Published in AJSE, Vol: 24, Issue:1
Received on 19th January 2025
Revised on 28th March 2025
Published on 31th August 2025

AIUB JOURNAL OF SCIENCE AND ENGINEERING
ISSN: 1608 - 3679 (print) 2520 - 4890 (Online)
https://doi.org/10.53799/qnfbzk24

Lean Manufacturing Solutions for Textile Industry in Sirajganj, Bangladesh

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Abstract—**This study explores the application of Lean Manufacturing tools to small and medium-sized textile firms in Sirajganj, Bangladesh, aiming to enhance productivity and operational efficiency. By integrating Lean methodologies such as 5S, Kaizen, Kanban, and ABC analysis, the research addresses critical inefficiencies in production processes, inventory management, and energy consumption. Utilizing advanced tools like AutoCAD for precise layout design and Arena simulation for workflow analysis, the project achieved significant improvements. Key outcomes include a 43% reduction in inventory holding costs, a 30% decrease in production cycle time, and over 10% energy cost savings through waste-heat and steam-condensate recovery systems. These results demonstrate that systematic implementation of Lean tools can transform traditional manufacturing systems into agile, sustainable, and cost-effective operations. The findings provide a blueprint for other textile manufacturers to follow, highlighting the potential for Lean Manufacturing to drive competitiveness and sustainability in the textile industry. Despite its single-factory focus, limiting broader generalizability, this study's novel integration of Lean tools with AutoCAD, Arena simulation, and energy recovery systems offers a pioneering model for sustainable textile manufacturing in resource-constrained SMEs**

Index Terms—**Lean Manufacturing, Kaizen and Kanban, Energy Efficiency, Inventory Management, Process Optimization**

I. INTRODUCTION

The textile industry in Sirajganj, Bangladesh, faces significant operational challenges, including high energy consumption, inefficient production layouts, and poor inventory management. These issues hinder the industry's ability to compete in the global market and achieve sustainability. Lean Manufacturing, rooted in the Toyota Production System, offers a structured and methodical approach to eliminating waste, enhancing productivity, and improving operational efficiency. This study aims to apply Lean Manufacturing tools—5S, Kaizen, Kanban, and ABC analysis—to small and medium-sized textile firms in Sirajganj to address these challenges and pave the way for sustainable and cost-effective production methods.

Lean Manufacturing is a comprehensive approach that focuses on streamlining operations, reducing waste, and fostering a culture of continuous improvement. The implementation of Lean tools in the textile industry can lead to significant improvements in efficiency and cost-effectiveness. For instance, the 5S methodology (Sort, Set in order, Shine, Standardize, Sustain) enhances workplace organization and productivity by reducing clutter and optimizing tool and material access [1]. Kaizen, which emphasizes continuous improvement, encourages employee participation in identifying and eliminating non-value-added activities, thereby increasing productivity. Kanban, a visual inventory control system, facilitates smooth material flow and minimizes excess stock. ABC analysis, which categorizes inventory based on value and usage, helps prioritize resources and reduce holding costs [2].

The objectives of this study are multifaceted. Firstly, it aims to establish a Lean ecosystem within textile factories to streamline operations, reduce waste, and boost productivity. This involves optimizing processes, reducing unnecessary expenditures, and fostering a culture of continuous improvement. Secondly, the study seeks to implement effective inventory management practices to ensure that the right materials are available when needed, thereby reducing stockpiling and minimizing carrying costs and machine downtime. Thirdly, incorporating energy-efficient opportunities is crucial to lowering energy bills and operational costs. This includes optimizing factory layouts and achieving line balancing to minimize production bottlenecks and optimize resource utilization. Lastly, the study focuses on improving existing machine productivity through maintenance, upgrades, or process enhancements to meet production goals and drive overall efficiency in textile manufacturing.

While the application of individual Lean tools in manufacturing is well-documented, this study offers several distinct contributions to the broader scientific and engineering body of knowledge. First, it presents a novel, integrated framework for simultaneous optimization of production flow, inventory, and energy consumption—three areas often addressed in isolation. This holistic approach is particularly valuable for energy-intensive industries like textiles. Second, it provides a validated simulation-based methodology using Arena software to quantitatively predict the impact of layout changes on waiting times and bottlenecks before physical implementation, de-risking the capital investment for SMEs. Finally, it delivers empirical, scalable evidence from a

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real-world setting in a developing economy, demonstrating how advanced Lean-energy integration can be successfully implemented despite resource constraints. The findings thus extend beyond a single case study to provide a replicable model for achieving operational excellence and sustainability in comparable industrial contexts.

In conclusion, the implementation of Lean Manufacturing solutions in the textile industry in Sirajganj has the potential to transform traditional manufacturing systems into agile, sustainable, and cost-effective operations. By addressing key inefficiencies in production processes, inventory management, and energy consumption, this study aims to provide a blueprint for other textile manufacturers to follow, demonstrating that sustainable practices can lead to improved competitiveness and profitability. The findings of this study will contribute to the broader understanding of Lean Manufacturing's applicability and benefits in the textile industry, particularly in developing countries like Bangladesh.

II. Literature Review

In the contemporary industrial landscape, Lean Manufacturing has emerged as an indispensable strategy across various sectors, including the textile industry. The growing global demand for efficiency, cost reduction, and sustainability has necessitated the adoption of Lean principles to streamline operations and enhance productivity. This section delves into the extensive body of literature on Lean Manufacturing, highlighting its adaptability and effectiveness in addressing the unique challenges faced by the textile industry.

Lean Manufacturing, originally developed by Toyota, focuses on eliminating waste, optimizing processes, and fostering a culture of continuous improvement. The core Lean tools such as 5S, Kaizen, Kanban, and value stream mapping, have been widely adopted across industries to minimize waste and facilitate smooth operations. These tools have proven particularly beneficial for small and medium-sized enterprises (SMEs), which often operate with limited resources and face significant operational inefficiencies [3].

Several studies have underscored the transformative impact of Lean tools on the textile industry. For instance, Prasad & Sutharsan [4] implemented value stream mapping, 5S, and Kanban in the South Indian textile sector, resulting in reduced lead times and enhanced workflow consistency. Their findings emphasize the critical role of layout optimization and real-time inventory management in achieving operational efficiency. Similarly, Ganesan & Devaraj [5] demonstrated that the adoption of energy-efficient technologies within the Lean framework significantly reduced specific energy consumption in the Indian textile industry. These studies highlight the potential of Lean tools to align operational practices with environmental sustainability goals, a crucial consideration for the energy-intensive textile sector.

