Exploring lean manufacturing drivers for enhancing circular economy performance in the pharmaceutical industry: a Bayesian best–worst approach

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Abstract

Purpose – The imperative to conserve resources and minimize operational expenses has spurred a notable increase in the adoption of lean manufacturing within the context of the circular economy across diverse industries in recent years. However, a notable gap exists in the research landscape, particularly concerning the implementation of lean practices within the pharmaceutical industry to enhance circular economy performance. Addressing this void, this study endeavors to identify and prioritize the pivotal drivers influencing lean manufacturing within the pharmaceutical sector.

Findings – The outcome of this rigorous examination highlights that "Continuous Monitoring Process for Sustainable Lean Implementation," "Management Involvement for Sustainable Implementation" and "Training and Education" emerge as the most consequential drivers. These factors are deemed crucial for augmenting circular economy performance, underscoring the significance of management engagement, training initiatives and a continuous monitoring process in fostering a closed-loop practice within the pharmaceutical industry.

Research limitations/implications – The findings contribute valuable insights for decision-makers aiming to adopt lean practices within a circular economy framework. Specifically, by streamlining the process of developing a robust action plan tailored to the unique needs of the pharmaceutical sector, our study provides actionable guidance for enhancing overall sustainability in the manufacturing processes.

Originality/value – This study represents one of the initial efforts to systematically identify and assess the drivers to LM implementation within the pharmaceutical industry, contributing to the emerging body of knowledge in this area.

Keywords Drivers of lean manufacturing, Sustainable lean implementation, Best–worst method (BWM), Pharmaceutical industry, Circular economy

Paper type Research paper

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1. Introduction

In the manufacturing sector, the term "lean" is a word which used to highlight the reduction of waste and uncertainty in the production process through scientific management and the core idea of lean manufacturing principles is to divide and enhance the manufacturing process (Du *et al.*, 2023). The development of manufacturing processes by Henry Ford and other manufacturers at the end of the 19th and beginning of the 20th centuries is when the lean notion first appeared (Dekier, 2012). In the last years, the concept of lean manufacturing has gained immense popularity among the manufacturing industries worldwide. Lean manufacturing is a concept focused on reducing waste and uncertainty in the production process. It has gained popularity in the manufacturing sector worldwide. Lean manufacturing aims to eliminate nonvalue-added items, enhance efficiency and simplify processes. The seven categories of waste considered in lean manufacturing are overprocessing, overproduction, high inventory, waiting time, unnecessary motion, defects and unnecessary transportation.

In the pharmaceutical industry, the adoption of lean manufacturing principles has led to improved product quality, cost reduction and increased productivity. However, implementing lean in this industry can be challenging due to regulatory complexities and the need for strict adherence to quality standards. Numerous investigations into the use of lean principles in pharmaceutical manufacturing have revealed positive results to boost the efficiency of their manufacturing process (Sharabati, 2023). One research by Bento and Tontini (2019) focused on the implementation of lean principles in production system of small and medium pharmaceutical enterprises. The authors include the unique features of small and medium-sized enterprises (SMEs) in this industry. They noted that the implementation of lean principles in the pharmaceutical industry can be challenging due to the complex regulatory environment, the need for strict adherence to quality standards, heavy equipment, long processing time, etc. To the best of the authors' knowledge, this research is the first to evaluate a pharmaceutical firm using these markers both statistically and qualitatively (Eskandari *et al.*, 2022).

The adoption of lean manufacturing principles in the pharmaceutical industry has been identified as a potential strategy for improving performance outcomes within a circular economy framework (Liu *et al.*, 2023). The circular economy (CE) offers a comprehensive framework that promotes resource efficiency, waste reduction and closed-loop systems to uncouple economic growth from resource consumption. A study by Arruda *et al.* (2021) reviewed CE adaptation, divided the criteria into three perspectives such as energy and material scarcity, environmental effects (solid waste, landfills, emissions or pollution) and financial implications (such as cost savings and higher income) are all factors that affect the availability of resources and described the industrial advantages. Also, research by Bag and Pretorius (2022) stated lean manufacturing and the circular economy can work together to create a positive feedback loop that benefits the environment and society at large, hence supporting sustainable growth in the manufacturing sector. The circular economy framework offers a comprehensive approach to resource efficiency and waste reduction. Lean manufacturing practices have been found to positively impact circular economy performance outcomes in the pharmaceutical industry. The circular economy prioritizes resource reuse and recycling to achieve a more comprehensive sustainability goal. The circular economy promotes maximizing the value of products, minimizing waste and ensuring sustainability in the pharmaceutical supply chain. Incorporating the concept of circular economy with lean manufacturing will help the pharmaceutical industries conserve raw materials, machinery, environment, etc. while lessening the operational cost. Implementing lean and circular economy practices in emerging economies presents unique challenges such as limited resources and infrastructure. However, lean manufacturing can help overcome these challenges and achieve long-term profitability.

Bangladesh's pharmaceutical industry is flourishing, with 257 licensed factories, of which 150 are operational. Implementing the CE in this industry would bring benefits such as reduced process time, by-product production and costs as well as ensuring a sustainable supply chain (Shi, 2022). However, emerging economies face challenges in adopting CE practices due to limited infrastructure, technology for waste management and lack of awareness among the consumers and policymakers. Lean manufacturing can help overcome these obstacles and achieve long-term profitability by improving efficiency and reducing waste (Salman *et al.*, 2023). This integration of lean principles with the circular economy can play a crucial role in sustainable development. Lean manufacturing has the potential to have a huge influence in emerging economies like Bangladesh, which has a bright future as an emerging market (Salman *et al.*, 2023). Due to the country's fast industrialization and urbanization, it is currently experiencing serious environmental and economic problems. The circular economy idea is gaining popularity in Bangladesh, according to research by Hussain and Malik (2020) because of its capability to support sustainable development. But the absence of proper technology and infrastructure for waste management and recycling is one of the key challenges (Hussain and Malik, 2020). Bangladesh, as an emerging market, can greatly benefit from the implementation of lean manufacturing. The country faces environmental and economic issues due to rapid industrialization and urbanization. While the circular economy idea is gaining popularity, the lack of waste management infrastructure and awareness among the consumers and policymakers pose challenges.

The adoption of lean manufacturing in the Bangladeshi pharmaceutical industry can lead to improved operational and financial performance. Productivity indicators such as reduced lead times, lower customer complaint rates, increased units produced per labor hour and improved equipment effectiveness can be achieved through lean practices. According to the studies of Kamble *et al.* (2020), Karam *et al.* (2018), Nenni *et al.* (2014), use of the lean approach is the only option for expanding the economy.

It provides a new method of measuring the integration of the circular economy with lean practices. A few drivers of lean manufacturing such as extension of product life, innovative business models, etc. are implemented to achieve the benefits of circular economy in pharmaceutical industry. Moreover, the study focuses on examining the extent to which lean manufacturing drivers are being implemented in Bangladesh's pharmaceutical business and how the circular economy paradigm is being integrated. Examining the possible synergies between lean manufacturing and circular economy concepts becomes imperative research, especially in the pharmaceutical industry, where resource efficiency and environmental issues are of utmost importance. The objective of this study is to investigate the factors that facilitate the improvement of circular economy performance in the pharmaceutical sector by utilizing lean manufacturing techniques. The ways to get the best performance outcomes, following research questions (RQs) are developed, such as:

RQ1. What are the specific drivers within lean manufacturing that play a pivotal role in improving circular economy performance in the pharmaceutical sector?

RQ2. How can a Bayesian best–worst approach be utilized to analyze and prioritize lean manufacturing drivers with the aim of enhancing circular economy performance in the pharmaceutical industry?

RQ3. Based on the Bayesian best–worst findings, what strategic pathways can be identified and recommended for the effective implementation of lean manufacturing drivers, fostering circular economy practices within the pharmaceutical industry?

