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System Dynamics-Based Circular Economy Model for Enhancing Environmental Sustainability in Bangladesh's Leather Industry

Abdullah Mohammad Khaled, Akteruzzaman Nadim, Chaity Dey, Md. Tanvir Hossai, Shahriar Islam Sium, Mahmudul Hasan Rohan, Md. Tanbir Hassan, Md Mahfuzur Rahman and Md. Muhtasim Fuad
Department of Industrial & Production Engineering
Jashore University of Science & Technology
Jessore-7408, Bangladesh
abdullahmdkhaled7@gmail.com, akhteruzzamannadim@gmail.com, chaitydeyctg@gmail.com, mdtanvirhossain.ai@gmail.com, sium.ipe.just@gmail.com, rohanovro756@gmail.com, tanbirhasan.mail@gmail.com, mrahman.ipe@just.edu.bd, fuadipe@gmail.com

Abstract

The leather industry is one of Bangladesh's most resource-intensive manufacturing sectors which contributes to severe environmental pollution through chemical wastewater discharge and a very inefficient recycling system. The principle of circular economy (CE) with the system dynamics (SD) approach has been taken in this study to evaluate the environmental sustainability of Bangladesh's leather industry and compare it with the European Union (EU), a relatively much better industry. A stock-flow simulation model was developed in VENSIM simulation to analyze the dynamic relationships among the multiple parameters such as production efficiency, pollution control, recycling capacity, and investment in sustainability. The parameters that are used are derived from secondary datasets and validated through comparative industrial reports. The result of the simulation reveals a scenario where almost every value of the EU maintains a higher value than Bangladesh, such as Good Management Practices, Environmental Sustainability Index (ESI) due to effective and strong regulation, better cost saving factor, larger investment in sustainability & advanced waste treatment, whereas Bangladesh's ESI improves whenever the primary factors are done more efficiently and cost effectively. The study concludes that enhancing management practices, policy enforcement, and technological reinvestment can significantly accelerate the transition toward a sustainable circular leather industry.

Keywords
System Dynamics (SD), Circular Economy (CE), Leather Industry, Sustainability Modeling, Environmental Sustainability Index(ESI).

1.Introduction
Leather is one of the predominant industries globally serving various purposes of accessories, garments, footwear and so on. It's reported that Bangladesh is the second-largest exporter of RMGs globally (BIDA, 2021). According to the Export Promotion Bureau (EPB), leather and leather products contributed $1245.18 million which is 2% of Bangladesh's total export in the fiscal year 2021-2022 (Bangladesh, 2022). However, it comes across several environmental sustainability challenges including waste mismanagement, using hazardous chemicals namely chromium and glutaraldehyde (Ferraris & et al., 2025), improper tanning technology, poor infrastructure and labor standards that prevent this industry from being widely recognized and salubrious. In Bangladesh, the CE model helps policymakers to make productive and long-run decisions on efficient production, resource circularity, and

consumption that result in sustainable growth (Ahmed & et al., 2022). Furthermore, notable barriers and tactics are identified to accomplish CE for acquiring sustainable growth in the leather products industry (Maliha & et al., 2023). However, already established studies seldom apply dynamic modelling to evaluate CE strategies in Bangladesh's leather sector, leaving a significant gap in quantitative tools for stakeholders and policymakers.

1.1 Research Objectives

The primary objective of this research is to establish a system dynamics-based circular economy model to advance environmental sustainability in Bangladesh's leather industry. The specific objectives are:

I. Identifying and analyzing key sustainability challenges In the leather industry of Bangladesh by data collection.
II. Constructing loop diagrams depicting dynamic relationships and feedback mechanisms among important sustainability factors.
III. Developing quantitative stock and flow diagrams for system simulation under different circular economy scenarios and values.
IV. Observing Environmental Sustainability Index (ESI) as a comprehensive performance measurement parameter & regulating simulation of scenarios assessing the impact of different interventions impact on sustainability.
V. Ensuring research-backed recommendations on strategies for effective circular economy implementation.
VI. Developing a replicable framework adaptable to other manufacturing sectors within similar contexts.

Finally, the study aims to extend its impact beyond the leather industry to support sustainable industrial development initiatives across emerging economies.