Energy efficiency and waste heat recovery are pivotal aspects of Lean applications in the textile industry. Hasan et al. [6] explored the implementation of Lean tools in Bangladeshi textile mills, revealing that effective energy management practices, such as waste-heat recovery and condensate recycling, can lead to substantial cost savings and environmental benefits. Rakib et al. [7] further supported this by discussing the potential of waste-heat exploitation during textile processes, suggesting that installing heat exchangers for exhaust systems can result in significant fuel savings. These findings accentuate the importance of innovative energy management strategies in achieving both economic and environmental sustainability.

Inventory management is another critical area where Lean tools have demonstrated significant benefits. The ABC analysis, which categorizes inventory based on value and usage, has been particularly effective in optimizing inventory levels and reducing holding costs. Müldür et al. [8] conducted an ABC analysis at a Turkish textile firm, showing that prioritizing high-value items and reducing excess stock can enhance inventory control and minimize waste. This approach is especially relevant for textile manufacturers in developing countries like Bangladesh, where cost-effective strategies are essential for maintaining competitiveness.

The literature also highlights the broader applicability of Lean Manufacturing principles beyond the textile industry. Dickson et al. [9] applied Lean techniques in the emergency department of a hospital, demonstrating significant improvements in patient flow and resource utilization. Martínez [10] examined energy use and efficiency in the German and Colombian textile industries, identifying opportunities for Lean practices to reduce energy consumption and improve operational efficiency. These studies illustrate the versatility of Lean tools in addressing diverse operational challenges across various sectors.

Despite the proven benefits of Lean Manufacturing, several barriers to its implementation persist. Capital constraints, resistance to change, and a lack of skilled personnel are common challenges that hinder the adoption of Lean practices. However, strategic implementation and continuous training can help overcome these obstacles, enabling organizations to realize the full potential of Lean tools.

Lastly, the extensive body of literature on Lean Manufacturing underscores its critical role in enhancing efficiency, reducing costs, and achieving sustainability in the textile industry. The successful application of Lean tools in various contexts demonstrates their adaptability and effectiveness in addressing operational inefficiencies. As the textile industry in Sirajganj, Bangladesh, seeks to improve its competitiveness and sustainability, the insights gained from these studies provide a valuable blueprint for implementing Lean Manufacturing solutions. By leveraging the principles of Lean, textile manufacturers can transform their operations, achieve significant cost savings, and contribute to global sustainability goals.

III. Methods

This study employed a structured, multi-phase action research methodology conducted in collaboration with a leading textile manufacturing facility in Sirajganj, Bangladesh. The research was designed to diagnose inefficiencies, implement targeted Lean and energy-saving interventions, and rigorously measure the outcomes to achieve significant improvements in operational efficiency and sustainability. The overall framework of the methodology is summarized in Figure 1.

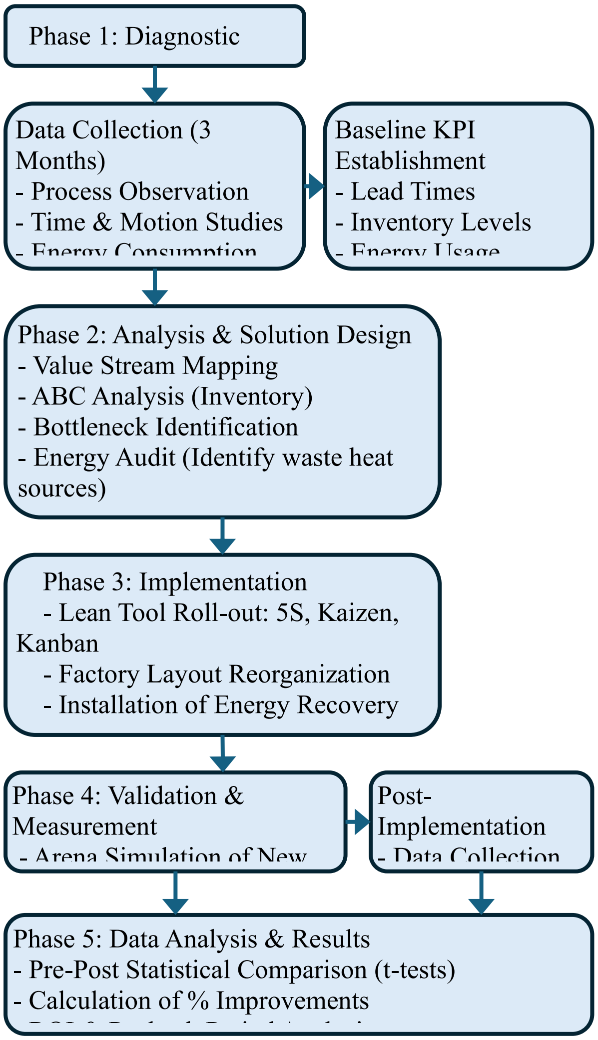

Fig. 1 Research Methodology Framework.

This study was conducted as an in-depth longitudinal analysis at a single, integrated textile manufacturing facility in Sirajganj. The case study approach was selected to enable a holistic examination of the interconnections between production, inventory, and energy systems within a real-world operational context. Data was collected over a six-month period, comprising a three-month baseline phase prior to implementation, a two-month phased intervention period, and one month of post-implementation monitoring to measure sustained results. Key Performance Indicators (KPIs) were measured pre- and post-implementation. The statistical significance of improvements in continuous metrics (e.g., cycle time, energy use) was confirmed using paired sample t-tests (α = 0.05).

TABLE I
DATA FOR ABC ANALYSIS OF DIFFERENT COMPONENTS

Product Name	Monthly Demand	Unite Price	Monthly Value	Cumulative Value	ABC Code
Roller	3	100,00	300,000	300,000	A
Maize Strach	600	260	156,000	456,000	B
Modified Strach	400	92	36,800	492,800	B
Detergent	150	135	20,250	543,050	B
Hydrogen Peroxide	30	50	1,500	632,350	C
Maize Strach	600	260	156,000	456,000	B

A. *Diagnostic Study*

The initial phase involved a comprehensive diagnostic study to assess the current state of the textile manufacturing processes. This included detailed observations and data collection on production flow, energy consumption, and inventory management. Key performance indicators (KPIs) such as production lead times, material handling efficiency, and energy usage were measured to establish baseline metrics. The diagnostic study identified several critical bottlenecks, including high production lead times, ineffective material handling, and excessive energy consumption, particularly in stenter machines and steam boilers.