By measuring the integration of the circular economy with lean practices, this study provides a new methodological approach and highlights the importance of incorporating circular economy principles in the pharmaceutical industry's operations. Aiming to answer the research questions, the Bayesian best–worst method (BWM), an optimal barrier mitigation route analysis tool, is used to identify the most effective path shapes for promoting lean manufacturing. In this study, a multicriteria decision-making model was created to assess the success of the circular economy in Bangladesh's pharmaceutical business. By visualizing and simulating the system's rise to the top of the fitness landscape, the BWM method identifies the optimum course of action for removing obstacles to lean implementation. The novelty of this work lies in its focus on implementing lean manufacturing drivers in the pharmaceutical industry of Bangladesh, which has not been previously explored. The study emphasizes the need to incorporate the circular economy paradigm into various aspects of the pharmaceutical industry operations, including logistics, procurement, design, production, marketing and communication. By measuring the integration of the circular economy with lean practices, the study introduces a new methodological approach.

The following is an outline of the article: Section 2 offers a comprehensive analysis of the existing literature on lean manufacturing practices and driver of implementing LM in the pharmaceutical sector in the circular economy context. Section 3 portrays the data collection procedure and computational phase of the proposed BWM framework. The findings and the validation of the study are shown in Section 4. Afterward a discussion of the implications of the study, Section 5 highlights the practical implication of the study and the insights gained from the investigation. Section 6 concludes the research work by discussing the findings and opportunities for future exploration.

2. Literature review

2.1 Current scenario of lean manufacturing practices and circular economy

Lean manufacturing was invented in the 1950s by Toyota in Japan, and many businesses all over the world have subsequently adopted it to boost their competitiveness. Numerous papers, including research carried out in diverse areas, such as India, provide evidence of lean practices. A considerable majority of businesses had incorporated various parts of lean manufacturing, according to Patel and Patel (2022), investigation into the extent of lean adoption and its effect on operational performance in Indian companies. Lean manufacturing was not commonly used in Indian organizations to enhance operational or quality performance, according to research by (Chugani *et al.*, 2017). Lean practices are not widely used in all industries in Bangladesh. However, research by Habib *et al.* (2023) in a packaging firm in Bangladesh showed that applying lean manufacturing principles helped solve problems with regard to reducing lead times. They suggested using lean practices in Bangladesh's packaging industry. For the ready-made garments (RMG) industry in Bangladesh to successfully implement lean, Kumar *et al.* (2022) emphasized the necessity for a comprehensive plan that includes a distinct vision, goals and objectives.

Researchers in several areas have looked into the potential advantages of lean practices in the particular sectors. Eskandari *et al.* (2022) looked into the possibility of giving Jordanian pharmaceutical manufacturing firms a competitive edge on the international market. The difficulties the Irish pharmaceutical industry had in implementing continuous improvement techniques like Lean Six Sigma (LSS) were investigated by McDermott *et al.* (2022). To ensure improved regulatory compliance, Jalundhwala and Londhe (2023) identified a number of enablers for operational excellence in the pharmaceutical sector. Some evidence of lean practices in different regions can be found in many publications such as (Garza-Reyes *et al.*, 2012; Ghosh, 2013; Krishnan *et al.*, 2022; Verma *et al.*, 2022; Citybabu and Yamini, 2022; Hasan *et al.*, 2022).

A systematic review by Lim *et al.* (2022) stated lean manufacturing and circular economy combination can help to the transformation of companies in a positive way. Numerous factors for achieving circular economy in the pharmaceutical industry while implementing lean manufacturing for sustainability is absolutely rudimentary. A significant determinant in the restricted implementation of lean techniques is the manufacturers' inadequate awareness (Singh *et al.*, 2021). Manufacturers are less likely to allocate resources towards the technologies when they possess insufficient knowledge and comprehension of them. The resulting decline in investment and interest may impede the progress of the multiple booming sectors, such as the manufacturing and pharmaceutical industry (Naseemullah, 2022). Nonetheless, considerable research has been conducted on the critical factors of lean implementation (Osman *et al.*, 2020; Ciliberto *et al.*, 2021; Debnath *et al.*, 2023a, b). Since a dearth of material that deals, especially, with Bangladesh's deployment of lean manufacturing in the pharmaceutical sector is existent, exploration in this field would help Bangladeshi policymakers and business leaders to better understand the potential advantages and difficulties of implementing lean practices in the pharmaceutical industry.

2.2 Drivers of implementing lean manufacturing in the pharmaceuticals industry to achieve circular economy

The two popular terms that have received the most attention in the manufacturing sector in recent years are Lean Manufacturing and Circular Economy (Shashi *et al.*, 2021; Sawe *et al.*, 2021; Ciliberto *et al.*, 2021; Touriki *et al.*, 2021; Khan and Haleem, 2021). Despite certain similarities, they use different underlying concepts and approaches. Waste reduction and operational performance have improved as a result of lean implementation (Habib *et al.*, 2023; Anwar *et al.*, 2023; Afum *et al.*, 2022). Through resource reuse and recycling, the circular economy seeks to reduce waste and improve sustainability (Palange and Dhatrak, 2021). According to Dey *et al.*, 2020), integrating lean and circular economy practices can enhance operational effectiveness and resource efficiency.

The pharmaceutical industry's goals for the circular economy can be achieved with the use of lean manufacturing techniques (Kazakova and Lee, 2022). The pharmaceutical sector can employ the many criteria listed in this section to accomplish its circular economy aims. The pharmaceutical industry can gain a thorough understanding of the components necessary for advancement in this discipline through lean integration (Januszek *et al.*, 2023). The drivers were found using the extensive literature review conducted for the study. To identify the context and drivers that can implement lean manufacturing in the pharmaceuticals industry to achieve circular economy, this study has reviewed prior studies. The key terms that have been utilized while conducting the literature search are "Lean manufacturing in pharmaceuticals industry" OR "Lean implementation to enhance circular economy performance" OR "Circular economy in pharmaceutical industry" OR "Lean manufacturing effects on circular economy performance" AND "Lean manufacturing drivers' assessment for achieving circular economy" OR "Possible driver to implement lean in pharmaceuticals industry". Google Scholar and the Scopus database were utilized for this literature search between the years 2016 and 2023. The drivers are presented in Table 1.

2.2.1 Economical and organizational context. The drivers of the economic and organizational setting, such as cost reduction (Nour and Laux, 2021; Nagaich, 2022) and quality augmentation (Yadav *et al.*, 2020), play a significant role in the implementation of lean. Cost reduction and quality enhancement are the main goals of lean adoption in the pharmaceutical sector (Nour and Laux, 2021; Nagaich, 2022). By reducing their negative effects on the environment and making the best use of their resources, businesses can improve their sustainability (Parmar and Desai, 2020). Implementing a strategic plan, being committed to it, allocating resources and standardizing play big roles (Yadav *et al.*, 2020).

2.2.2 Knowledge and learning context. Sharing of knowledge is essential for the adoption of lean successfully (Rana and Kaushik, 2018). Effective strategies include encouraging the exchange of best practices, offering chances for training and development and encouraging