2. Literature Review

2.1 Circular economy in industries

Circular Economy (CE) is a sustainable development framework where by-products are reused or recycled instead of the traditional linear model " take-make-dispose". This strategy ensures optimum resource utilization by reducing dissipation and minimizes negative impact on the environment. CE is a basically closed-loop system that balances economic growth and environmental stability through proper resource management. Especially in the textile and leather industry, this approach has become more important as both resource usage and waste generation rate are increasing gradually. It transforms textile and clothing sectors into more sustainable, environmentally friendly and regenerative systems through product durability, recycling and waste minimization (Saha & et al., 2024). Similarly, implementation of CE in the leather industry makes the waste management system more efficient and helps in preserving natural resources like energy, minerals and water (Akbar & et al., 2025).

In recent research studies it has been unveiled that, the successful execution of circular economy (CE) depends upon the mutual coordination of technological, financial and institutional factors. The CE framework has been enforced successfully in developed countries, whereas it is challenging to implement this strategy in developing countries like Bangladesh due to confined knowledge. Regulatory, infrastructure and institutional constraints are greater barriers in this regard. For instance, poor waste management, insufficient waste refinery and unorganized supply chain in the tanneries located in Hazaribag and Savar are responsible for not transforming into a closed-loop generation system.

2.2 Bangladesh's leather industry sustainability challenges

The relation among people, environment, and economy represents an essential part of sustainable industrial development. A sustainable environment is crucial for maintaining resource availability and long-term productivity. Environmental sustainability refers to balancing the qualities valued in natural and biological environments, preserving natural resources, and protecting ecosystems for both current and future generations (Fatema & et al., 2023). In recent years, developed countries have integrated sustainable practices into their manufacturing systems and adopted environmentally responsible production practices. Before buying products from another country, they strictly observe the conditions under which the product is made.

The system alternation has created both challenges and opportunities for Bangladesh's leather industry to meet international sustainability. Our primary goal is to achieve environmental sustainability. But economic sustainability is closely related to environmental sustainability; thus, the sectors that want to achieve economic sustainability can do some of the tasks, such as: (1) Investment in innovative technologies, (2) Efficiency of resource use, (3) Traceability of raw skin and hides (Omoloso & et al., 2020). These tasks can help the leather industry to become more productive and profitable. Moreover, investment and proper resource utilization in innovative technology lessens dissipation that helps to attain environmental sustainability. As a result, it is possible to produce high-quality leather products from both user and environmentally friendly aspects. But limited access to green technology, weak policy practices and inadequate infrastructure act as still major obstacles in achieving sustainable production strategy in leather industry in Bangladesh.

2.3 Application of System Dynamics in Circular Economy:

The System Dynamics (SD) approach is recognized as an effective way to model complex circular economy transitions. The transformation to a sustainable system depends on feedback loops, time delays, and non-linear relationships revealed by the SD model. Decision-makers in the manufacturing sectors require tools to deal with complexity in Circular Economy (CE) transitions, underscoring the necessity for SD modeling. System dynamics helps in proper decision-making by analyzing overall performance, production, supply chain management, and sustainability by CLD, SFD, and temporal delays using software such as VENSIM, STELLA, POERSIM, etc. It leads the leather industry to be more efficient and sustainable in manufacturing by minimizing waste, utilizing resources effectively, and reducing energy and labor consumption through simulation (Kaur & Kander, 2023). The application of system dynamics in the circular economy framework has demonstrated the significance of analyzing systemic effects of multiple intervention strategies. For example, SD models have been applied to study waste management systems in China and India, support industrial evaluation, and assess textile recycling processes. SD-based computational simulations also allow researchers to continuously evaluate the combined effects of product design strategies and business models aimed at both slowing and closing resource loops within the circular economy.

Although SD has been widely used worldwide, a notable research gap exists in Bangladesh. Bangladesh's leather industry faces several challenges in implementing SD model simulations, including insufficient access to technology, incompetent infrastructure for SD modeling, limited financial support, and notable organizational policy issues (Haq & et al., 2023). This gap creates a great opportunity for implementing SD in the Bangladesh leather sector for sustainable operations and policy practices.