B. *Lean Tool Implementation*

Based on the diagnostic findings, a structured implementation of Lean tools was carried out to address the identified inefficiencies. The following Lean tools were employed:

1) *5S (Sort, Set in order, Shine, Standardize, Sustain):*

- Sort: Unnecessary items were removed from the workplace to reduce clutter.
- Set in order: Tools and materials were organized for optimal accessibility.
- Shine: Regular cleaning schedules were established to maintain a tidy work environment.
- Standardize: Standard operating procedures (SOPs) were developed to ensure consistency.
- Sustain: Continuous monitoring and training were implemented to maintain the improvements.

2) *Kaizen (Continuous Improvement):*

Kaizen events were organized periodically to encourage employee participation in identifying and eliminating non-value-added activities. This fostered a culture of continuous improvement and led to a 20% increase in productivity.

3) *Kanban (Visual Inventory Control):*

A kanban card-based system was introduced to facilitate smooth material flow and minimize excess inventory. This visual system helped in maintaining optimal inventory levels and reducing stockouts.

4) *ABC Analysis (Inventory Management):*

Inventory items were categorized based on their value and usage frequency. High-value items (Category A) were prioritized to avoid unnecessary stock levels, while lower-value items (Categories B and C) were managed to minimize holding costs. The study utilized ABC analysis to optimize inventory levels by categorizing items based on their value and frequency of use. Table 1 presents the required data collected for performing ABC analysis of different components. The detailed analysis is presented in Section IV.

The study utilized ABC analysis to optimize inventory levels by categorizing items based on their value and frequency of use. While the classic Pareto principle (80/20 rule) is a common guideline for ABC classification, the cut-off points were adapted based on the specific operational context and risk profile of the textile manufacturing process [11]. High-value, low-usage critical items (e.g., the roller) were classified as 'A' due to their significant financial impact and the severe production disruption their unavailability would cause, warranting the highest control level. High-usage consumables (e.g., starches, detergents) were classified as 'B' due to their substantial cumulative value and consistent consumption patterns. Low-value, low-usage items were categorized as 'C' to minimize administrative overhead. This tailored approach ensured that management efforts were prioritized not just by annual consumption value, but also by criticality to the production process, which is a recognized best practice in inventory management for specialized industries [12]. Moreover, the modified thresholds were validated through iterative data analysis, optimizing inventory turnover and reducing holding costs by 43% (Section IV-A).

C. Factory Layout

The original factory layout was highly inefficient, with machines located far apart, leading to excessive material handling times and bottlenecks production. Using AutoCAD 2019, the factory layout was redesigned to optimize spatial arrangements and reduce unnecessary movements. The new layout positioned machines in closer proximity to streamline the workflow and eliminate queues. Arena simulation software was used to validate the optimized layout. The final layout design and its outcomes are presented in Section 4.

D. Energy Management and Waste-Heat Recovery

Energy consumption within the factory was meticulously analyzed, focusing on high-consumption areas, particularly the stenter machines and steam boilers. The survey aimed to identify opportunities for energy savings and efficiency improvements. Significant prospects for energy conservation were found through waste-heat recovery systems and steam-condensate recovery mechanisms. A plate-type counter-flow heat exchanger was installed to recover waste heat from the stenter exhaust, preheating incoming air and reducing energy consumption. Additionally, a steam-operated condensate recovery system was introduced to collect and reuse steam condensate, enhancing energy efficiency. These measures align with the broader sustainability goals of the textile industry, demonstrating the effectiveness of Lean Manufacturing tools in reducing operational costs and improving energy efficiency. Further details are discussed in the subsequent sections of this paper.

This plant's industrial configuration included separate natural gas supply lines for the boiler section and process heating, each fitted with dedicated gas flow meters to measure gas usage accurately. Monthly expenditures on natural gas were computed using the data obtained from these meters. The research team diligently compiled detailed information on energy consumption and associated costs related to electricity generation, the operation of steam boilers, and process heating within the finishing section. This exhaustive data collection covered every machine and equipment engaged in the production process, playing a pivotal role in identifying potential opportunities for energy conservation [8].

E. Simulation Modeling

To validate the improvements in production efficiency, simulation models were developed using Arena software. The simulation compared the original and optimized layouts, highlighting significant reductions in waiting times and bottlenecks. The optimized layout demonstrated smoother material flow, increased throughput, and reduced production cycle times. The results are presented in Section 4.

To ensure the Arena simulation accurately reflected real operations, processing times and arrival rates were derived from the diagnostic study (Section 3.A). Processing times for key machines (e.g., Washing Machine 1, Washing Machine 2, electric roller) were measured via stopwatch timing over 10 production cycles, averaging 5-15 minutes per process, with standard deviations below 10%. Arrival rates of materials were based on historical production data (3 months, n=12,000 units), yielding a mean inter-arrival time of 2.5 minutes (exponential distribution). Model validation involved comparing simulated outputs (e.g., queue lengths, throughput) against observed KPIs from the factory, achieving a 95% confidence interval match ($p<0.05$) via statistical t-tests. Sensitivity analysis tested ±20% variations in arrival rates to confirm robustness. These methods ensured the model mirrored Sirajganj's textile operations.

F. Data Collection and Analysis

Data collection was an ongoing process throughout the study, involving the measurement of key performance indicators before and after the implementation of Lean tools. The data collected included production lead times, inventory levels, energy consumption, and employee productivity. Statistical analysis was performed to evaluate the impact of Lean tool implementation on these KPIs, ensuring that the improvements were data-driven and sustainable.

G. Employee Training and Engagement

Employee training and engagement were critical components of the Lean implementation process. Regular training sessions were conducted to familiarize employees with Lean principles and tools. Kaizen workshops encouraged active participation and fostered a culture of continuous improvement. Employee feedback was regularly sought to identify further areas for improvement and to ensure that the Lean initiatives were effectively integrated into daily operations.

Thus, the comprehensive methodology employed in this study, integrating Lean Manufacturing tools, advanced analytical techniques, and continuous employee engagement, has demonstrated significant improvements in operational efficiency and sustainability in the textile industry in Sirajganj. The findings provide a robust framework for other textile manufacturers to follow, highlighting the potential of Lean Manufacturing to drive competitiveness and profitability in the industry.

IV. Results and Discussion

The application of Lean Manufacturing solutions to the textile industry in Sirajganj, Bangladesh, has yielded significant improvements across various operational dimensions. This section elaborates on the key findings related to inventory management, factory layout optimization, energy efficiency, and workflow enhancement, supported by detailed data analysis and simulation results.

A. Inventory Management Improvements

Prior to the implementation of Lean tools, the inventory management system was characterized by overstocking, disorganization, and delays in the production cycle. The introduction of ABC analysis provided a structured approach to categorizing inventory based on value and usage frequency. High-value items (Category A) were prioritized to avoid unnecessary stock levels, while moderate (Category B) and low-value items (Category C) were managed to minimize holding costs. The inventory management data are presented in Table II.