Context	Sl.	Drivers	How does it affect pharmaceutical industry	Sources
Economical and organizational	1	Cost cutting	Pharmaceutical firms seek to optimize resource utilization, remove waste and streamline processes by implementing lean concepts. This lean methodology supports the larger goals of circular economy performance in addition to lowering costs	Nagaich (2022), Hariyani and Mishra (2022b), Nour and Laux (2021)
	2	Shorter time to market	Pharmaceutical firms can respond to market demands more quickly by streamlining their supply chain, manufacturing and research and development operations through the adoption of lean concepts. By encouraging resource efficiency, this quicker time to market not only boosts competitiveness but also adheres to the circular economy's tenets	Nenni *et al.* (2014)
	3	Adherence to regulations	Lean methodologies, which prioritize waste reduction strategies, energy-efficient practices and raw material optimization, align with the objectives of the circular economy. This results in a comprehensive and compliant approach to pharmaceutical manufacturing that strikes a balance between regulatory requirements and sustainable and circular practices	Solís-Quinteros *et al.*, (2021), McKie *et al.*, (2021)
	4	Top management commitment	Top executives' dedication shapes organizational culture and has an impact on decision-making procedures. Within the framework of lean methodologies, it entails cultivating an attitude that places emphasis on productivity and incorporate principles of the circular economy into the manufacturing cycle of pharmaceuticals	Hariyani and Mishra (2022a, b), Parmar and Desai (2020), Elkhairi *et al.* (2019)
	5	Quality augmentation	Pharmaceutical firms may secure the manufacturing of high-quality medicines, streamline processes and eliminate defects by implementing lean principles. In addition to meeting legal requirements, this dedication to quality advances resource efficiency, a cornerstone of the circular economy's tenets	Yadav *et al.* (2020)
	6	Standardization	Pharmaceutical businesses may more efficiently pinpoint areas for improvement because of standardized processes, which reduces environmental impact and promotes continual process optimization. The pharmaceutical sector may actively support a more circular and sustainable approach by incorporating lean-driven standardization	Yadav *et al.* (2020)

(*continued*)

Table 1.
Drivers for implementing lean manufacturing in the pharmaceutical industry to enhance circular economy performance outcomes

Context	Sl.	Drivers	How does it affect pharmaceutical industry	Sources
	7	Innovative business models	Pharmaceutical firms should reconsider established procedures and integrate lean concepts, which prioritize efficiency and waste reduction, by adopting innovative and creative methods to business. A creative business plan can inspire the creation of fresh approaches that support the objectives of the circular economy, such maximizing resource utilization and reducing environmental effect	Aloini *et al.* (2020), Pieroni *et al.* (2019)
	8	Systems with closed loops	Lean principles encourage the development of goods and procedures that permit material reuse, recycling and remanufacturing. This strategy makes it easier to develop closed-loop systems where resources are continually reused, lowering the need for virgin materials and fostering a more circular and sustainable economy	Achillas and Bochtis (2020), Sosnowski and Cyplik (2022)
Knowledge and learning	1	Ongoing development	Lean approaches offer an organized framework for continuous improvement, encouraging a flexible and creative culture. Pharmaceutical firms can find opportunities to reduce waste, maximize resource utilization and improve overall efficiency by routinely evaluating and improving their operations. The objectives of the circular economy are easily aligned with this iterative method	Parmar and Desai (2020), Yadav *et al.* (2020)
	2	Employee involvement	Employee involvement promotes a continuous improvement culture and gives staff members the ability to offer creative solutions for reducing resource inefficiencies and optimizing procedures. By encouraging responsible resource usage and waste reduction, this cooperative method not only improves the efficiency of operations but also adheres to the circular economy's tenets	Parmar and Desai (2020), Osman *et al.* (2020), Yadav *et al.* (2020)
	3	Training and education	Through the provision of specialized expertise and abilities to their workforce, pharmaceutical businesses may cultivate a lean culture and improve their performance in the circular economy. Employees can be empowered by training programs to recognize and reduce inefficiencies in production processes	Parmar and Desai (2020), Elkhairi *et al.* (2019)

(*continued*)

Table 1.

Context	Sl.	Drivers	How does it affect pharmaceutical industry	Sources
	4	Customer contentment	Pharmaceutical firms can meet consumer requests with promptness and consistency by implementing lean techniques that enhance efficiency and reliability. Furthermore, there is a growing correlation between environmental responsibility and customer pleasure as society places a higher priority on sustainability. Putting circular economy principles into practice	Hariyani and Mishra (2022a), Goshime *et al.* (2019)
	5	Collaboration and communication	Good channels of communication make it easier to share knowledge and best practices, which makes it possible to incorporate the concepts of the circular economy with ease. A harmonious environment for adopting lean approaches is created when varied stakeholders have effective communication and share a common understanding	Osman *et al.* (2020), Elkhairi *et al.* (2019)
	6	Demand from consumers and awareness	Lean can be used to increase consumer demand and knowledge of the circular economy by highlighting the worth and advantages of sustainable practices and products. Lean also makes it possible for visible supply chains and unambiguous labeling, giving customers the freedom to make educated decisions and advancing the circular economy by their buying actions	Hunka *et al.* (2021), Aloini *et al.* (2020)
Technological and resource management	1	Operational efficiency	Pharmacies may save money, increase productivity and guarantee a more sustainable use of supplies by reducing waste and enhancing overall operational efficacy. Lean approaches emphasize material reduction, reuse and recycling, which supports the circular economy and increases resource efficiency	Panigrahi *et al.* (2023), Salonitis and Tsinopoulos (2016)
	2	Resource optimization	Just-in-time manufacturing and ongoing improvement are two lean concepts that help to optimize production processes, cut down on extra inventory and use less energy. By encouraging sustainable resource management, this not only improves operational efficiency but also adheres to the fundamental principles of the circular economy	Salonitis and Tsinopoulos (2016)

Table 1. (*continued*)

Context	Sl.	Drivers	How does it affect pharmaceutical industry	Sources
	3	Capacity utilization	By reducing material and energy waste, efficient capacity utilization fosters sustainability in the sector. Furthermore, the pharmaceutical industry is prioritizing environmental responsibility more and more; therefore, integrating lean principles is essential to meeting both ecological and circular economy objectives	Laskowski (2017), Nenni *et al.* (2014)
	4	Process mapping	One of the most important parts of lean techniques is process mapping, which helps companies optimize their workflows, cut waste and boost productivity. Creating a map of the manufacturing process makes it possible to identify areas where sustainable practices, including recycling and material reuse, can be implemented to support the circular economy	Abusaq *et al.* (2023), Proença *et al.* (2022), Pereira *et al.* (2019)
	5	Continuous monitoring process	Continuous monitoring process distinguished by its capacity to track and evaluate in real time, which makes it easier to take a complete and adaptive approach to managing resources and sustainability. It makes sure that resource optimization measures in the pharmaceutical industry, where accuracy and compliance are crucial, are in line with the circular economy principles	Swarnakar *et al.* (2020)
	6	Sustainable supplier selection	Materials from sustainable providers frequently have a smaller environmental impact. An essential component of the circular economy is resource efficiency, which is enhanced by using these materials into lean manufacturing techniques	Debnath *et al.* (2023a)
	7	Digitalization	Lean can help digitalize the circular economy by including IoT devices, data analytics and automation which utilize data and technology to streamline processes, boost productivity and facilitate better resource management. Lean principles promote the use of digital tools in order to track material flows, streamline operations and find areas for improvement	Zu Castell-Rüdenhausen *et al.* (2021), Hedberg and Šipka (2021)
	8	Extension of product life	Lean can be used to extend product life in the circular economy by putting in place tactics that maximize product use, maintenance and repair. Producers can increase the lifespan of their products through remodeling, remanufacturing and repair by implementing lean practices	Fontana *et al.* (2021), Milios (2021)

Source(s): Authors' own contribution

Table 1.

cross-functional cooperation (Rana and Kaushik, 2018). According to Elkhairi *et al.* (2019), training and education are essential success elements. Employee engagement and communication are crucial (Osman *et al.*, 2020). The goal is to foster learning environments and invest in training programs.

2.2.3 Technological and resource management context. For the pharmaceutical business to implement lean and the circular economy, effective management of technological resources is essential (Laskowski, 2017). Considerations like capacity utilization and operational strategy are crucial (Laskowski, 2017). Process mapping enables remedial measures by identifying waste, inefficiency and quality issues (Habib *et al.* , 2023b). Continuous monitoring makes it easier to discover waste in real time and improves the performance of the supply chain (Swarnakar *et al.*, 2020).

Organizations should concentrate on organizational and economic issues, encourage knowledge exchange and learning and effectively use technical resources if they want to successfully adopt lean manufacturing and develop a circular economy in the pharmaceutical sector.