2.4 System Dynamic implications in Bangladesh's leather industry:

Currently, there is no renowned study on integrating System Dynamics (SD) with the Circular Economy (CE) for the sustainability evaluation of Bangladesh's leather industry. CE economy operation refers to a sustainable environmental system that minimizes waste generation, indicating a potential research direction for this paper. The gap in SD implementation is the main encouragement for this paper. SD implementation gap offers both challenges and opportunities for Bangladesh's leather industry. Integrating SD modeling with circular economy regulations makes a promising opportunity, transforming a non-linear process into a closed-loop system. SD modeling highlights the interconnection among environmental, economic, and influential factors. Researchers can provide industry owners with evidence-based tools to guide them towards sustainable development by developing an SD model, while maintaining competitiveness in the international market.

These approaches help achieve SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 13 (climate action), adopted by the United Nations (UN) in 2015 as part of the 2030 Agenda for Sustainable Development Goals.

3. Methodology

3.1 Research Framework

The principle of circular economy (CE) integrated in the system dynamics (SD) is the approach that has been taken here for the environmental sustainability in the leather industry. The system dynamics framework is chosen due to its ability to capture dynamic feedback relationships among multiple variables like production volume, waste generation, recycling fraction and management actions over time in the Bangladesh and EU's data.

The casual loop diagram (CLD) was developed to identify the interdependencies among the components such as recycling capacity, resource consumption & sustainability. The framework structure was guided by the CE strategies emphasizing waste minimization, resource efficiency, and regenerative production systems.

The framework aligns with the triple-bottom-line approach by integrating environmental, economic, and operational performance indicators. This enables the model to dynamically represent how managerial and technological improvements propagate through the production system, ultimately influencing the Environmental Sustainability Index (ESI) of the industry.

3.2 Model Structure and Development

The model was developed in VENSIM PLE, structured into five dynamically linked subsystems that collectively represent the sustainability performance of the leather industry:

Recycling System (RS)

A primary factor of environmental sustainability. The leather industry is one of the highest waste material generators as almost 75-80% of it turns out as waste material (Sathish et al., 2021a). The solid waste generation especially the Chromium-containing Sludge is one of the main harmful objects of this industry. This is grouped around recycling drivers, recycling capacity & recycling efficiency.

Environmental Pollution (EP)

One of the main drivers of sustainability is the contest of environmental pollution. The leather industry which already creates a large amount of waste creates a high environmental pollution, which is normally affected by the production volume, toxic chemicals, solid waste generation, waste water generation & CO_2 emissions.

Sustainable Resource Capacity (SRC)

The resource consumption sustainability indicates the ratio of raw material input, waste generated, recovered materials and their possible reuse over time. It also affects the energy consumption and the investment in the sector quite more.

Good Management Practices (GMP)

The factor that runs the all the above mention sector is the management board. This includes the cost saving factor, regulation strength and market incentive. This factor controlled and decided the initiative needed to do better in the other factors influencing environmental policy compliance & production efficiency.

Environmental Sustainability Index (ESI)

The comprehensive measurement system where the progress towards environmental sustainability is detected. This indicator is affected by multiple parameters and shows the future prospect the current situation can take. So, the commutation of other major important variables makes the result of a composite sustainability score. Each subsystem consists of stocks, flows, and auxiliary variables, interconnected through cause–effect relationships.
Key functional relationships include (Figure 1):

Figure 1. Core Causal Relationships in the Leather Industry Sustainability Model

3.2.1 Casual Loop analysis

The total system dynamics of the circular economy is based on a set of reinforcing and balancing feedback loops, visualizing the Casual loop diagram (CLD). These loops identify the dynamic relationships and feedback mechanism among multiple factors. The diagrams reveal the system's behavior as:

- Environmental Degradation Loop(B1): The loop illustrates the impact on the primary production stage. It shows that the increase in raw hide input leads to more tanning which increases the waste generation output. This results in an increase in total output of contamination.

- Recycling Loop (R1): The loop highlights the relation of waste generation and recycling. If a system is effective with increased production and waste generation the environmental impact can be minimized.
- Finished Product Circularity Loop (R3 & R4): These loops show a long-term impact of CE principles as an increased manufacturing the waste amount may also increase. If there are effective mechanisms for recovering where a more percentage of waste may be reused is manufacturing, closing the material loop and enhancing the SRC (Figure 2).