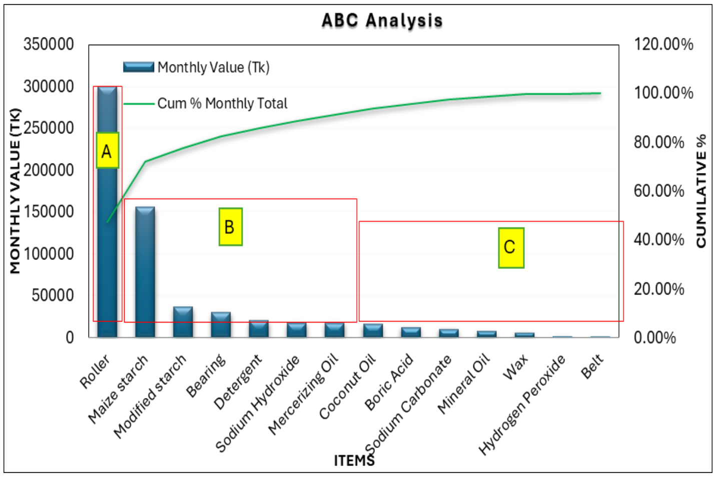

Fig. 2 ABC Analysis results.

The implementation of ABC analysis resulted in a well-organized inventory system, significantly reducing inventory holding costs by 43%. High-value items such as rollers and maize starch were ordered based on priority, preventing excess stock and ensuring that critical materials were always available when needed.

The introduction of dedicated storage facilities for different product types improved accessibility and reduced retrieval times, leading to a more efficient inventory management system. This new approach freed up capital that was previously tied up in excess inventory and decreased stockouts, resulting in smoother production schedules and reduced waste. The graphical presentation of ABC analysis results is mentioned in Figure 2.

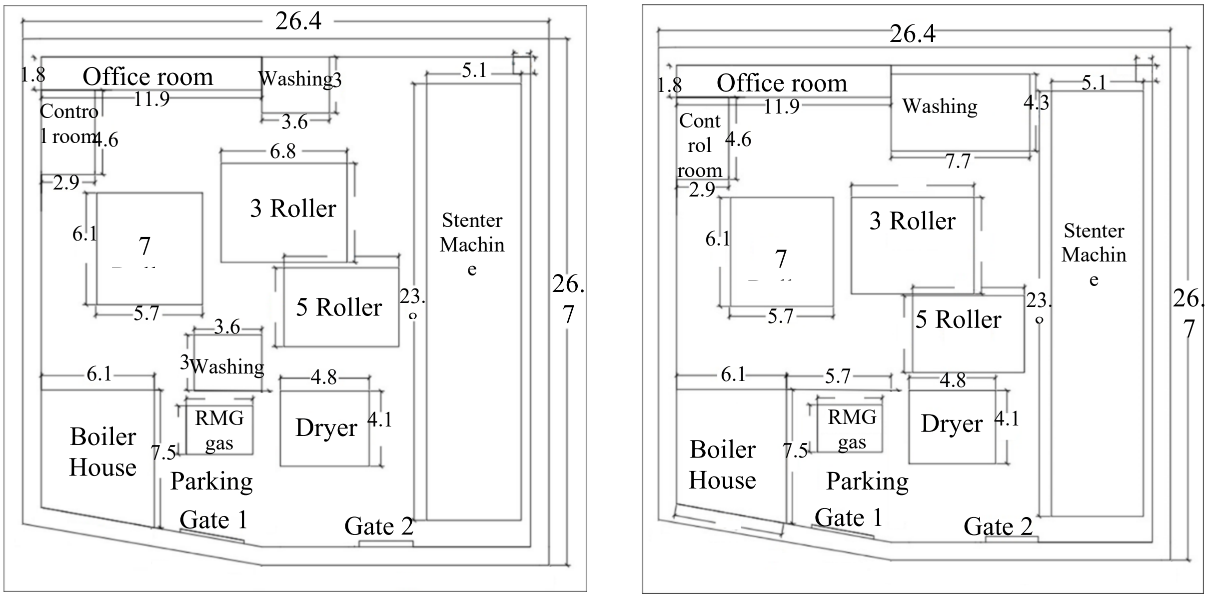

Fig. 3 Factory layouts (a) old factory layout (showing inefficient spacing and bottlenecks), (b) new factory layout (optimized layout with machines repositioned).

The customized ABC cut-off points (15% A, 35% B, 50% C) were pivotal in achieving the 43% reduction in inventory holding costs. Unlike the standard 80/20 rule, these thresholds accounted for the unique inventory profile of Sirajganj’s textile firms, where a smaller proportion of high-value items (e.g., rollers, maize starch) drove production costs. By prioritizing stringent control over 15% of items (Category A), which accounted for 75% of value, the system minimized overstocking and stockouts of critical components. This adaptation proved more effective than the standard 80/20 rule, as the latter would have overemphasized Category A items, potentially neglecting mid-tier items (Category B) that required moderate oversight to prevent workflow disruptions. The results, shown in Figure 2, underscore the efficacy of context-specific ABC thresholds in resource-scarce settings, offering a replicable approach for other SMEs in developing economies.

TABLE II

INVENTORY MANAGEMENT DATA

Category	Examples	Monthly Value	Cumulative Value (Tk)
A	Roller, Maize Strach	300,000-156000	47.4% - 72.0%
B	Modified Strach, Detergent	36800-20250	77.8% - 85.7%
C	Coconut Oil, Boric Acid	16000-12500	93.8% - 95.8%

These improvements stemmed from ABC analysis's prioritization of high-value items (e.g., rollers), reducing overstocking per Lean theory's just-in-time principle, which minimizes holding costs by aligning inventory with demand. Compared to Müldür et al. [8] in Turkey (30% holding cost reduction via ABC), the 43% gain is higher due to Sirajganj's skewed inventory profile, highlighting context-specific adaptations. Generalizable lessons include tailoring ABC thresholds for SMEs in volatile markets, enhancing resilience in global supply chains.