2.3 Existing methods and rationale behind this study

Numerous lean development strategies have been discovered in previous studies. Several academic papers have included an implementation framework diagram. Using a framework, Sieckmann *et al.* (2018) highlighted the aspects that make lean successful as well as its obstacles and suggests a method for implementing lean production system that takes into consideration the special characteristics of small and medium-sized enterprises (SMEs) in the pharmaceutical sector. Other works have described the lean adoption framework specifically for SMEs and not only the frameworks but also the difficulties they encountered (Almanei *et al.*, 2017). Although there are many authors who researched lean for all category industry. Among them one is Karam *et al.* (2018) who adopted the lean manufacturing philosophy in a Romanian pharmaceutical business. Nagaich (2022) examined the pharmaceutical industry's use of lean methodologies, removal of waste and elimination of nonvalue-added activities. Roadmaps have been utilized in other studies for the lean transformation. Seleem *et al.* (2020) developed a path for lean manufacturing for industrial businesses based on the limits of the company and the predetermined strategic goals. A positive feedback is presented by Cekerevac *et al.* (2022) where it is shown that lean production affirmatively added value to the companies in the post-COVID-19 period with some examples as evidence. Obstacles and enablers of circular supply chain management were highlighted by Khan and Ali (2022), while Patwa *et al.* (2021) investigated the implementation of circular economy in emerging economies. Research on the dynamic evolution of the industrial circular economy has been conducted (Ding *et al.*, 2020). However, there is a gap in examining the adoption of lean manufacturing to enhance circular economy performance outcomes in the pharmaceutical industry, which our study addresses using the Bayesian BWM.

The current methods for studying lean implementation drivers in THE pharmaceutical industry includes a fuzzy decision-making and evaluation laboratory (DEMATEL) approach is used by Parmar and Desai (2020), to identify the enablers of sustainable lean six sigma in the manufacturing organization by evaluating the cause and effect enablers. A multi-level approach was taken by Schmitt *et al.* (2021) to recognize the potentials of lean from circular perspective. Similar study was found where the author Jaiswal *et al.* (2021) used a gray DEMATEL technique to recognize barriers of lean. An ontological approach was adopted by Morseletto (2023) to outline the factors that influence whether an economy is linear or circular. Some authors Nagaich (2022) used statistical analysis by SPSS and the drivers and barriers of lean manufacturing. As there is no thorough investigation on the drivers of lean manufacturing in the pharmaceuticals industry to enhance circular economy performance outcome using the Bayesian BWM method, this study will contribute in this area and will provide a guiding about the implications of this study for successfully adopting and implementing lean manufacturing in the setting analyzed and assisting decision-makers and industry leaders in making strategic and tactical choices on the managerial level. A study by Santos *et al.* (2023) used the graph theory to find the leanness of automotive industry supply chain management. However, significant absence of Bayesian BWM for analyzing sustainability in the circular economy context clearly depicts the unexplored opportunities of study in this field. Comparing sustainability in a circular economy to the contemporary methods such as the graph theory or probabilistic graph theory, Bayesian BWM exhibits superior performance due to its incorporation of the decision-maker's preferences and subjective evaluations of alternative performance and criterion weights (Ferdoush *et al.*, 2024). By doing so, the Bayesian BWM offers a more comprehensive analysis that duly acknowledges the intrinsic uncertainty associated with the circular economy framework (Ferdoush *et al.*, 2024). Since they might not overtly consider subjective assessments or uncertainty, by enabling decision-makers to integrate prior information into the analysis and update their opinions in light of observed data, the Bayesian framework facilitates the formulation of more precise and robust decisions (Ruberg *et al.*, 2023).

3. Methodological framework

This study evaluated the key drivers for implementing lean manufacturing using the Bayesian BWM framework. The data collection process included three distinct stages of gathering feedback from experts. During the first stage, a survey questionnaire was emailed to 26 experts using Google Forms with the goal of validating, refining and grouping the identified key drivers for subsequent analysis. A total of 19 experts replied, yielding a response rate of 73.07%. The purposive sampling method, also known as judgmental or selective sampling, was used in this study. It is a nonprobability sampling technique and unlike the random sampling methods, purposive sampling involves the deliberate selection of participants based on the specific criteria or characteristics relevant to the research objectives (Palit *et al.*, 2022; Ali *et al.*, 2022). The chosen participants had direct involvement and active engagement within the pharmaceutical industry. The experts were selected based on the criteria of possessing in-depth knowledge of lean manufacturing, circular economy practices, the pharmaceutical industry, supply chain management, sustainability and a minimum experience of seven years in the relevant sector. For this study, professionals from well-known companies and organizations were chosen using purposeful sampling. By ensuring a wide pool of responders, this technique reduces the possibility of biases and offers a well-rounded portrayal of opinions. The selection of experts was based on a range of factors, such as professional experience, academic background, expertise in lean and industry management and participation in sustainable projects as well as a diversity of opinions and pharmaceutical production experiences. A summary of the experts' profiles who participated in the study has been provided in (Table S1, see supplementary material).

Following that, the experts were then asked to complete a BWM survey form to develop the "Best to Others" and "Others to Worst" matrices. In the following stage, a BWM survey form was created and given to the experts to produce the "Best to Others" and "Others to Worst" matrices. About 19 experts who were in the initial group were asked to participate in the Bayesian BWM study again. Out of the invited experts, 15 responded, resulting in a response rate of 78%. Subsequently, the data obtained through the survey were utilized to apply the Bayesian BWM method, enabling the estimation of the final weights of the identified drivers along with the credal ranking. The results were then shared with the 15 experts who took part in the second stage. A 100% response rate was achieved since all of the requested experts responded. Our study is designed to recognize personal decision-making trends. For this reason, the number of respondents included in this study is adequate to capture a variety of viewpoints. The framework of this research methodology is illustrated in Figure 1. Following the identification of the drivers, the experts guided the grouping of these drivers into three primary clusters: economical and organizational, knowledge and learning and technological and resource management. Table 1 summarizes the three key clusters and their respective drivers.

3.1 Bayesian best–worst method (BWM)

Rezaei (2015) introduced the BWM as a reliable multicriteria decision-making (MCDM) technique for pairwise comparisons. The Bayesian BWM is an improved version designed for group decision-making, providing accurate rankings with fewer data requirements (Debnath. *et al*., 2023a, b). Compared to other approaches like the analytic hierarchy process (AHP), the BWM is simpler and more consistent (Liang *et al*., 2020). In group decision-making, the Bayesian BWM integrates preferences effectively by determining aggregate final weights for multiple decision-makers (Mohammadi and Rezaei, 2020). It considers the group decision from a probabilistic perspective, ensuring comprehensive and unbiased analysis (Yanilmaz *et al*., 2021).

The following present the major steps of the Bayesian BWM adopted from Debnath *et al.* (2023a, b):

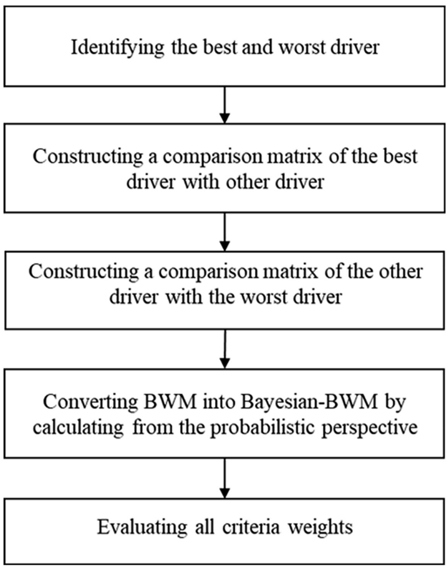
Step 1: Identifying the best and worst criterion

Step 2: Constructing the pairwise comparison of best to others

Step 3: Constructing a pairwise comparison of others to worst

Step 4: Calculation of aggregated weight

The details of the above-mentioned method are presented in the supplementary file (see section 3.1 in supplementary file).