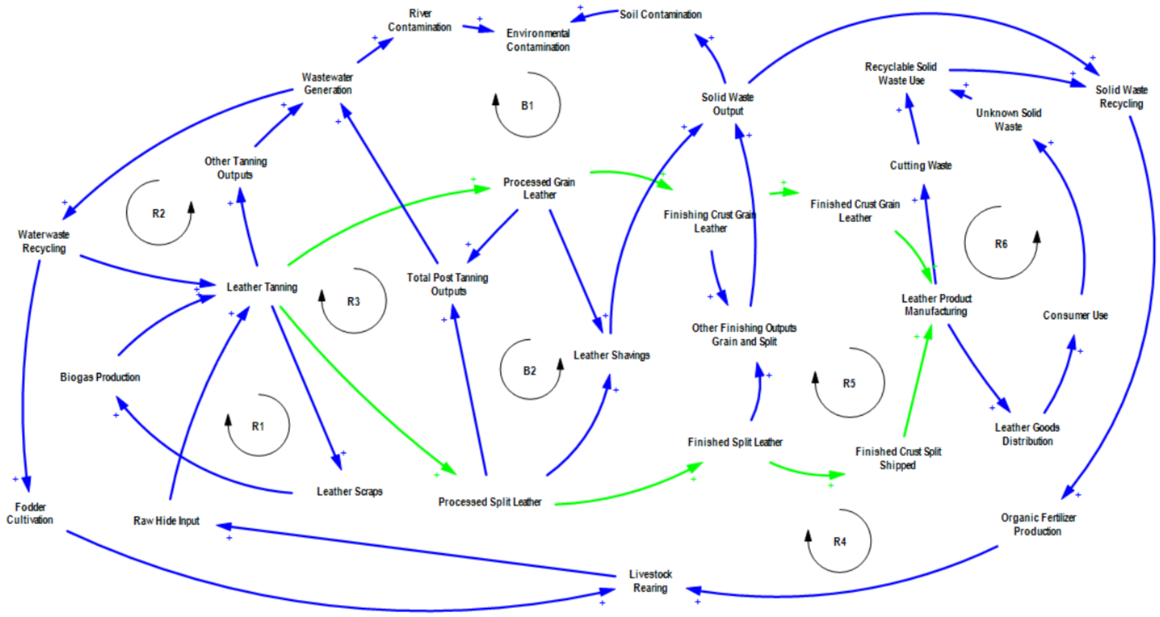

Figure 2. Causal Loop Diagram (CLD) of Key Dynamic Relationships in the Circular Leather Industry

3.3 Simulation Setup

Model simulation was conducted over a 120-month period using numerical stability and dynamic accuracy. The initial variable values were based on conditions that are normal and general in both Bangladesh's leather industry and European Union's leather sector. The analyses were performed by various parameters to observe the effect on the ESI flow trajectory (Figure 3).

The simulation was designed to allow multiple value chance and testing policy or scenario change including the obtained data of:

- European Commission (Commission, 2020)
- Bangladesh Department of Environment (DoE) and Bangladesh Tanners Association Reports (Environment, 2018)