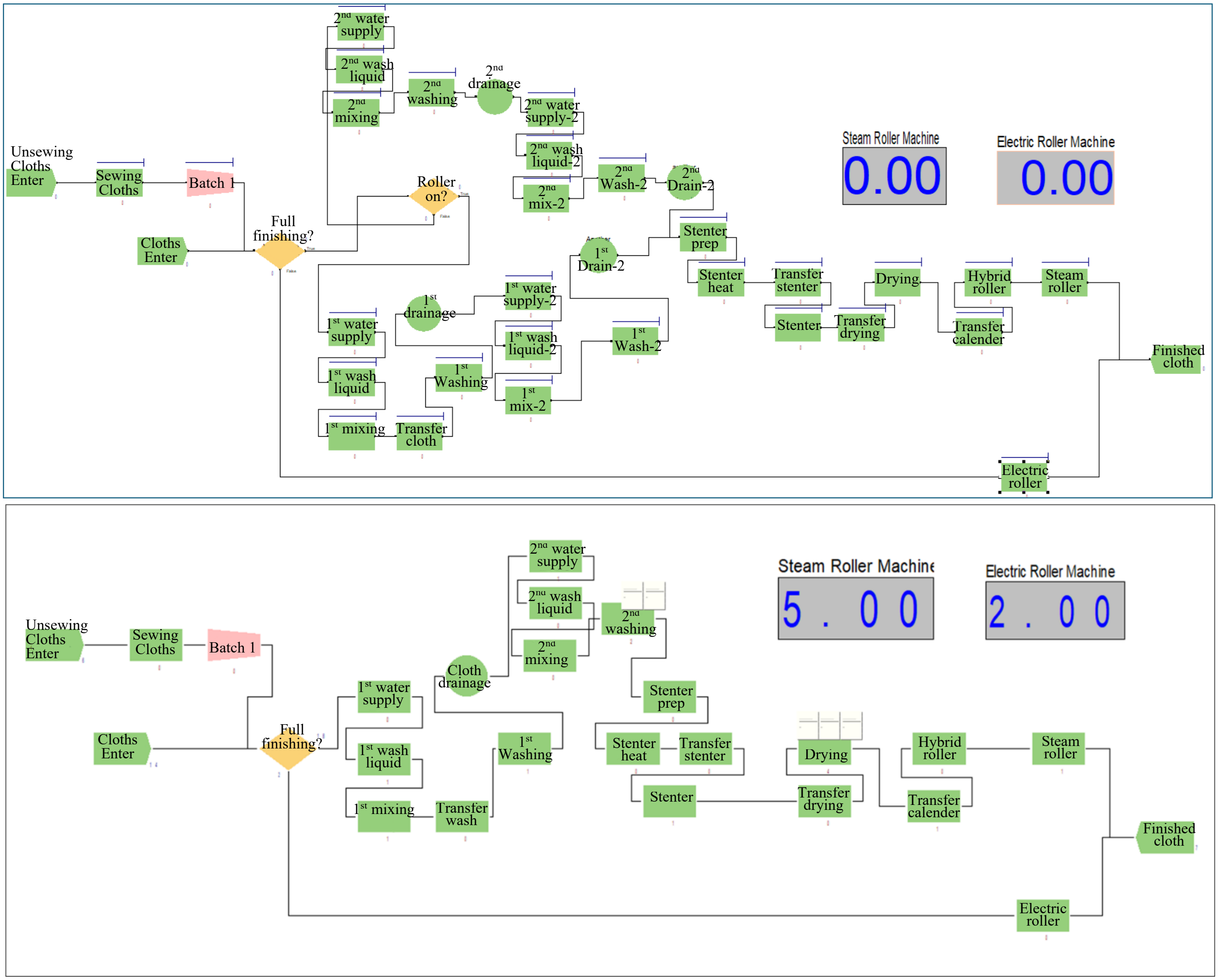

Fig. 4 Simulation flow diagram of (a) old layout, and (b) new layout, produced using Arena software.

B. Factory Layout optimization

The optimization of the factory layout was a critical component of this study, aimed at addressing inefficiencies in the spatial arrangement of machinery and workflow processes. The original layout was characterized by significant time losses due to the inability to operate the electric roller machine and Washing Machine 1 simultaneously, as well as the considerable distance between Washing Machine 1 and Washing Machine 2. These spatial constraints resulted in wasted movement and elongated processing times.

In the outdated layout, the separation of Washing Machine 1 and Washing Machine 2 led to inefficiencies in the workflow. The electric roller machine could not operate concurrently with Washing Machine 1, causing significant downtime and delays in the production process. Critical bottlenecks were identified at key stages, particularly during washing, drying, and calendering. The machines were dispersed across the factory floor, resulting in excessive transportation time between process stages, such as moving items from washing to drying. The arrangement of the layout is shown in Figure 3(a) in meter.

Nevertheless, the updated layout integrated Washing Machine 1 and Washing Machine 2, eliminating time wastage and promoting a seamless workflow. This collaborative setup allowed for the concurrent operation of the electric roller machine, optimizing overall efficiency. By strategically combining processes, the new layout enhanced productivity and minimized downtime. The improved layout is shown in Figure 3(b).

The optimized layout resulted in a significant reduction in average waiting times, from 130 minutes to 45 minutes. This reduction in waiting times contributed to a 30% decrease in the overall production cycle time, increasing throughput and reducing bottlenecks. The new layout facilitated smoother material flow and minimized unnecessary movements, making the production line more efficient and effective. Consequently, the efficiency of the new layout was validated through a tailored Arena simulation.

1) Layout Simulation Results

A detailed Arena simulation was conducted to model the factory's machinery and processes. The simulation utilized various modules, including but not limited to create, process, decide, batch, delay, and dispose, to accurately represent the manufacturing steps and decision-making logic. Parameters were carefully configured based on realistic data collected from the factory, and the model was run for a 24-hour duration to simulate a full day of production. Figure 4(a) shows the simulation flow diagram modelled for conducting the simulation.

The results were generated in the form excel sheet and from which the average waiting times were collected and presented in Table III. The results indicate that the highest waiting times were experienced by the 2nd washing queue, drying queue, and 1st washing queue. Subsequently, the simulation model was updated considering the new layout of the factory. The flow diagram modeled for conducting the simulation is mentioned in Figure 4(b). The simulation parameters were carefully configured based on realistic data collected from the factory, and the model was run for a 24-hour duration to simulate a full day of production.

