

CIRCULAR ECONOMY IN TEXTILE MANUFACTURING: AI-DRIVEN APPROACHES TO WASTE REDUCTION

<https://doi.org/10.5281/zenodo.15203509>

Hikmatillo Umarhojiyev

Co-founder of Findecor (AI Furniture and Décor Assistant);

Graduate Student at Golden Gate University, CA, USA.

Abstract

Global textile and apparel production ranks among the most environmentally taxing industries due to its significant material waste alongside high water usage and carbon emissions. Linear production systems generate about 92 million tons of textile waste each year as 87% of fibers end up in landfills or are burned. Circular economy principles allow businesses to eliminate waste by implementing smart design practices along with reuse and recycling methods and efficient resource usage. The study examines artificial intelligence's role as a revolutionary force in making textile manufacturing more sustainable.

In addition, this study examines how AI technology applications throughout the value chain—including zero-waste pattern making and predictive analytics as well as energy management and automated textile recycling—lead to significant reductions in material waste and water conservation while boosting energy efficiency. Case studies from practical implementations demonstrate environmental advantages and financial efficiencies. The research highlights AI's essential role in synchronizing the fashion sector with sustainable objectives while establishing U.S. dominance in clean manufacturing innovation.

Keywords

Circular Economy, Artificial Intelligence, Textile Manufacturing, Waste Reduction, Sustainable Fashion, Recycling, Predictive Analytics

Introduction

The worldwide fashion and textile industry stands as one of the five primary industrial contributors to environmental damage by producing 10% of global carbon emissions along with 92 million tons of waste each year (Fortuny Sicart, 2023; Roland Berger, 2024). Under the prevailing linear “take-make-dispose” model, resources are extracted, consumed, and discarded without recirculation, leading to 87% of textiles being incinerated or landfilled. Moreover, the industry consumes 93 billion cubic meters of water per year and generates 20% of global

industrial wastewater. In the United States, up to 85% of discarded textiles are not recycled, compounding environmental stress (Roland Berger, 2024).

The circular economy model redesigns current wasteful systems to extend material lifecycles through recycling processes and innovative product design. Textile circularity faces significant obstacles stemming from material diversity and supply chain complexity as well as end-of-life inefficiencies. The current situation necessitates artificial intelligence (AI) to address systemic inefficiencies because it has become increasingly essential for resolution. AI facilitates real-time optimization along with predictive planning and process automation which provides substantial opportunities for reducing waste. This paper explores how AI is enabling circularity across three dimensions of textile production: material use, water conservation, and energy efficiency. The evaluation focuses on AI's impact in post-consumer textile recycling and how it helps close the sustainability loop for better outcomes.

AI Solutions for Reducing Fabric Waste

Fabric waste is a major environmental issue in the fashion industry, often resulting from inefficient cutting, over-ordering, and inaccurate demand forecasting. Traditionally, up to 15% of fabric is wasted during the cutting process due to suboptimal pattern layouts and production planning (Chao, 2023). AI-driven innovations are now enabling textile manufacturers to significantly reduce this waste across several stages of production.

One major development is zero-waste pattern design enabled by machine learning. Shelly Xu Design (SXD), for instance, has developed an AI-based platform that converts traditional pattern layouts into interlocking designs, maximizing fabric utilization. In pilot implementations, SXD reduced fabric waste by up to 46%, saving over 41,000 meters of fabric in a single season (Bansal, 2023). These tools surpass traditional nesting software by incorporating adaptive design intelligence, accounting for material constraints, product specifications, and leftover inventory.

In manufacturing, systems like IntelloCut automate fabric allocation and cutting strategies using AI to forecast exact fabric needs and optimize layouts in real time. Duc Hanh Garment JSC used IntelloCut to reduce fabric waste to just 1.7%, with a 2.2% decrease in material costs (Coats Digital, 2022). Furthermore, predictive analytics are being used for demand forecasting to prevent overproduction, a significant source of inventory waste. For example, Nike's acquisition of AI startup Celect improved forecasting accuracy by 85%, minimizing unsold stock and enabling leaner production strategies (Forde, 2019). These advancements demonstrate that AI can substantially enhance material efficiency while supporting circular economy objectives.

Water Conservation through AI in Textile Processing

The textile industry consumes vast amounts of water especially during dyeing and finishing stages which represent 20% of worldwide industrial water pollution. The production of one kilogram of cotton fabric demands 10,000 liters of water and the production of wool uses up to 170,000 liters (Roland Berger, 2024). Artificial intelligence offers an effective approach to water conservation through optimization of water usage while minimizing chemical waste and supporting closed-loop water systems.