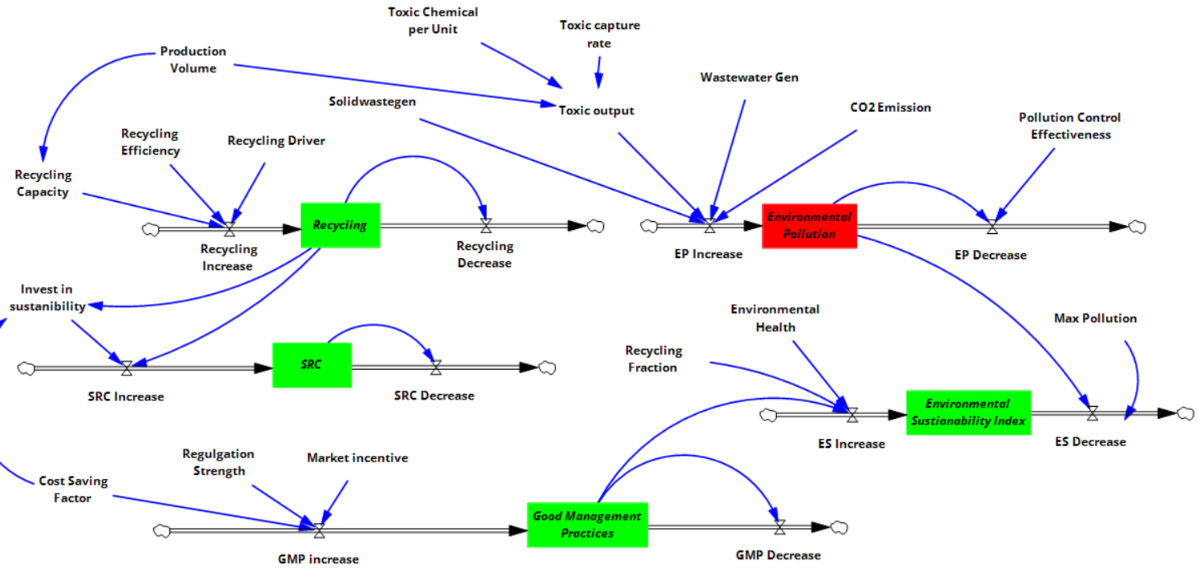

Figure 3. Stock flow diagram for assessing environmental sustainability of circular leather industry

3.4 Data Collection and Parameterization

The data were mainly collected from secondary sources for parameters ensuring comparability between the EU & Bangladesh contexts. Multiple parameters and variables such as the CO_2 emission, wastewater & solid-waste generation, pollution control efficiency was extracted and estimated from sources. Proxy values were derived from analogous industries or normalized to reflect dynamic behavior (Sathish et al., 2021b).

3.5 Model Validation

The model validation was done through key approaches:

- **Structural validation:** ensured logical coherence of causal linkages, feedback direction, and subsystem consistency with theoretical and empirical understanding of leather manufacturing systems.
- **Behavioral validation:** comparing simulation outputs with observed industrial patterns such as pollution, production growth, and recycling reported in prior studies.

3.5.1 Sensitivity analysis

a sensitivity analysis was conducted to evaluate the robustness of the model by varying the key parameter within plausible ranges. Parameters as recycling fraction, toxic capture rate were varied individually by ±(9-10%) from their baseline values. The simulation results indicates that ESI is very sensitive to changes in certain parameters. Despite parameter variation, the systems behavior remained consistent confirming the structural stability & reliability.

The simulation system shows reliable correlation with data indicating rising sustainability rates in improved management and recycling situations and decreasing performance in less regulated environments.

3.6 Limitations and Model Boundary

The model simulation was done by feedback mechanism and secondary datasets with generalized assumptions for regional comparability. Due to the limited availability of plant-level data in Bangladesh, several simplifying assumptions were required including relatively production volumes, average CETP efficiency values driven from removal ranges & linear relationship between investment in sustainability in pollution control & recycling performance.

Socioeconomic dimensions such as labor conditions & market fluctuations were excluded due not having required data available and maintaining focus on the environmental dynamics. The model used data that was available but in the case of the Bangladesh extensive data source was unavailable. Nevertheless, the structure of the model allows future integration of economic and social indicators. This enables a more comprehensive system dynamic framework on the leather sector.

4. Data Collection

The utilized data for this model initializing and parameter calibration were obtained primarily from secondary sources, focusing on the European union & Bangladesh leather industry. In addition to the secondary literature, empirical data from the Bangladesh's leather sector were incorporated available. Reported wastewater from operating tanneries in Savar Tannery Industrial Estate typically ranges between 0.8-1.2m^3/m^2 of processed leather, meanwhile chromium concentrations in untreated effluents have been observed between 50–300 mg/L prior to CETP treatment. Removal efficiencies of the CETP in Savar have been reported as 30-60% depending on operations. This observation were used to calibrate & validate parameter ranges for the model (Table 1).

Data selection followed three key criteria:

- Representativeness of industrial-scale operations
- Availability of environmental and resource-efficiency indicators
- Compatibility with normalization for System Dynamics simulation.