Source(s): Authors' own contribution

Figure 1. Framework of research methodology

4. Analysis and results

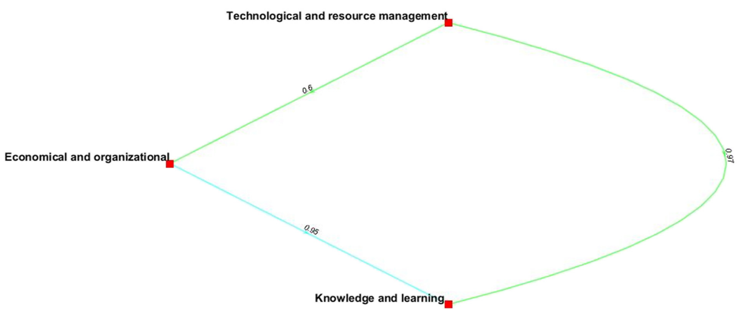
4.1 Result analysis of the study

This section displays the drivers' established rankings as determined by the Bayesian BWM. For each cluster, the authors have established a weighted directed graph.

Figure 2 shows the credal ranking of the three clusters. The most significant of the three clusters was technological and resource management (0.376), which was followed by economic and organizational (0.359) and knowledge and learning (0.263). The technological and resource management cluster's drivers require special attention from managers since they are more important than those of the other clusters. However, the economic and organizational clusters are close to the technological and resource management cluster in terms of weight, which suggests that in order to successfully apply lean practices in pharmaceutical supply chain, managers and policymakers must pay attention to both clusters. Furthermore, it was discovered that the technological and resource management cluster had more implementation than the economical and organizational cluster (0.97 confidence-level) and the knowledge and learning cluster (0.6 confidence-level). Once more, with 0.95 confidence-level, the economical and organizational clusters were more widely used than knowledge and learning. Although it relies on the expert's perspective, a 0.55 threshold has been used in this study to denote substantial confidence in the assessment of the confidence values. On the routes of Figure 2 are the determined statistical probability confidence scores. Figure 3 displays the local ranking of the drivers in the technological and resource management cluster.

The most important driver is continuous monitoring process for sustainable lean implementation (0.263), which is followed by capacity utilization (0.194), resource optimization (0.159), operational efficiency (0.148), sustainable supplier selection (0.124) and digitalization (0.115), respectively. The continuous monitoring process for sustainable lean implementation counted significantly higher than other drivers among those in the technological and resource management cluster. Figure 3 uses colored links to illustrate the network between the cluster's drivers in the areas of technology and resource management. Figure 4 shows the relative importance of several economic and organizational factors in a given area.

The most significant drivers are management involvement for sustainable implementation (0.209), followed by cost cutting (0.207), standardization (0.167), adherence to regulations (0.142), shorter time to market (0.141) and quality augmentation (0.136) in that order. Management involvement for sustainable implementation measured greater importance than other drivers within the economic and organizational cluster's drivers. In Figure 4, we see how the factors that make up the economical and organizational cluster are related to one another through a color-coded network. The knowledge and learning cluster's local ranking of influential factors is shown in Figure 5.



Source(s): Authors' own contribution

Figure 2.
Illustration of ranking of major clusters

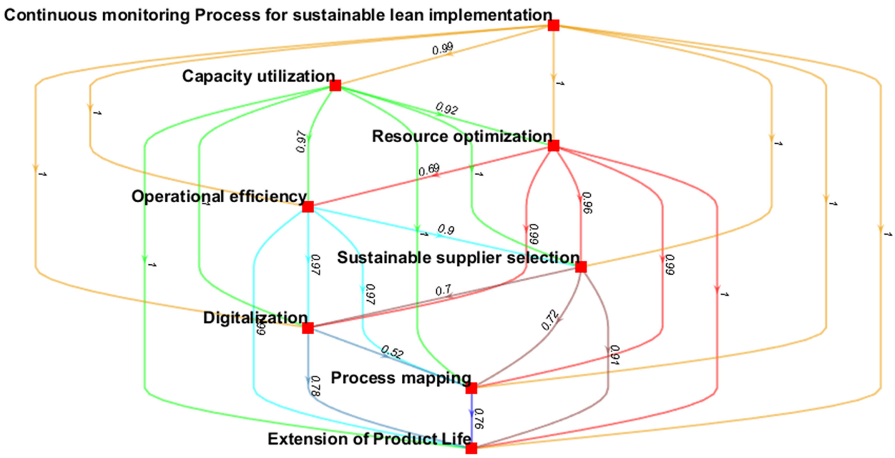


Figure 3. Ranking of the technological and resource management–related drivers

Source(s): Authors' own contribution

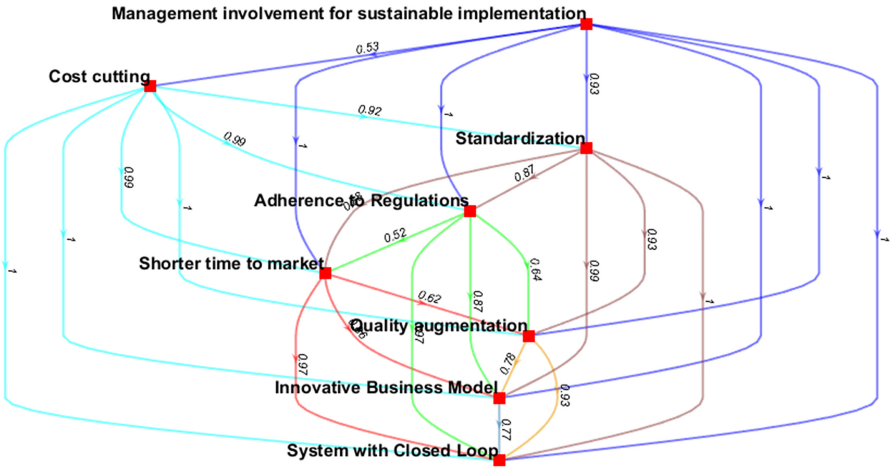
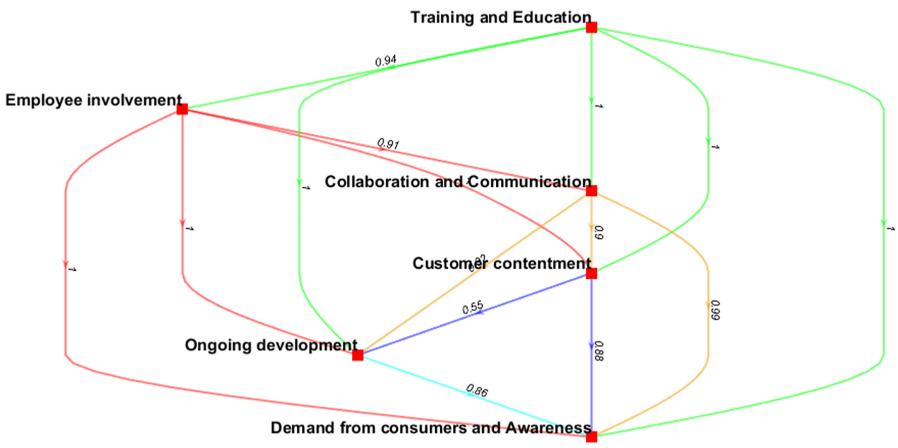