AI optimization of dyeing processes stands out as one of the highest impact applications. Advanced dyeing systems utilize both past data and instantaneous environmental conditions including temperature and pH levels alongside fabric characteristics to perfect dye formulas which reduces re-dyeing requirements. Ekoten Tekstil adopted AI-driven quality monitoring systems which enabled early defect detection leading to substantial reductions in both reprocessing requirements and water consumption (Michel, 2025). These systems minimize waste through precise chemical application and avoidance of dye batch overcorrection.

The adoption of AI-enabled smart water management systems is expanding beyond traditional process control applications. The combination of IoT sensors with AI platforms enables real-time water usage tracking along with leak detection and reuse opportunity assessment. Certain systems facilitate water recycling at the location by assessing when water quality standards allow for safe recirculation. AI enables efficient irrigation systems for cotton farming which optimize water usage by analyzing soil and weather conditions to minimize upstream resource consumption (Roland Berger, 2024).

These technologies result in dual benefits: The application of these technologies produces both environmental preservation by decreasing freshwater usage and industrial financial advantages through reduced water expenses and regulatory adherence. AI-driven water management systems form the foundation for developing a circular textile model that treats water as a limited resource which must be reused.

AI-Driven Energy Efficiency in Textile Manufacturing

Energy demands for textile production remain high because spinning, dyeing, drying, and finishing require large amounts of power. Energy inefficiencies lead to increased greenhouse gas emissions as well as higher operational expenses which together expand environmental impact. Manufacturers are leveraging AI technologies more frequently to address energy inefficiencies by tracking and optimizing energy use across their operations at a larger scale.

Real-time monitoring and predictive analytics through AI-based Energy Management Systems such as Schneider Electric's EcoStruxure and Honeywell Forge optimize power loads and operation schedules. These platforms enable factories to recognize operational inefficiencies including idle machines and HVAC overuse as well as outdated equipment. The use of an Energy Management System enabled a manufacturer to both minimize unused lighting during non-working hours and fix a defective HVAC filter which resulted in quantifiable energy usage reductions (AltEnergyMag, 2024).

AI delivers substantial benefits through its implementation of predictive maintenance systems. AI systems can identify initial signs of machine wear or imbalance by continuously processing data from sensors. The system avoids equipment failures and maintains optimal operational performance. Smartex.ai utilizes computer vision together with machine learning technology to observe knitting machines for performance problems and defects which helps in scheduling maintenance and reducing energy waste from faulty equipment (Roland Berger, 2024).

AI optimizes energy-intensive auxiliary systems such as compressed air and steam that frequently lack monitoring. Targeted interventions produce significant cumulative results. The Boston Consulting Group forecasts that industrial energy efficiency powered by AI technology might cut global emissions by 10% before 2030 (AltEnergyMag, 2024). Each percentage of savings in the textile industry results in both cost reductions and sustainability improvements. AI serves as a pivotal element in the creation of manufacturing systems that are both energy-efficient and circular.

AI and Post-Consumer Textile Recycling

Although circular textile systems primarily work towards minimizing production waste reduction, post-consumer textile recycling stands as a crucial field of development. The amount of textiles recycled worldwide stays below 15%, with only less than 1% of these textiles being transformed into new clothing according to NIST (2022). The main challenge in sorting used clothes for recycling comes from their complex mix of different fiber blends, colors, and materials. Through AI and automation technologies textiles undergo a transformation in identification and sorting to achieve a better prepared state for recycling.

Hyperspectral imaging systems together with computer vision technology enable the Fibersort machine to rapidly assess fabric composition with an accuracy rate reaching 95%. The advanced Smart Sorting System from the H&M Foundation together with HKRITA achieves rapid classification of garments by both material type and color in milliseconds while surpassing manual methods in both speed and

precision (HM Foundation, 2024). Refiberd, a U.S.-based startup from 2025 developed technology that prevents 70% of textile waste from reaching landfills through precise detection of blended materials like cotton-elastane which allows for textile-to-textile recycling.

Research is underway for AI-driven robotic disassembly systems that remove non-recyclable components such as zippers and buttons from garments which traditionally needed human labor to accomplish. Artificial intelligence streamlines chemical recycling treatment parameters through material composition assessment to boost yield and minimize environmental impact.

The implications are profound. The deployment of AI-powered systems leads to better recyclable quality and larger quantities which enables textile recycling to reach economic feasibility. These innovations help build domestic recycling capabilities while minimizing textile waste exports and fostering a sustainable circular economy model.