Table 1. Parameter values for the System Dynamics simulation model

Name	EU Value	Bangladesh Value	Source / Basis
Pollution Control Effectiveness	0.8–0.95	0.3–0.5	EU BAT reference; Bangladesh CETP efficiency studies (~47% removal, variable)
CO_2 Emission (per m²)	~8 kg CO_2 e/m²	~0.4–0.8 kg CO_2 e/m²	EU "Green Deal Leather" (COTANCE, 2024); BD LCA case studies (Dhaka tanneries)
Wastewater Generation	0.12–0.13 m³/m²	~1.0 m³/m²	EU BAT / water-use norms; Bangladesh case studies (Savar CETP, Hazaribagh)
Solid Waste Generation	~2.6 kg/m²	~4–8 kg/m²	EU SER waste survey; Bangladesh sector waste composition studies
Environmental Health of Area	0.6	0.2–0.4	Proxy based on EU environmental performance vs. Bangladesh local pollution levels
Recycling Fraction (initial)	0.10–0.25	0.02–0.08	LIFE project / EU waste recovery rates; BD limited recycling infrastructure
Recycling Driver	0.6–1.0	0.2–0.5	Derived proxy from market & policy incentives
Cost Saving Factor (per tonne recycled)	30–100 / t	10–40 / t	Derived from waste management savings & reuse case studies
Regulation Strength	0.8–0.95	0.2–0.4	EU environmental enforcement vs. BD weak enforcement record
Market Incentive	0.6–0.9	0.1–0.4	Based on eco-label adoption & export incentive studies
Toxic Chemical per Unit (Cr conc. raw effluent)	10–50 mg/L	50–300 mg/L	EU treated effluent compliance (< 2 mg/L); BD raw effluent studies(Hazaribagh/Savar CETP)
Toxic Capture Rate	0.85–0.95	0.3–0.6	Removal efficiency of treatment plants (EU BAT vs BD CETP)

5. Result & Discussion

The simulation shows the variables' effect on different situations. It is showing that the primary five indicators that show the conditions and future prospects of the leather industry are very different in both Bangladesh and the EU. In the Sustainable Resource Consumption & recycling the resource we can see a common flow. In both cases in the fixed production volume the amount of waste material that is generated is different, with the addition of other parameter perspectives like recycling driver, recycling capacity, investment in sustainability etc. causes a different type of flow. In the case of Europe, the rate of resource consumption & recycling is high at a good rate but in the case of Bangladesh both are at a bad rate/amount. Here in a test (T1) the variable of recycling driver, cost saving factor has been changed only a few and increased. This sudden change resulted in a much positive spike in the value (Figure 4).

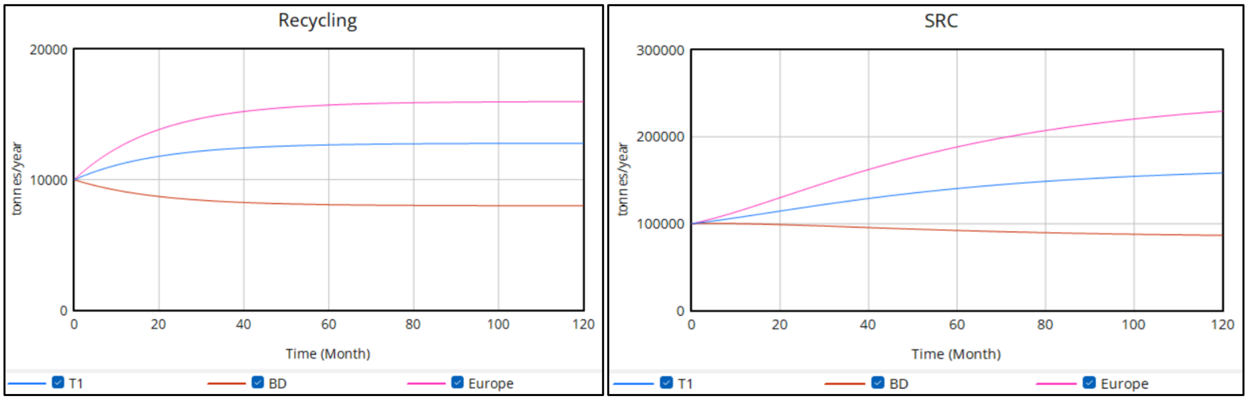

Figure 4. Comparison between multiple recycling and resource consumption scenario

