Facilitating Sustainability in the Fashion Industry with Machine Learning

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The fashion industry has long been a field that cultivates artistic expression and cultural refinement, but in recent years, it has also become synonymous with overproduction, waste, and environmental degradation. Fast fashion, an industry model that capitalizes on short production cycles and mass-produced, low-cost clothes, has severely intensified these issues. Textile production alone accounts for nearly 10% of global carbon emissions, surpassing emissions from all international flights and maritime shipping combined (Maiti, 2025). However, at the same time, new technologies like machine learning are reshaping the industry by optimizing material selection, refining production processes, and influencing consumer behavior. While these advancements can reduce waste and improve supply chain efficiency, they also present significant ethical concerns, especially regarding the acceleration of consumption through hyper-personalized experiences and real-time trend forecasting.

The central research question of this paper explores whether machine learning actively mitigates unsustainable practices within the fashion industry or inadvertently reinforces them. To investigate this, I employ the analytical framework of technological momentum, which states that new technological systems must first align with society's goals and contexts before they can be accepted and eventually embedded in social structures (Molella, 2005). The outline of this paper will begin by establishing the background and significance of sustainability challenges within the fashion industry, followed by an explanation of how machine learning is being used to address these challenges. Subsequently, the methodology will delve into examining machine learning applications through technological momentum, supported by qualitative and quantitative analyses. The literature review will then examine relevant studies and insights from scholars and professionals, and finally, I will analyze the positive applications, risks, and adoption challenges

of machine learning technologies in promoting sustainability, employing the technological momentum framework again. Ultimately, I argue that the extent to which machine learning fosters sustainability is largely dependent on its guiding development—whether for sustainability or profit-driven mass production.

Background and Significance

The fashion industry generated over $1.7 trillion in revenue in 2023 according to researchers at ASU, proving its vast socio-economic influence (Dhiwar, 2024). This was a 13.7% year-over-year economic growth rate, demonstrating the ever-growing presence and influence on not just the industry but the global economy as a whole. However, this does not come without mention of its role in resource consumption, waste generation, and environmental degradation. There is a massive reliance on petroleum-based textiles, excessive water usage, and carbon emissions, which all play a major role in its eco-harmful nature. A study released by the European Parliament found that 20% of the world's water pollution was due to textile production alone. To make a single cotton t-shirt, it is estimated that 2,700 liters of fresh water are required over the entire process, enough to meet one person's drinking needs for over two years. This is not even to mention the washing process that people perform over the lifetime of their clothes. Additionally, fast fashion has exacerbated this problem—accelerating production cycles and creating a culture of disposing of textiles after minimal wear. Global textile production has more than doubled since 2000, with predictions of 145 million tons of items produced per year by 2030 (European Parliament, 2020). Business models that aim to fix this through methods like clothing rental, circular fashion (designing clothes in a manner that would make recycling easier), or slow fashion (encouraging consumers to buy clothes of better quality that last longer)

are limited to expensive, high-end brands. Most of these synthetic fabrics are made from fossil fuels, which contribute to plastic pollution in the ocean. Many of these materials take hundreds of years to break down in landfills, with recycling systems simply not being efficient enough to keep up.

Even further, fast fashion leads to serious ethical concerns regarding the actual production processes. To keep up with demand, many companies rely on factories where workers are paid poorly and work in extremely unsafe conditions. Nowadays, in the apparel industry, it's common to take production to developing countries like Bangladesh, India, and China to take advantage of cheap labor and fewer regulations (GWU Law, 2021). Companies like H&M now feature 52 "micro-seasons" annually—one per week—sacrificing quality for quantity. Going along with this, the rapid trend cycle known as "micro-trending" only exacerbates this issue, encouraging fast fashion companies to engage in these unethical production practices by seeking frequent, short-lived trends that thrive off copying other designs (GWU Law, 2021). Much of this mirrors the growing threat of social media's impact on attention spans and dopamine demands, with apps like TikTok and Instagram encouraging a culture of short, but frequent spikes of entertainment (Nussenbaum, 2023). In the instance of fashion, this means people perceive more reward when they frequently obtain more clothes that are quick to impress and can be discarded without much loss before moving on to the next trend.