Discussion and Policy Implications

Artificial intelligence implementation within textile manufacturing demonstrates technological advances while also creating major effects for policy development and sustainable industry innovation. Case studies demonstrate AI's ability to provide real environmental and economic advantages through fabric waste reduction of over 40%, water consumption decrease in dyeing processes by up to 95%, and double-digit energy usage optimization. The findings demonstrate that artificial intelligence functions beyond productivity enhancement to become a strategic element in establishing a textile circular economy.

This technological shift supports national sustainability goals in accordance with the energy reduction targets set by the U.S. Department of Energy and EPA's sustainable water use programs. AI creates process-level efficiencies which help national frameworks achieve quantifiable progress that supports both the Paris Agreement commitments and the UN Sustainable Development Goals especially SDG 12 around Responsible Consumption and Production.

However, widespread adoption faces barriers. Many small and medium-sized businesses (SMEs) face a deficit in funds and digital foundations alongside a shortage of skilled employees to effectively deploy AI technologies. The government and industry groups need to overcome these barriers through digital innovation grant expansion as well as technical training programs while also backing AI standardization efforts within manufacturing settings. Effective AI deployment requires both energy-efficient computation and unbiased decision-making to ensure ethical standards and avoid unforeseen negative impacts.

Furthermore, inter-industry collaboration is crucial. The textile industry requires policymakers, fashion brands, tech developers and recycling operators to work together creating interoperable systems and data-sharing protocols to enable AI functionality throughout the textile supply chain. AI systems that operate through stakeholder collaboration can drive the fashion industry to shift from separate sustainability projects toward complete circular practices. The United States will establish its dominance in green innovation while developing a durable textile economy ready for future challenges.

Conclusion

The development of artificial intelligence stands as a fundamental technology driving progress towards a circular economy within the textile industry. AI solutions throughout the value chain minimize waste and improve operational efficiency while establishing closed-loop systems to protect environmental resources. AI-powered tools such as zero-waste design software and cutting optimization platforms used in fabric production have shown material savings of up to 90%, which results in decreased costs and reduced resource consumption. AI-powered dyeing systems combined with water management technologies reached water savings of up to 95% while also achieving substantial chemical discharge reductions during processing. AI-based energy management systems paired with predictive maintenance solutions achieve quantifiable energy savings while reducing emissions to meet worldwide climate objectives.

AI's contribution to textile recycling stands out as the most revolutionary development in the industry. New sorting technologies enable the recovery of previously inaccessible waste materials which facilitates large-scale fiber-to-fiber recycling processes. Through robotic disassembly and AI-driven chemical recycling methods the fashion industry can achieve a state of perpetual garment renewal which will reduce dependency on new raw materials. These advancements represent not just technological successes but vital approaches to achieving national sustainability targets and establishing U.S. dominance in eco-friendly manufacturing innovation.

Despite existing challenges related to adoption expenses and infrastructure needs the progress cannot be denied. Through the integration of AI technologies with policy initiatives and industry partnerships we can create a regenerative textile economy that functions in a circular manner to minimize environmental damage while conserving resources and recovering value continuously.

REFERENCES:

- AltEnergyMag. (2024, September 20). *Implementing AI for energy efficiency in manufacturing*. <https://www.altenergymag.com/>
- Bansal, R. (2023, August 31). *Design Disruption: Crafting a technology that eliminates fabric waste*. Texfash. <https://www.textfash.com/>
- Chao, E. (2023, November 19). *How AI can improve sustainability in fashion*. The Statesman. <https://www.sbstatesman.com/>
- Coats Digital. (2022). *Case study: Duc Hanh Garment JSC – IntelloCut*. <https://www.coatsdigital.com/>
- Energy.gov. (2023). *Smart manufacturing: U.S. Department of Energy programs*. <https://www.energy.gov/>
- Forde, M. (2019, December 9). *Company of the year: Nike*. Supply Chain Dive. <https://www.supplychaindive.com/>
- Fortuny Sicart, A. (2023, February 13). *Circularity in fashion, powered by AI*. ClimateChange.ai. <https://www.climatechange.ai/>
- Global Textile Times. (2023). *AI-driven textile dyeing: Efficiency and sustainability*. <https://www.globaltextiletimes.com/>
- HM Foundation & HKRITA. (2024). *AI-powered smart garment sorting system*. <https://www.hmfoundation.com/>
- Michel, S. (2025, February 17). *AI innovation driving water efficiency in textile manufacturing*. Textile Network. <https://www.textile-network.com/>
- NIST. (2022). *Improving resource efficiency for the textile industry (Workshop report)*. <https://www.nist.gov/>
- Refiberd. (2025). *Intelligent sorting for textile-to-textile recycling*. <https://www.refiberd.com/>
- Roland Berger. (2024). *From waste to worth: Fashion industry report*. <https://www.rolandberger.com/>