The environmental pollution amount also shows a similar trail on the flow. In the change of variables toxic chemical generation per unit & toxic capture rates shows that the pollution is more in Bangladesh compared to the EU but as further change shows that the pollution is possibly lower than the EU in the test(T1) (Haq, 2023). The good management practices also indicate the same result as the index value is much higher in the EU and much less in Bangladesh. But the change in the variable, 'cost saving factor' increases it to a much better flow and future prospect (Figure 5).

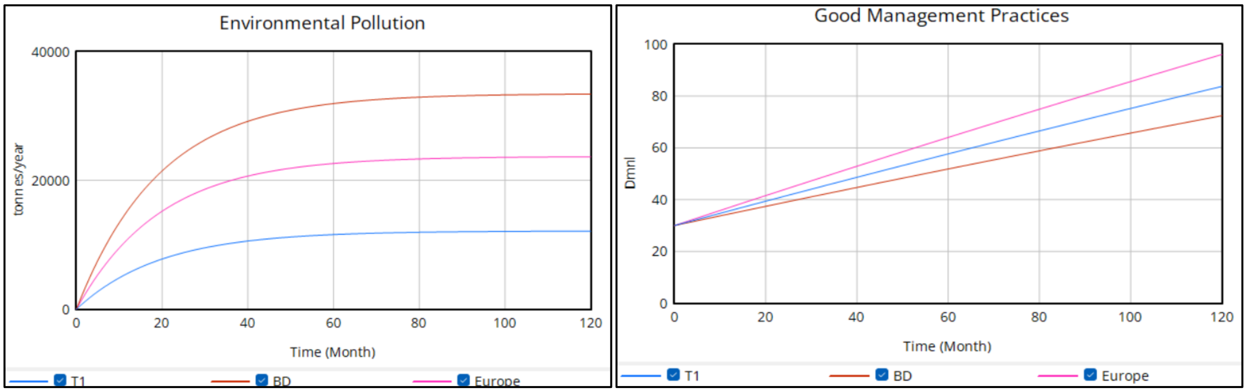

Figure 5. Comparison between effects on policy improvement based on different scenarios.

The main & final indicator, the environmental sustainability index shows rather positive future indicators. If the current index value is taken into account and done the simulation it shows the index progress as a show progressive flow. In the simulated timeline the increase of Bangladesh's index is not much but the progression of the Eu is much better. And in the test (T1) simulation the slight change of variables as 'Environmental health' and 'recycling fraction' & other stocks shows that a good increase in the index occurs. This means change in the variables and works raise the value of the ESI (Figure 6), which indicates that with effort the index and future can be done better (Consortium, 2021).

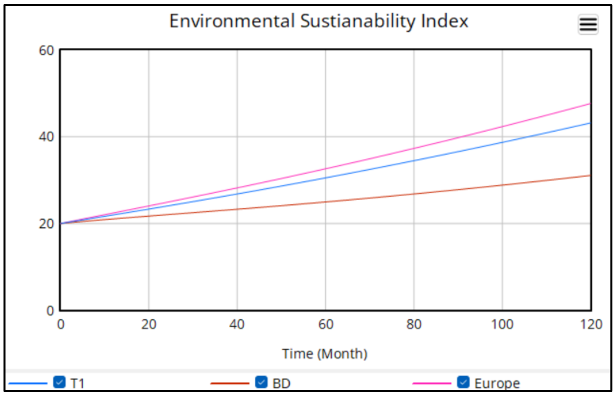

Figure 6. Comparison between increasing ESI in different scenarios.

This particular increasing flow of the index rate is due to some main factors (Alfarisi, 2020). The factors like, recycling driver, recycling capacity, investment in sustainability, cost saving factor, toxic waste generation, toxic waste capture rate, environmental pollution are the main indicators that shows how the country's leather industry is doing in their environmental sustainability program. One of the main things that is noticeable here is the result. It is seen that whenever the investment in sustainability and cost saving factor is involved the flow rate is affected by large (Survey, 2022).