Figure 4. Ranking of the economical and organizational–related drivers

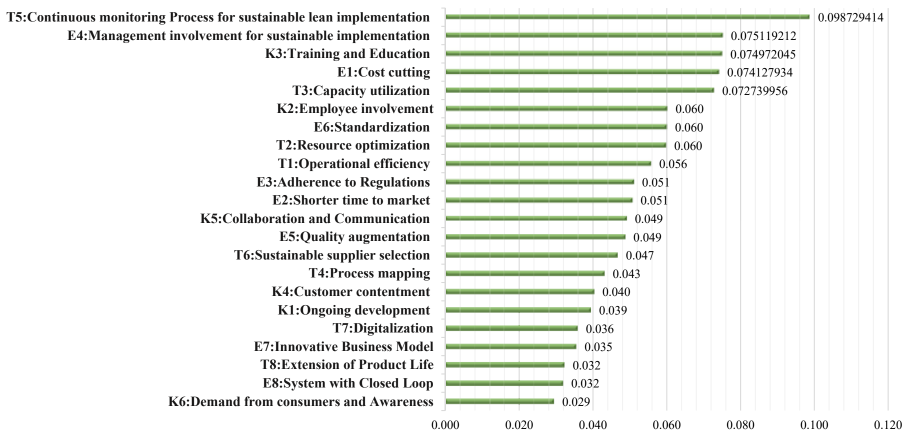
Source(s): Authors' own contribution

The three most significant drivers among the cluster's six drivers are the continuous monitoring process for sustainable lean implementation (0.262), capacity utilization (0.193) and resource optimization (0.158). In comparison to all other drivers in this cluster, the continuous monitoring process for sustained lean implementation is determined to be much more influential (with a threshold of 0.55). To determine the relative importance of each of the 22 drivers, we multiplied their weights at the cluster level by their weights at the local-level. Figure 6 shows the drivers' overall standings across the globe. Continuous monitoring process for sustainable lean implementation (0.99) is the most significant driver, according to the study, whereas demand from consumers and awareness is the least significant driver (0.031). In addition, the confidence score matrices for all clusters have been presented in Table S2-S5 (see supplementary material).



Source(s): Authors' own contribution

Figure 5.
Ranking of the knowledge and learning–related drivers



Source(s): Authors' own contribution

Figure 6.
Global ranking of the drivers related to lean implementation in pharmaceutical industry

It can be concluded that, technology and resource management is the most significant driver among the other ones as one of the main components of the lean methods is careful resource management, which guarantees that raw resources are used wisely, and waste is reduced throughout the whole manufacturing process. This coherence with the goals of the circular economy is essential because it encourages the conservation, reuse and recycling of resources in a closed-loop system. Thus, the key to promoting sustainability in the pharmaceutical business and moving it in the direction of a more ecologically conscious and circular future is the mutually beneficial interaction between lean implementation, technology and resource management.

4.2 Validation of the result

In this crucial part of the study, the pharmaceutical sector's identified drivers for sustainable lean manufacturing were thoroughly tested through an organized interaction with the industry experts. The research, which employed a three-phase methodology, featured a targeted group of 15 seasoned professionals, all of whom had an extensive understanding of lean procedures and at least seven years of experience in the pharmaceutical manufacturing industry. The specialists were carefully chosen according to their broad experience, current positions in the pharmaceutical industry and knowledge of lean manufacturing concepts. This criterion guaranteed the relevance and insightfulness of the comments and insights received. Following the conversations, all the participants agreed on the significance and applicability of these factors, confirming the initial research findings. In the subsequent phase, the focus shifted to categorizing these drivers within the framework of a circular economy. In order to ensure a complete grasp of each driver's functions and interrelationships, the participants examined how each fit into the larger objective of sustainability and resource conservation. Lastly, the study showed the experts an organized model that prioritized the drivers according to their significance and influence by utilizing the Bayesian BWM. The participants gave this model a critical evaluation, confirming the ranking order and providing suggestions for improving the priority for the pharmaceutical industry's real-world application. During these stages, the interaction with professionals in the field not only confirmed the study's conclusions but also added useful insights. The suggested drivers for sustained lean adoption in the pharmaceutical business were shown to be both theoretically sound and practically feasible through a multifaceted validation procedure. This study's conclusion opens the door for the pharmaceutical sector decision-makers to successfully apply lean approaches within a framework of the circular economy, promoting a more resource-efficient, economical and sustainable production environment.

5. Discussion and implications of the study

5.1 Discussion of the findings

According to the findings of the Bayesian BWM framework developed in this study, several key drivers for implementing lean manufacturing in the pharmaceutical industry to enhance circular economy performance outcomes have been identified.

The "Continuous Monitoring Process for Sustainable Lean Implementation (T5)" is the first and most significant driver. This driver places a strong emphasis on the value of routinely evaluating how operations are progressing, creating clear goals and targets, monitoring results and measuring and analyzing the application of lean manufacturing and sustainability efforts. Organizations can remove waste, maximize resource usage and gradually increase operational efficiency thanks to continuous monitoring. Key performance indicators (KPIs) can help organizations prevent setbacks and work towards continual improvement (Henrique *et al.*, 2021). "Management involvement for sustainable implementation (E4)" is the second important factor. Leading the sustainable adoption of lean manufacturing practices is essential for success. Their participation is crucial for integrating sustainability and circular economy principles into the organization's strategic objectives. They support a culture of environmental stewardship and continual improvement, offer the resources required and show the organization's dedication to sustainable development. Gaining employee buy-in and guaranteeing the success of lean implementation initiatives depend heavily on top management's active involvement and support. Sieckmann *et al.* (2018) also showed from the existing literature that a lack of commitment from management poses a substantial barrier to the implementation of a lean production system, particularly in the small and medium-sized pharmaceutical industries.

The "Training and Education (K3)" driver is the third one. A skilled workforce must be created in order to adopt lean manufacturing successfully. Organizations equip workers with the knowledge and abilities they need to spot waste, streamline operations and adopt sustainable practices. Lean principles, circular economy ideas, waste minimization strategies and sustainable manufacturing methods can all be covered in training programs to help employees contribute to improving organizational performance.

"Cost cutting (E1)" is the fourth driving force. By reducing waste, boosting efficiency, and maximizing resource utilization, businesses can cut costs while improving their performance in the circular economy. Inefficient processes, excess inventory, and waste disposal costs can all be reduced by using lean concepts to help identify and eliminate non-value-added operations. Organizations can increase financial sustainability and support the circular economy by putting cost-cutting initiatives into place. Lean principles assist in identifying and eliminating non-value-added operations, which lowers expenses associated with excess inventory, waste disposal, and inefficient processes (Chahal and Narwal, 2017).

"Capacity utilization (T3)" is the fifth driver. Utilizing capacity effectively is essential for effectively satisfying market demand. Organizations can maximize capacity utilization with the aid of lean manufacturing techniques including just-in-time production, balanced production flow, and efficient inventory management. Organizations can improve operational efficiency and support the circular economy by making efficient use of resources and coordinating output with market demands (Mankazana and Mukwakungu, 2018).

The "Employee Involvement (K2)" driver is the sixth driver. Success depends on including workers in circular economy and lean manufacturing initiatives. Employees have important knowledge about waste production and operational inefficiencies. Organizations can tap into employees' knowledge and ideas by developing a culture of continuous improvement and involving them in problem-solving, decision-making, and improvement projects, greatly enhancing the effectiveness of lean implementation and the circular economy.

The "Standardization (E6)" driver is the seventh driver. Promoting efficiency and reducing errors within the organization requires the establishment of standardized procedures and standards. Process variation may result in longer wait times, bottlenecks and extra time for material handling (Debnath *et al.*, 2023a, b). Lean manufacturing strives to eliminate process variances and waste, and this is made possible through standardized work procedures, practices and instructions. Standardization boosts the performance of the circular economy, encourages sustainable practices and improves operational efficiency (Thanki *et al.*, 2016).

The "Resource Optimization (T2)" driver is the eighth driver. In the pharmaceutical sector, resource optimization is a key factor in improving the performance of the circular economy. The pharmaceutical industry is becoming more and more aware of the significance of effective resource management in an era where sustainability is a major priority in order to minimize environmental damage and maximize economic rewards (Dossou *et al.*, 2022). The sector needs to strategically move toward circular economy concepts because of its reliance on a variety of raw materials, energy-consuming processes and complex supply chains. Pharmaceutical firms may minimize waste generation and their environmental impact by optimizing their use of resources, including raw materials, water as well as energy (Aithal and Aithal, 2023).