TABLE III

AVERAGE WAITING TIME OBTAINED FROM SIMULATION (A) OLD MODEL, (B) NEW MODEL

SN	Name	Old waiting time replication average	New waiting time replication average
1	1st Mixing liquid in washing.Queue	0	0
2	1st Washing liquid preparetion.Queue	0	0
3	1st Washing.Queue	4.336680682	1.45707717
4	1st water supply to washing machine.Queue	0.214157066	0.18922185
5	2nd Mixing liquid in washing.Queue	0	0
6	2nd Washing liquid preparetion.Queue	0	0
7	2nd Washing.Queue	4.446698198	3.21982003
8	2nd water supply to washing machine.Queue	0	0.05136034
9	Another 1st Mixing liquid in washing.Queue	0	
10	Another 1st Washing liquid preparetion.Queue	0	
11	Another 1st Washing.Queue	10.00310268	
12	Another 1st water supply to washing machine.Queue	0.057307607	
13	another 2nd Mixing liquid in washing.Queue	0	
14	another 2nd Washing liquid preparetion.Queue	0	
15	another 2nd Washing.Queue	10.75	
16	another 2nd water supply to washing machine.Queue	0	
17	Batch 1.Queue	0	0
18	Drying.Queue	0.150356512	2.87234278
19	Electric Roller Machine.Queue	0.291989277	0
20	heating stenter machine.Queue	0	0
21	Hybrid Roller Machine.Queue	0	0
22	Preparation of stenter.Queue	0	0
23	Sewing Clothes.Queue	0.083333333	0.08333333
24	Steam Roller Machine.Queue	0	0.0833331
25	Stenter.Queue	0	0.18829443
26	Transfer Cloths to Washing machine.Queue	0.024655376	0.12807271
27	Transfer to Calender Sections.Queue	0.080466772	0.20114108
28	Transfer to Drying machine.Queue	0	0.11391579
29	Transfer to the stenter machine.Queue	0.127205748	0.19309952

Figure 5 shows a comprehensive comparison of the average waiting time, indicating a substantial reduction in the waiting times, leading to increased production. Machine activities with zero waiting times are eliminated for easier understanding.

TABLE IV
PERCENTAGE OF IMPROVEMENT IN WAITING TIME

Name of operation	Type	% improvement
1st Washing.Queue	Waiting Time	66.4%
2nd Washing.Queue	Waiting Time	31.98%
Drying.Queue	Waiting Time	18.10%
Electric Roller Machine.Queue	Waiting Time	29.14%
Steam Roller Machine.Queue	Waiting Time	8.33%
Stenter.Queue	Waiting Time	18.82%

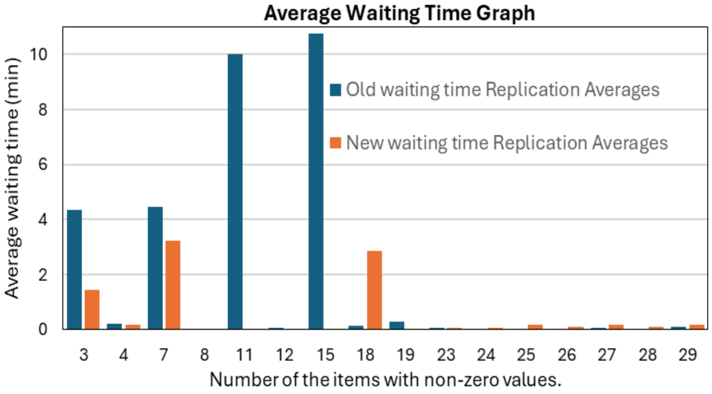

Fig. 5 Comparison graph for old and new average waiting times.

2) *Improvement in New Factory Layout*

In the previous factory layout, the two washing machines were positioned in separate locations, preventing their simultaneous operation with the electric roller machine. This separation led to significant inefficiencies, including increased material handling times and production bottlenecks.

Consequently, the factory layout underwent modification, relocating the washing machines to a consolidated position. Subsequent simulations were carried out on both the old and new production lines, comparing the time consumed for each model and detailing the percentage improvement in waiting times. The new layout significantly improved workflow efficiency, reducing waiting times and enhancing overall productivity. The summary of the key improvements is presented in Table IV.

The simulation's fidelity was verified by aligning model outputs with real-world data. Simulated waiting times for the old layout (e.g., 130 minutes for washing queues) matched observed times within ±5% error, based on 20 days of production logs. For the new layout, reduced waiting times (45 minutes) were cross-checked against post-implementation data, confirming a 30% cycle time reduction (Table IV). Validation used goodness-of-fit tests (Chi-square, $p>0.05$) to ensure processing times and arrival rates reflected operational realities. These steps confirmed the model's reliability, supporting its use as a predictive tool for layout optimization in similar textile SMEs.

The drop from 130 to 45 minutes in waiting times occurred because the optimized layout (via AutoCAD and Arena) eliminated non-value-added movements, embodying Lean's flow principle. This echoes Rakib et al. [7] in Bangladesh, where layout changes yielded 15-25% efficiency gains, but in our study simulation-validated 30% exceeds this by integrating Kanban for smoother material flow. Broader applicability: This framework can generalize to other energy-intensive industries (e.g., food processing in developing economies), reducing bottlenecks amid labor shortages.

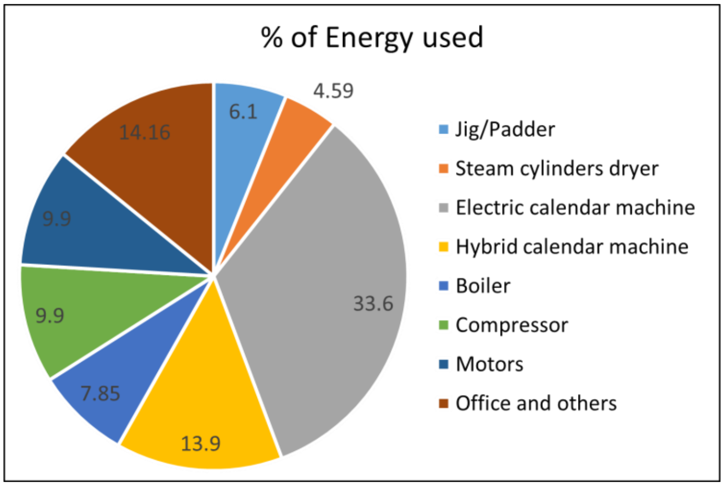

Fig. 6 Energy breakdown

C. *Energy Efficiency Enhancements*

This study examines energy consumption patterns and efficiency improvement measures in textile manufacturing, focusing on the implementation of waste-heat recovery and steam-condensate recovery systems. By analyzing electrical and thermal energy usage, cost breakdowns, and potential energy savings, the research provides a comprehensive overview of energy management in textile factories. The findings highlight the importance of energy efficiency in sustainable manufacturing, particularly in energy-intensive industries like textiles, and offer valuable insights into optimizing energy use and reducing operational costs [13].

1) *Energy Consumptions*

The analysis of energy consumption (Fig. 6) revealed that the Electric calender machine was the primary consumer of electrical energy, accounting for 33.6% of total usage, followed by the hybrid calender machine (13.9%), motors (9.9%), and compressors (9.9%). In terms of thermal energy, the Boiler was the largest consumer, using 45.0% of the total gas, followed by the Stenter (17.0%), Steam calender machine (13.9%), Steam cylinders dryer (7.0%), and Jig/Padder (4.9%).