6. Conclusion

The system dynamic and circular economy-based model simulation demonstrated how interconnected multiple variables such as pollution control effectiveness, investment in sustainability, management practices, recycling capacity influence not only each other but also the environmental performance of the leather industry. The simulation result gives us a view of the higher quality of the European Union's leather sector's environmental performance than Bangladesh's due to multiple factors like stronger regulation, higher recycling efficiency, and greater technological investment.

The model shows one particular trail about the key drivers particularly the investment in sustainability, cost-saving reinvestment. The result in the test (T1) shows that increase in this factor heavily influences the activities and management's decision. This implements the fact that all decisions first should be economically viable and beneficial only that it has a higher chance of implication. Also, it is seen that strengthening circular practices such as recycling and waste recovery and higher pollution control would yield measurable long-term benefits.

This framework offers business executives a measurable and adaptable instrument for assessing the impact of circular economy efforts. Future research should incorporate social and economic factors, expand to multi-sectoral comparisons, and validate the model with real plant-level data to improve its forecasting capability and policy relevance.

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Biographies

Abdullah Mohammad Khaled is an undergraduate student in Industrial & Production Engineering at Jashore University of Science and Technology (JUST). His academic interests include machine learning, system dynamic simulation, machine design and their application on the manufacturing and industrial system for better efficiency.

Akteruzzaman Nadim is an undergraduate student in Industrial and Production Engineering at Jashore University of Science and Technology (JUST), Bangladesh. His academic interests include manufacturing engineering, materials processing, and the application of machine learning in industrial systems. He aims to pursue advanced studies in manufacturing and build a career in sustainable industrial engineering.

Chaity Dey is an undergraduate student in Industrial & Production Engineering at Jashore University of Science and Technology (JUST). Her core interests center on supply chain optimization, including demand forecasting, logistics network design, and inventory management. She is particularly focused on how data-driven methods such as operations research, and system simulation can enhance end-to-end supply chain performance and resilience.

Md. Tanvir Hossain is currently pursuing a Bachelor of Science in Industrial and Production Engineering (IPE) at Jashore University of Science and Technology (JUST). His academic interests focus on machine learning, system dynamics, and their applications in improving industrial processes, automation, and decision-making.

Md. Shahriar Islam Sium is an undergraduate student in Industrial & Production Engineering at Jashore University of Science & Technology. His professional focus encompasses advanced 3D CAD design, engineering simulation and applied research. Mr. Sium utilizes tools such as SolidWorks and CATIA for sophisticated part, assembly, surface modeling and employs ANSYS for Finite Element Analysis and Computational Fluid Dynamics to guide design optimization.

Mahmudul Hasan Rohan is an undergraduate student in Industrial & Production Engineering at Jashore University of Science and Technology (JUST). His academic interests include machine learning, system dynamics simulation, materials science, artificial intelligence and aerodynamics, with a focus on applying these fields to optimize manufacturing and industrial systems.

Md. Tanbir Hasan is an undergraduate student in Industrial & Production Engineering at Jashore University of Science and Technology (JUST). His core interests include Computer Aided Design (CAD), Computational Fluid Dynamics (CFD), Artificial Intelligence (AI), and AI-driven industrial systems. Mr. Tanbir utilize tools such as SolidWorks, NX, and ANSYS. He is passionate about applied research and innovation in industrial systems.

Dr. Md. Mahfuzur Rahman is an Assistant Professor in the Department of Industrial and Production Engineering at Jashore University of Science and Technology (JUST). His research focuses on circular manufacturing, decision analysis, supply chain barriers, and sustainability. He also works in advanced materials and manufacturing, including graphene, CNTs, plasmonic nanoparticles, carbon-based composites, electromagnetic shielding, supercapacitors, and capacitive deionization (CDI).

Md. Muhtasim Fuad is a dedicated professional currently serving as a Junior Officer in the Supply Chain Management Department at Kiam Metal Industries Limited, a sister concern of the BRB Group. In this role, he contributes to the smooth functioning of procurement, logistics, and inventory management, gaining valuable hands-on experience in the complexities of industrial supply chains.