However, machine learning might have the potential to ameliorate this unsustainable situation. By utilizing basic algorithms that now don't even use that much processing power, we can improve supply chains, reduce overproduction, and help companies make more informed decisions about materials and production processes. Predictive technology can also help brands produce only what will sell, reducing waste. According to Csanàk (2020), artificial intelligence is

already fundamentally changing the fashion industry by enhancing efficiency across various areas like trend forecasting, item production, and consumer experience. He describes tools such as virtual style assistants, retail inventory management, and personalized sizing solutions; and one specific example, the Nike Fit app, uses AI for precise foot measurements, which was responsible for a massive improvement in the customer shopping experience.

One of the most notable advancements in machine learning is material selection and supply chain optimization. AI-driven systems can predict the most sustainable materials to use in production based on things like durability, recyclability, and environmental impact (Therala, 2024). Brands are increasingly incorporating generative AI models that design textiles with reduced waste in mind, including 3D-printed fabrics and biodegradable alternatives. One such example is Generative Adversarial Networks (GANs)—algorithms that can create highly realistic digital samples—which consist of two neural networks that work together to refine their quality through an adversarial process. These types of technologies decrease the need for physical prototypes, saving fabric and energy during manufacturing. Additionally, machine learning has the potential to optimize supply chain operations, inventory management, demand forecasting, order fulfillment, and more (Arora et al., 2023). This can inherently enhance overall efficiency, reduce costs, and lead to greater consumer transparency and satisfaction.

Unfortunately, machine learning also has the potential to worsen the issue. Though exciting and useful in theory, these algorithms that create highly personalized shopping experiences can end up encouraging people to buy more than they otherwise would, and the cycle of overconsumption increases (Bhardwaj & Fairhurst, 2010). By leveraging large-scale data analytics and mining to pinpoint individual consumer preferences, targeted recommendations and advertisements are enticing to retailers as they have been proven to

increase customer loyalty and contribute to brand growth (Aqrabawi, et al., 2024). Furthermore, AI-driven marketing strategies not only increase overall consumption but also accelerate product turnover, as consumer demands shift rapidly to follow algorithmically identified trends and recommendations (Ademtsu et al., 2023). These fleeting, rapid trend cycles contribute to short-lived products and excessive waste generation from the consumer and manufacturing standpoint.

Beyond sustainability, some people fear that automating the creative process might interfere with fashion's intrinsic cultural and artistic value, as machine-generated designs might lack human creativity and authenticity. As Debbie McKeegan (the CEO of TexIntel, an established textile manufacturing company) puts it, this digital transformation offers a bridge "between tradition and innovation in the fashion industry," and it is important to stress these tools' purpose as a way to enhance design curation, not replace it (2025).

Consequently, this creates a difficult paradox where, on one hand, machine learning can help sustainability efforts, but on the other, it can be used to drive excessive consumption and blur the line between automation and art if not implemented responsibly. Exploring this tradeoff is crucial to understanding responsible innovation in digital design, and it is essential to be mindful of how each level of production, starting at design, impacts sustainability and cultural value.

Methodology

In an attempt to investigate this problem, several techniques will be employed to examine the role of machine learning in promoting sustainability. One such technique is the analytical framework known as technological momentum, which will be key to discovering the relationship between technology and society over time. Developed by Thomas P. Hughes, this framework

posits that technology evolves from being initially very flexible and subject to societal influence to increasingly rigid and resistant to change (Bakker, 2018). Thus, it can allow us to analyze how machine learning applications in the fashion industry can go from just concepts to industry norms. Technological momentum can also help us understand the fashion industry's sustainability problems since this overproduction of textiles is a relatively new problem, especially with the recent rise of digitally available fast fashion. This is in accordance with the ever-growing presence of intelligent algorithms that influence material choices and production processes and track consumer behavior, creating hyper-personalized experiences that encourage an increased demand.

On top of this, the concept of technological momentum can help settle the debate between two widely used competing frameworks—technological determinism and the social construction of technology (SCOT)—which offer different perspectives on the relationship between society and technological innovation. Technological determinism argues that technology drives societal behavior, with things like online shopping, algorithmic predictions, and user-specific advertising leading to more consumption than eras without technology (Wyatt, 2008). Social media also allows trends to spread and change more rapidly than ever before. Under this deterministic view, AI and machine learning might be seen as the primary forces of industry change, rather than the response to consumer demand. On the other hand, SCOT proposes that society shapes technology (Bijker et al., 1987). In this sense, there is a general lack of consensus as to what sustainability in the fashion industry looks like, with vast consumer behavior gaps and a low demand for sustainable products, which complicates its implementation. Using this framework, one might argue that our societal values will shape the development of sustainable fashion technology. Ultimately, by framing this research around technological

momentum—a perspective that combines both frameworks—I aim to better understand how AI-driven sustainability measures can become adopted in the industry, or conversely, how these innovations may reinforce existing unsustainable behaviors.

