advancements on enhancing sustainability across the whole supply chain, including activities ranging from sourcing raw materials to distributing finished products. Approaches to improve the efficiency of the supply chain minimize the environmental effects and increase the visibility and capacity to track products will be analyzed using LSS concepts and technology-driven solutions. The author will investigate potential avenues for integrating circular economy principles such as waste minimization, repurposing and recycling into the industrial sectors of Saudi Arabia.

7. Conclusion

The major contribution of this work is an analysis of the elements that affect the effective use of LSS in eco-friendly production processes which in turn improves ES. The research offers significant insights for firms aiming to optimize resource efficiency, increase satisfaction with clients and promote ongoing development, ultimately leading to greater sustainable production and improved ES. The study's focus is on these components and the connections between them to achieve this goal. This study's results show that data-driven RT and LSS are key to promoting sustainable manufacturing practices consistent with other studies. The findings indicate that the capabilities of LSS have a direct influence on ES and RT. Furthermore, it has been observed that LSS indirectly affects ES through the process of its integration with LSS and RT. It has been shown that the combination of these procedures results in a more effective enhancement of ES. The study's results should be regarded carefully owing to the following limitations:

The research examines the effects of LSS and RT on ES in Saudi Arabian food and chemical manufacturing enterprises limiting generalizability. Furthermore, it is important to note that the research relies on survey data collected from specific organizations and it is entirely possible that some survey oversights in design were made. The lack of development of RT and LSS in the Saudi Arabian industrial environment makes it difficult for participants to become familiar with these new techniques. However, the author was careful to include only those who had some background knowledge of these concepts. The increased prevalence of the food manufacturing industry in the sample is due to the Saudi Arabian environment.

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