Adoption of Sustainability-Related Technology and Practice in Denim Manufacturing: A TOE Framework Approach

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Introduction and Literature Review: The global fashion industry has increasingly come under scrutiny due to its significant environmental impacts, particularly in manufacturing processes that heavily rely on water, chemicals, and energy resources (Iqbal & Su, 2025; Islam et al., 2021). Despite numerous technological advancements, sustainable practices remain inconsistently adopted in denim manufacturing, creating substantial environmental burdens (Pal & Gander, 2018). Existing literature highlights that adopting sustainability-related technologies and practices can significantly mitigate these environmental impacts (Iqbal & Su, 2023). Denim manufacturing, infamous for its water-intensive and chemically dependent processes, poses specific sustainability challenges that demand targeted solutions (Islam et al., 2021). Pal and Gander (2018) emphasized the importance of technological innovations such as ozone bleaching and laser finishing, which reduce water and chemical use significantly. The integration of recycled materials, specifically pre- and post-consumer recycled yarns, is noted as an effective measure for reducing environmental impacts and supporting circular economy initiatives (Sandvik & Stubbs, 2019). However, there remains a gap in empirical examinations of the adoption processes within specific factory settings, especially within large-scale denim production facilities. This study addresses this gap by exploring sustainability-related technology and practice adoption in a major denim fabric factory over a two-year observation period, guided by the Technology-Organization-Environment (TOE) framework (Tornatzky & Fleischer, 1990). The TOE framework systematically explores internal and external factors influencing technology adoption (Oliveira & Martins, 2011). The objective of this research is to systematically document, analyze, and interpret the adoption of sustainability-related technologies and practices such as reductions in chemical use, improved water and energy management, and incorporation of recycled materials in denim manufacturing. This study will contribute significantly to the existing body of knowledge on sustainability transitions in textile manufacturing.

Methodology: This qualitative case study adopts an in-depth observational approach to explore the adoption of sustainability-related technologies and practices within a large denim fabric factory in Bangladesh. Data collection occurred over a two-year period from January 2023 to December 2024, employing multiple qualitative methods to ensure triangulation and enhance reliability (Denzin & Lincoln, 1994; Golafshani, 2003). Primary data were collected through direct observations, semi-structured interviews, and document analysis. Direct observations were systematically recorded through field notes, detailing specific sustainability practices such as reduction in dyes, reuse of

chemicals, water, and energy conservation techniques, and the integration of recycled yarn as raw materials. Document collection included internal sustainability reports and technical specifications, provided by factory management, facilitated significantly by a co-author who serves as an executive at the factory, thus granting privileged access to authentic data. Data analysis followed thematic analysis guidelines, where initial coding categorized raw data into descriptive codes linked to the (TOE) framework dimensions (Braun & Clarke, 2006). Triangulation among different data sources was applied rigorously to ensure the accuracy and validity of findings, reducing researcher bias and enhancing reliability (Patton, 1990). The involvement of an executive as co-author also provided vital contextual understanding, enriching data interpretation and ensuring accuracy in representing organizational dynamics and decision-making processes within the denim fabric factory setting.

Results and Discussion: The themes generated from the data analysis were organized according to the TOE framework (Figure 1).

Technology: During the two years of observation, the factory significantly replaced the granular dyes with eco-friendly liquid dyes, where the proportion of liquid dyes has been raised from 40.76% to 94.80% in Indigo dyeing. Liquid Indigo needs 33-35% less Sodium hydrosulfite-sodium dithionite-hydrose ($Na_2S_2O_4$) than conventional granular dyes. Alkali (Sodium Hydroxide) consumption in fabric dyeing has also been reduced significantly to make an impact on the neutralization of effluent. During the observation period, the Sodium Hydroxide consumption was reduced from 0.0565 kg/yds to 0.0384 kg/yds, which is approximately 32.04% while the factory ensured the same quality of fabric. Furthermore, the Sodium Hydroxide solution in the Mercerizing process is being reused for new batches after filtering, and this leads to cost and workload reduction, and a reduced load on the effluent treatment plant. The factory adopted STF (Shrink to Fit) technology (Levi's, 2025) in denim finishing, which resulted in the average steam use being reduced by 11.95% in the last two years.

Organization: Due to occupational safety measures and other sustainability practices, the injury rate dropped from 8.12 (year 2023) to 5.04 (year 2024) in the finishing and mercerizing department. Before 2023, the factory did not have established internal compliance. During the data collection period, the factory has established compliance measures to ensure workers' safety, environmental policy, adherence to regulations, and preventing and detecting rule violations. These sustainability practices improved the average employee retention rate. Apart from an improved employee retention rate, the number of buyers (brands) in 2024 also increased by 34.5% than in 2023.

Environment: Observations and interview data suggest that the factory started using both pre-consumer cotton and post-consumer Polyester Yarns as raw materials. These recycled yarns consist of 31.4% of the total yarn they are using and increased by 3.74% in the last two years. Findings suggest that the adoption of the practice of water reuse has a significant impact on the total water consumption by the factory. In January 2023 the intensity of water consumption was 0.0195 m^3/yds, whereas in December 2024 it was 0.0158 m^3/yds. The groundwater lifting intensity was 0.0211 m^3/yds in January

2023, as a result of sustainable process optimization and reuse of water the lifting intensity was reduced to 0.0164 m^3/yds in December 2024. In turn, this water-saving practice reduced the water discharge amount in the effluent treatment plant which saved 10.99% cost of wastewater treatment. These sustainability-related and cost-saving practices are providing the factory with a competitive advantage in the denim fabric market. One executive (P1) mentioned, “Comparing the overdyeing cost in 2023 was $0.21 but in 2024 it has come down to $0.14 in 2024. A 33.33% reduction in cost gave the management a fine edge to compete with other competitors”. Findings also suggest that the adoption of sustainability-related technology and practices is significantly influenced by foreign brands. The factory has a constant fear that if they do not comply with the brands’ suggestion, they might lose the orders.

Discussions and Implications: The study found that adopting sustainability-oriented technologies and practices within the denim manufacturing factory significantly reduced chemical and water consumption, improved workplace safety, and enhanced compliance and market competitiveness. Findings highlight the critical influence of external pressures from international buyers on driving sustainable practices in large-scale textile operations.

The findings of this study reinforce the theoretical proposition that environmental factors, such as buyer pressure and compliance requirements, act as dominant external enablers of technological and sustainable innovations in developing-country contexts. Overall, the study broadens the TOE framework by integrating cost-saving and competitive-advantage outcomes as mediating mechanisms linking sustainability adoption with firm performance.

Practically, this study offers actionable insights for textile and apparel manufacturers seeking to balance sustainability and profitability. The factory’s measurable reduction in water consumption and wastewater treatment costs demonstrates that sustainability-oriented technological investments can yield tangible economic benefits. Managers in similar production contexts can leverage water reuse systems and recycled fiber utilization not only to comply with international buyer requirements but also to strengthen their competitive positioning in global markets.

The two-year observation period (2023–2024) provides strong longitudinal insight but may not capture long-term sustainability outcomes. Future work may analyze multiple denim manufacturers or different textile sectors to identify cross-industry adoption patterns and validate the TOE framework more broadly. Incorporating quantitative measures (e.g., cost–benefit analysis, emission reduction metrics) can strengthen empirical support and statistical reliability.

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Figure 1. Themes Generated through Data Analysis