The remaining factors are "Operational Efficiency (T1)," which aims to increase process efficiency, "Adherence to Regulations (E3)," which ensures compliance with legal requirements, "Shorter Time to Market (E2)," to remain competitive, "Collaboration and Communication (K5)," which fosters collaboration and knowledge sharing, "Quality Augmentation (E5)," which emphasizes product quality and "Sustainable Supplier Selection (T6)" selecting sustainable-minded vendors. It is crucial to remember that all drivers contribute to the implementation of lean manufacturing and raising the performance outcomes of the circular economy, even though certain drivers are more significant than others. The drivers' relative importance in the context of this study is shown by the ranking.

There have been a few studies on lean practice to improve circular economy performance outcomes in different industries and economic contexts, but this research is very different from those earlier studies in several key ways. For instance, Yadav *et al.* (2020) identified and quantified the interrelationships between the drivers for implementing lean manufacturing in the pump parts manufacturing organization in the context of the Indian economy perspective using the hybrid fuzzy analytical hierarchy process (FAHP)-decision-making trial and evaluation laboratory (DEMATEL) tools. Their outcome showed that "improved shop-floor management," "quality management," and "manufacturing strategy" were the most significant drivers for adopting lean manufacturing. Again, Dehdasht *et al.* (2020) used the TOPSIS method to identify and rank the most important factors influencing successful and long-term adoption of sustainable lean practices in the Malaysia's construction industry. The study found that the top drivers for implementing lean manufacturing in the pharmaceutical industry were "continuous monitoring process for sustainable lean implementation," "management involvement for sustainable implementation," "training and education," "cost cutting" and "capacity utilization." This study is the first of its kind because no other research has focused on identifying the drivers, especially in the pharmaceutical business utilizing the Bayesian BWM technique. This study differs from earlier ones in a number of ways. A number of industries and economic scenarios have been studied in the past to see how lean implementation affects performance outcomes. However, this study is the first to clearly define and rank the Bayesian BWM technique's drivers for lean deployment in the pharmaceutical sector. This study offers important insights into how lean manufacturing techniques might improve circular economy performance outcomes in the pharmaceutical industry by adopting the circular economy approach.

5.2 Theoretical implications

The results of this study enhance the comprehension of the elements that lead to the performance improvement of the circular economy, as perceived by practitioners. It is possible to prioritize the drivers and allocate attention to them in the proper sequence by employing our methodologies. The significance of conducting regular assessments of operational progress, establishing unambiguous objectives and targets, overseeing outcomes and quantifying and analyzing the implementation of lean manufacturing and sustainability initiatives – a process known as continuous monitoring – must be underscored. This must be completed before the organization commences the lean implementation process. Management involvement is an additional critical element that propels the implementation of lean principles. The active participation of these personnel is critical for the effective integration of sustainability and circular economy principles into the organization's strategic objectives. Furthermore, they exemplify the institution's dedication to sustainable development through the provision of essential resources, cultivation of an environment conscious of environmental stewardship and ongoing enhancement and reinforcement of said culture. Succeeding in the implementation of lean manufacturing requires the cultivation of a proficient workforce. The various firms equip their personnel with the requisite knowledge and competencies to identify waste, optimize operations and demonstrate a steadfast dedication to environmentally friendly practices. To enable personnel to contribute to the enhancement of organizational performance, training programs may encompass a range of subjects such as lean principles, circular economy concepts, waste minimization techniques and sustainable manufacturing procedures. Consequently, training and education for employees are paramount.

Although the analysis primarily focuses on case studies originating from pharmaceutical corporations, the created methodology demonstrates applicability to several other domains of endeavor. Due to this, the process of overcoming a variety of substantial obstacles can be intricately connected to the structural foundation that this research provides. By optimizing production processes while considering their impacts on natural resources, the environment, and the workplace, lean practices can contribute directly to the realization of sustainable development goals (SDGs).

The literature already available on the application of lean gains various theoretical insights from this study, including:

(1) Emphasizing the critical driving factors that will drive the implementation of LM in the burgeoning pharmaceutical sector.

(2) Constructing a unified MCDM framework while utilizing the Bayesian BWM method to evaluate and rank the primary drivers.

(3) To get a comprehensive understanding of the potential effects of LM deployment on the pharmaceutical industry productivity and mitigate any adverse environmental effects.

(4) Establishing a framework for more comprehensive investigations that would provide decision-makers with a depth of knowledge regarding the factors influencing the adoption of lean manufacturing practices across various manufacturing sectors.

5.3 Managerial and policy implications

For managers, consultants and industry experts striving to implement lean manufacturing and move the pharmaceutical business toward a circular economy, the study's findings have important ramifications. Managers may prioritize their efforts and create action plans in accordance with the study's primary drivers by understanding them. Lean implementation, for instance, can be made sustainable by beginning with a focus on the continuous monitoring process. For the implementation to be successful, management support and involvement are essential and training and education programs can enable staff to contribute successfully. Managers may establish responsible and effective plans for implementing lean manufacturing in their organizations by matching their strategies with the prioritized drivers. The study emphasizes the value of waste reduction and performance enhancement, which are important objectives for businesses pursuing profitability. The pharmaceutical industry managers should become aware of these drivers and work to embrace lean manufacturing practices in order to achieve their objectives.

The results also have ramifications for those who make policy. According to the study, laws should be put in place to encourage capacity utilization and cost-cutting advantages for companies that are sustainable. This may encourage additional pharmaceutical-makers to embrace lean manufacturing techniques. To improve the performance of the circular economy overall, policymakers should concentrate on encouraging the development of sustainable technologies in the sector. Policymakers can aid in the accomplishment of circular economy objectives by promoting the shift to a low-carbon economy and corporate sustainability. In conclusion, this study offers insightful information for managers, consultants and decision-makers that will help them comprehend the key elements influencing the adoption of lean manufacturing and its fusion with circular economy principles in the pharmaceutical business. Improved environmental sustainability, lower costs and better performance outcomes can result from putting the drivers in place and adjusting policies in accordance with them.

6. Conclusion, limitations and future directions

The integration of sustainable lean practices and the circular economy has gained significant popularity in recent years due to its potential to reduce adverse environmental impacts in the pharmaceutical industry. However, there is a research gap in understanding the implementation of lean practices in the pharmaceutical sector to enhance circular economy outcomes. This study aimed to address this gap by utilizing a Bayesian BWM framework to identify the critical drivers for lean implementation and their order of importance. The study began by identifying relevant drivers through a comprehensive literature search, which were then validated through expert feedback. A survey was conducted among the specialists to assess and categorize the selected drivers into three groups: economical and organizational, knowledge and learning and technological and resource management. The Bayesian BWM method was applied to rank the drivers and determine their order in the context of the circular economy. The findings of the study highlighted that the drivers "continuous monitoring process for sustainable lean implementation (T5)", "management involvement for sustainable implementation (E4)" and "training and education (K3)" were the top three drivers for the lean manufacturing in the pharmaceutical industry. These drivers play a crucial role in facilitating the successful adoption and implementation of lean practices. Policymakers and industry leaders should prioritize these drivers to simplify the integration process and promote sustainable lean implementation.

It is important to acknowledge the limitations of this study. While the study identified 17 drivers of sustainable lean implementation and categorized them into different groups, it does not claim to have captured all the drivers that contribute to lean philosophy in the pharmaceutical industry. Further research can explore additional drivers and group them into logical categories to compare the results with the current study. Additionally, the focus of this study was limited to the circular economy perspective in the context of the pharmaceutical industry in Bangladesh. Future studies can explore other economic contexts and examine the interrelation of these drivers using modeling approaches such as interpretive structural modeling (ISM) and fuzzy total interpretive structural modeling (fuzzy TISM). To enhance the robustness of the findings, alternative pairwise comparison approaches and other MCDM techniques such as fuzzy VIKOR and fuzzy TOPSIS can be applied to compare and validate the proposed conceptual framework. Furthermore, the outcomes of this study may vary for other service sectors, and researchers can conduct further analysis in different industries to assess the generalizability of the findings.