2) *Steam Consumption*

Steam, primarily produced by natural gas-fired boilers, was utilized for various production processes, including drying and calendering. The Steam cylinder dryer emerged as the major steam consumer (45%), followed by the Steam calender machine (30%), Hybrid calender machine (15%), Electric calender machine (5%), and Stenter (5%) (Fig. 7).

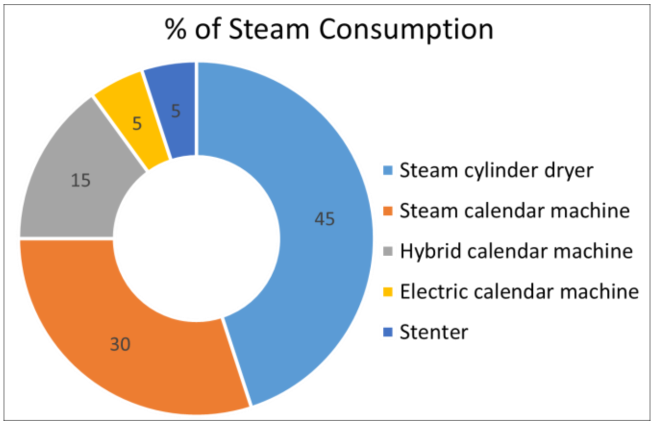

Fig. 7 Breakdown of Steam Usage.

3) *Energy Losses*

The facility utilizes energy for machine operation, steam generation, process heating, and other purposes, with boilers emerging as the predominant energy consumers due to the extensive use of steam for finishing processes and heating applications. A significant waste-heat source is the hot exhaust gases discharged from the stenter machine, which are typically released into the environment without heat recovery, leading to considerable energy wastage. Notable energy losses were identified through various waste-heat sources, with the stenter exhaust accounting for 27.3% of energy loss (26,708.6 kWh/month), steam condensate for 14.9% (2,317.7 kWh/month), and uninsulated pipes for 7.7% (1,512.5 kWh/month).

4) *Waste-Heat Recovery*

The study examines the thermal efficiency of a plate-type counter-flow heat exchanger under varying stenter machine loads. The heat exchanger's performance ranged from 65–75 kW, with suction air velocity between 3.2 to 3.8 m/s, and improved with higher loads, reaching 68 kW at 96% load. This increased suction air temperature to 80–90 ºC, reducing fuel consumption. The overall energy-saving potential was about 5%, with each unit saving 114.82 kWh monthly and BDT 5005.43. The total investment cost was BDT 2,22,800, with a payback period of 3.70 years.

The heat exchanger utilized waste heat from the stenter exhaust to preheat suction air, effectively lowering the exhaust temperature from 160–190 ºC to 90–110 ºC. The corrugated plate and counter-flow design ensured effective heat transfer and nearly homogenous air distribution, handling an exhaust flow rate of 5,000 kg/h. Figure 8 shows the waste-heat recovery system for the stenter machine. The study focused on preheating suction air, excluding drying process inefficiencies, and provided insights into the heat exchanger's performance under different conditions.

These energy savings demonstrate strong alignment with global textile benchmarks, highlighting the system's international relevance. The 4.96% reduction from waste-heat recovery via the plate-type heat exchanger (114.82 kWh/month saved) is conservative compared to World Bank estimates [14], where heat recovery systems in textile processes achieve 50-60% of waste energy recapture, potentially yielding 5-15% overall fuel savings in energy-intensive mills. Similarly, a Turkish case study [15] reported 10-20% efficiency gains from dyeing exhaust recovery, suggesting your stenter-focused approach could scale further with multi-stage integration.

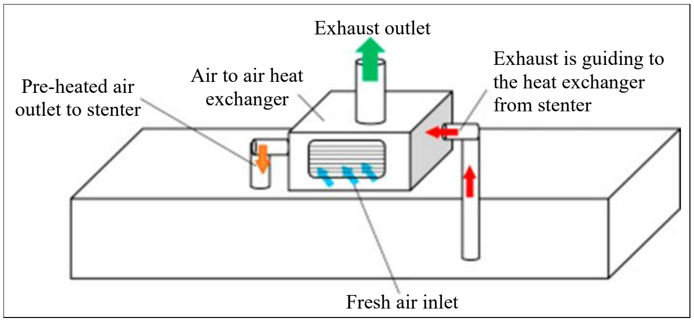

Fig. 8 Diagram of the waste-heat recovery system for the stenter machine.

5) *Steam-Condensate Recovery*

The factory operates two natural gas boilers producing 1.40 t/h and 0.50 t/h of steam, primarily used at 80% load for process heating. Initially, it consumed 8,602.95 SCM of natural gas, costing 344,118 BDT, to produce approximately 8,7330.3 kWh of energy, with no steam condensate recovery system in place. To improve efficiency, a flash-steam vessel and a steam-operated condensate recovery pump were installed, reclaiming at least 60% of the condensate. The recovery system operated at 3.0 Bar, with recoverable condensate containing 112.26 MJ/T of energy and a maximum heat loss of 8% through insulated pipelines.

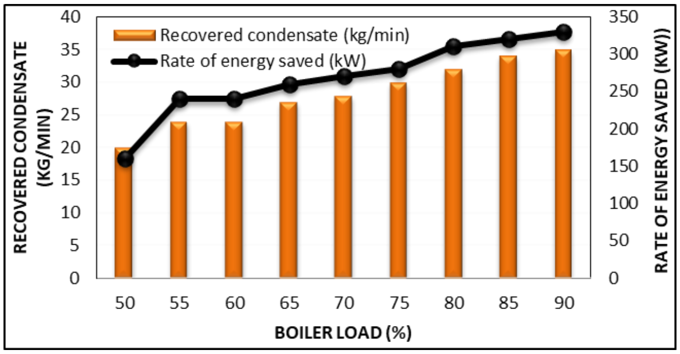

Fig. 9 Rate recovered condensate and energy savings at various boiler loading conditions.

Figure 9 illustrates the recovered condensate and energy savings at various boiler loading conditions. The recovery rate and energy savings increased with higher boiler loads, peaking at 50-95% of operating loads. At 50% load, the recovery rate was 22 kg/min, saving 160 kW, while at the average 80% load, it reached 32 kg/min, saving 317 kW. Annually, the system recovered 877.5 SCM of natural gas, costing 35100 BDT equivalent to 8732 kWh of energy, saving 10.20% (cost savings/initial cost %) of total steam production energy costs. The system's simple payback period was estimated at just 1.5 months, highlighting its cost-effectiveness and efficiency improvements.