In summary, this study contributes to the understanding of lean implementation in the pharmaceutical industry by providing a framework and identifying the key drivers for sustainable lean implementation. The findings offer valuable insights for policymakers and industry leaders to improve decision-making and promote the successful adoption of lean manufacturing practices. However, further research is needed to explore additional drivers, compare different sectors and validate the proposed framework using other MCDM techniques.

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Supplementary material

The confidence score matrices for all clusters have been presented in Table S2-S5 (see supplementary material).

Total experts	Experience	Designation	Number of experts	Percentage
For determining and clustering the key driver for implementing lean manufacturing				
N = 19	More than 16 years	Executive Director	4	21.05
		General Manager	3	15.79
		Assistant General Manager	2	10.53
		Manager	2	10.53
	10–16 years	Executive Director	3	15.79
		General Manager	2	10.53
		Assistant General Manager	1	5.26
	7–10 years	Manager	2	10.53
For determining the ranking of key drivers using Bayesian BWM				
M = 15	More than 16 years	Executive Director	3	20.00
		General Manager	2	13.33
		Assistant General Manager	2	13.33
		Manager	1	6.67
	10–16 years	General Manager	3	20.00
		Assistant General Manager	2	13.33
		Academic (Professor)	1	6.67
	7–10 years	Manager	1	6.67

Source(s): Authors' own contribution

Table S1. Summary of the participating experts' profiles

Cluster	C1	C2	C3
C1. Economical and organizational (0.359)	0.0000	0.9493	0.3958
C2. Knowledge and learning (0.263)	0.0507	0.0000	0.0301
C3. Technological and resource management (0.376)	0.6042	0.9699	0.0000

Source(s): Authors' own contribution

Table S2. Confidence score of cluster level

Economical and organizational	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*
E1: Cost cutting	0.0000	0.9885	0.9874	0.4665	0.9937	0.9044
E2: Shorter time to market	0.0115	0.0000	0.4778	0.0089	0.5910	0.1573
E3: Adherence to regulations	0.0126	0.5222	0.0000	0.0102	0.6097	0.1663
E4: Management involvement for sustainable implementation	0.5335	0.9911	0.9898	0.0000	0.9957	0.9190
E5: Quality augmentation	0.0063	0.4090	0.3903	0.0043	0.0000	0.1106
E6: Standardization	0.0956	0.8427	0.8337	0.0810	0.8894	0.0000

Source(s): Authors' own contribution

Table S3. Economical and organizational–related confidence scores

Table S4. Knowledge and learning–related confidence scores

Knowledge and learning	*K1*	*K2*	*K3*	*K4*	*K5*
K1: Ongoing development	0.0000	0.0076	0.0001	0.4521	0.1038
K2: Employee involvement	0.9924	0.0000	0.0808	0.9902	0.8872
K3: Training and education	0.9999	0.9192	0.0000	0.9997	0.9947
K4: Customer contentment	0.5479	0.0098	0.0003	0.0000	0.1296
K5: Collaboration and communication	0.8961	0.1128	0.0053	0.8704	0.0000

Source(s): Authors' own contribution

Table S5. Technological and resource management–related confidence scores

Technological and resource management	*T1*	*T2*	*T3*	*T4*	*T5*	*T6*
T1: Operational efficiency	0.0000	0.3157	0.0349	0.9567	0.01	0.883
T2: Resource optimization	0.6843	0.0000	0.0904	0.9846	0.000413	0.951
T3: Capacity utilization	0.9651	0.9096	0.0000	0.9997	0.016534	0.998
T4: Process mapping	0.0433	0.0154	0.0003	0.0000	0.556	0.297
T5: Continuous monitoring process for sustainable lean implementation	0.9797	0.99950	0.983	0.557	0.0000	0.259
T6: Sustainable supplier selection	0.1172	0.0488	0.002	0.703	0.3358	0.0000

Source(s): Authors' own contribution

3.1 Bayesian Best–Worst Method (BWM)

The following present the major steps of the Bayesian BWM (Debnath *et al.*, 2023):

1. *Identifying the best and worst criterion:* Consider a group of criteria, denoted as $E = \{E_1, E_2, \ldots\ldots\ldots, E_n\}$, that are being evaluated by k experts. At first, each expert is tasked with selecting the best (E_C^k) and worst (E_U^k) criterion from the set of criteria E. During this phase, experts make these selections without engaging in pairwise comparisons. Expert k considers the best criterion to be the most significant, whereas the weakest criterion is considered the least significant. It is important to note that different experts may have different perspectives on what they perceive to be the best and worst choices depending on their own criteria.

2. *Constructing the pairwise comparison of best to others*: Expert k generates a pairwise comparison matrix to compare the best criterion (E_C^k) with the other criteria in set E. To indicate their choice for the best criterion above the others as chosen in the previous stage, each expert assigns a number between one and nine. One implies that the two criteria are equally important, but nine shows that E_C^k is much more important. The "Best to Others" vector represents the pairwise comparisons' result of expert n, represented by B_C^k as follows:

$$B_C^k = b_{C1}^k, b_{C2}^k, \ldots\ldots\ldots, b_{Cn}^k\,;\; k = 1, 2, 3, \ldots\ldots, K \tag{1}$$

where the preference of an expert k for the best criteria E_C^k over $e_i \in E$ is represented by b_{Ci}^k.

3. *Constructing a pairwise comparison of others to worst:* Like before, expert k creates a pairwise comparison matrix to compare the worst criterion (E_U^k) with other criteria in set E. The "Others to Worst" vector represents the pairwise comparisons' result of expert n, denoted as B_U^k.

$$B_U^k = \left(b_{1U}^k, b_{2U}^k, \ldots\ldots\ldots, b_{nU}^k\right)^T \tag{2}$$

where the preference of an expert k for the worst criteria E_U^k over $e_i \in E$ is represented by b_{Ui}^k.

4. Calculation of aggregated weight: The Bayesian BWM uses a probabilistic technique to determine the combined weights $(u^* = u_1^*, u_2^*, \ldots\ldots..u_n^*)$ from all K experts as well as the individual weights $(u^k), where\, k = 1, 2, \ldots..K$; for each expert. This method calculates aggregated weights using probabilistic principles and takes into consideration all expert input to determine the overall relevance of the criterion. It also computes the individual weight of each expert, showing their contribution to the final outcomes.

$$B_C^k | u^k \sim multinomial(1/u^k), \forall k = 1, 2, \ldots.., K, \tag{3}$$

$$B_C^k | u^k \sim multinomial(u^k), \forall k = 1, 2, \ldots.., K, \tag{4}$$

$$u^k | u^* \sim Dir(\gamma * u^*), \forall k = 1, 2, \ldots.., K, \tag{5}$$

$$\gamma \sim gamma(0.1, 0.1) \tag{6}$$

$$u^* \sim Dir(1) \tag{7}$$

The probabilistic model defined by equation (7) involves a multinomial distribution denoted as multinomial, a Dirichlet distribution denoted as Dir and a gamma distribution denoted as gamma (0.1, 0.1). Unfortunately, there is no direct mathematical solution available for this model. Markov-chain Monte Carlo (MCMC) sampling is used to obtain the result. MCMC sampling involves creating random samples from the probability distribution to approximate the solution. It is a computationally intensive process but necessary to compute the desired output in this case.

In the context of MCDM, the weight vector $u_i = (u_1, u_2, u_3, \ldots\ldots\ldots.u_n)$ is commonly used. This weight vector is subject to the condition $\sum_{i=1}^{n} u_i = 1$, indicating that the weights assigned to each criterion should add up to one. Additionally, each u_i the value must be greater than or equal to zero $(u_i \geq 0)$. The weighting of each criterion (e_i) can be considered a probabilistic or random event, where u_i represents the likelihood of that event occurring. This formulation aligns with the principles of the probability theory, where $\sum_{i=1}^{n} u_i = 1$ and $u_i \geq 0$ can be mathematically derived as equivalent statements. Thus, the constructing probabilistic models is crucial in the context of decision-making (Yang *et al.*, 2020).

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