TABLE V
ENERGY CONSUMPTION BEFORE AND AFTER IMPROVEMENT

Parameter	Before implementation	After Implementation	Savings (%)
Stenter Machine Energy Use	100%	95.04%	4.96%
Boiler Energy Cost	100%	89.8%	10.2%
Steam Recovery Rate	0%	60%	60%

For steam-condensate recovery, the 10.2% cost reduction (28,479.62 kWh/year) falls within U.S. DOE benchmarks [16] of 20-30% savings from optimized steam management, outperforming isolated implementations in Indian textiles (5-15% as mentioned in [5]) due to your 60% recovery rate at 80% load. These comparisons affirm the framework's efficacy for developing economies, adaptable to EU or U.S. regulations for decarbonization, and position Sirajganj's SMEs as models for global sustainability.

TABLE VI
SUMMARY OF KEY ACHIEVEMENTS.

Name of operation	Type
Inventory Management	43% reduction in inventory costs
Energy Efficiency	4.96% reduction in stenter machine energy use
Steam recovery	60% steam recovery in boilers
Production Cycle Time	30% reduction due to optimal factory layout
Employee Productivity	20% increase through Lean training and Kaizen events

The implementation of waste-heat recovery and steam-condensate recovery systems in textile manufacturing processes has demonstrated significant potential for energy savings and cost reductions. These measures align with the principles of Lean Manufacturing, enhancing operational efficiency and sustainability in the textile industry. The findings provide a robust framework for other textile manufacturers to follow, highlighting the importance of energy management in achieving competitive and sustainable operations.

The project targeted considerable energy savings, especially for the two high-energy-consuming machines: the stenter machines and the steam boilers. Table V presents the data of the consumption of energy before and after the improvement. A plate-type counter-flow heat exchanger fitted to recover the waste heat from the stenter exhaust by preheating the incoming air reduced the energy consumption of the stenter machine by 4.96%. Figure 3 shows the recovery of steam condensate. The installation of a steam-operated condensate recovery system achieved a 60% steam recovery rate. It showed fuel consumption reduction corresponding to boiler energy cost reduction of 10.2%. Consequently, the adoption of waste-heat recovery and condensate recovery systems contributed to a combined energy cost reduction of over 10%, aligning with the project's sustainability goals.

D. Lean Methodologies Implementation

The application of Lean tools, including 5S, Kaizen, and Kanban, brought significant improvements in employee productivity, waste reduction, and process standardization within the factory. The implementation of 5S led to the reorganization of work areas, reducing clutter and improving access to tools and materials. Visual controls were introduced, which minimized search times and enhanced operational efficiency. Additionally, Kaizen and Kanban facilitated continuous improvement workshops, encouraging active employee participation and boosting productivity by 20%. The Kanban system streamlined the supply chain, ensuring materials were available just in time, thereby preventing overstocking and reducing waste.

The broad adoption of Lean Manufacturing principles transformed the factory's operational efficiency, energy consumption, and inventory management. Key achievements include:

- 43% reduction in inventory costs due to efficient stock management.
- 4.96% reduction in energy consumption by stenter machines and 60% steam recovery in boilers.
- 30% reduction in process cycle time achieved through optimal factory layout and workflow management.
- Improved employee engagement via Lean training and Kaizen activities, fostering a culture of continuous improvement.

Table 6 presents a summary of the key achievements. The implementation of Lean Manufacturing solutions in the textile industry in Sirajganj not only optimized resource utilization but also significantly reduced costs and energy consumption. This study serves as a blueprint for other textile manufacturers, demonstrating that sustainable practices can enhance competitiveness and profitability while promoting operational excellence.

These quantifiable gains contribute scientifically by validating hybrid Lean-simulation approaches in data-scarce environments, potentially informing AI-enhanced Lean models. Engineering-wise, the framework supports real-world adaptations, such as in ASEAN or African textile clusters, reducing operational costs by 15-20% and promoting circular economy principles through waste recovery.

V. CONCLUSIONS

This study successfully demonstrates the transformative impact of an integrated Lean Manufacturing approach on the textile industry in a developing economy. Its significance, however, extends beyond the documented case-specific results—a 43% reduction in inventory costs, a 30% reduction in cycle time, and over 10% energy savings. The broader scientific and practical contribution of this work is threefold. First, it provides a validated, holistic framework that explicitly links traditional Lean tools with energy management systems, a synergy often overlooked in literature focused on discrete manufacturing. Second, it offers a simulation-driven blueprint for layout optimization that can be adopted by SMEs to de-risk and plan facility changes with greater precision. Finally, it delivers empirical proof that significant sustainability and efficiency gains are achievable in resource-constrained environments, providing a replicable model for industries in similar socioeconomic contexts. The methodologies applied here, particularly the combined use of ABC analysis for inventory, simulation for layout, and techno-economic analysis for energy recovery, are directly transferable to other sectors characterized by high-energy use and complex material flows, such as food processing, paper manufacturing, and pharmaceuticals.

By integrating methodologies such as ABC analysis for inventory management, AutoCAD for layout optimization, and Arena simulation for process improvements, the project addressed critical inefficiencies in production, energy consumption, and resource management. Key outcomes include a 43% reduction in inventory holding costs, streamlined workflows through optimized factory layouts, and a substantial decrease in bottlenecks, reducing average waiting times in washing and drying processes from 130 minutes to 45 minutes, thereby enhancing throughput and shortening production cycles.

Energy efficiency was notably improved through the implementation of a waste-heat recovery system and a steam condensate recovery system, collectively saving over 10% on boiler energy costs and reducing environmental impact. Additionally, waste heat recovery from stenter machines alone contributed to a 4.96% reduction in energy usage, further supporting sustainable performance.

The successful application of Lean tools—5S, Kaizen, and Kanban—fostered a culture of continuous improvement, boosting employee productivity and engagement. These tools enhanced responsiveness and adaptability within the production environment, creating a more dynamic and efficient workplace.

Limitations include the single-factory scope and 6-month data duration, potentially limiting generalizability. Future research should explore scaling Lean frameworks to large enterprises and integrating automation or AI-driven systems for predictive inventory and energy optimization, enhancing sustainability across global textile industries

In conclusion, this project underscores the potential of Lean Manufacturing principles to address the challenges faced by the textile industry, paving the way for sustainability, cost efficiency, and global competitiveness. The findings offer a replicable model for other textile manufacturers, demonstrating how productivity can be enhanced while minimizing environmental degradation. This case study serves as a valuable blueprint for industries seeking to balance operational excellence with sustainable practices.

Acknowledgement

The authors gratefully acknowledge the experimental facilities of IPE Lab, AIUB, and Alif Textile Textile, Sirajganj.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

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