In addition, both qualitative and quantitative data will be utilized to investigate these issues. Case studies from brands currently using machine learning to enhance sustainability will be analyzed to determine the current, existing impact of these technologies. I include both high-end and fast fashion brands to capture a broad perspective, namely the Nike Fit AI-powered sizing tool, H&M's supply chain management AI integrations (AI Expert Network, 2023), and Stella McCartney's use of AI in sustainable material selection (Peres et al. 2020). Using cases like these, we can analyze whether there is an actual meaningful gain in AI applications to promote sustainability, or if they are merely being used to promote existing consumption patterns.

To complement these case studies, surveys and interview data will be analyzed to gauge perceptions of machine learning's impact on sustainability and its effectiveness. Industry professionals, including fashion designers, supply chain managers, and sustainability experts are one subset that will provide concrete evidence of the success or failure of AI-related integrations, as well as first-hand opinions. In addition, surveys and interviews performed on the consumer group as a whole can help determine how personalized shopping experiences influence purchasing behavior and evaluate how these are being perceived.

Literature reviews are another avenue of research that I will explore, mainly in the form of academic papers, industry reports, and articles. I focus on sources that explore AI's impact on supply chain efficiency and waste reduction, as well as the ethical side of AI-driven marketing and consumer targeting. I also look at the bigger picture: how fast fashion and online shopping

shape socio-environmental issues, and how predictive analytics in trend forecasting can either help curb overproduction or make it worse. Then, by using literature to also explore frameworks such as technological determinism and SCOT, I compare how different perspectives interpret machine learning's role in sustainability.

Literature Review

In an article written by two California-based researchers, Gupta and Dubey (2024) highlight several massive roadblocks the fashion industry faces in achieving sustainability, namely automated textile sorting and fabric traceability. They emphasize that even though the textile industry puts out billions of garments annually, recycling rates still sit below 1%, largely because the sorting of textiles by fiber type remains manual, costly, and error prone. They aim to tackle this problem by leveraging Convolutional Neural Networks (CNNs) trained on microscopic images of different fabrics, achieving an accuracy of around 90%. Their study is an important example of a case that proves relatively inexpensive hardware paired with advanced machine learning methods like CNNs can, in fact, reliably classify fabric types at scale—something current manual methods struggle to accomplish accurately and efficiently.

Their second major contribution addresses fabric traceability, proposing a method using UV markers read by object detection models. Gupta and Dubey demonstrate that this method achieves a high detection accuracy (93% to 98%), even after multiple wash cycles and common fabric challenges like creasing and fading. They even suggest integrating this into broader applications, like using blockchain technology to track information about textiles throughout their lifecycle, which would better enable stakeholders—from manufacturers to disposal services—to enforce circular economy initiatives. Connecting this back to my research, Gupta

and Dubey's findings provide compelling evidence supporting the role of AI-driven technology in scaling sustainable fashion practices. Their use of deep learning not only advances traceability but also paves the way for reducing textile waste, aligning closely with circular economy models. However, their focus on technology-driven solutions also raises further questions about consumer behavior and policy implementation, as these technologies do have the potential to influence habits, industry adoption, and environmental policies.

Another interesting piece of literature I came across during my research was an article written by Kachbal et al. (2024) which investigates "recommender" systems using deep learning, essentially aiming to enhance personalized fashion recommendations. Their research introduces two primary recommendation approaches: "context-aware" recommendations, which consider factors like climate and occasion, and "outfit-based" recommendations, which suggest coordinated, multi-item outfits rather than individual textiles. With these machine learning systems, they can more deeply understand consumer preferences, body types, and lifestyle factors, significantly improving the likelihood of satisfactory recommendations. Furthermore, Kachbal highlights how these recommendation systems can influence people to make more sustainable fashion choices overall by integrating ethical parameters like organic cotton content and carbon footprint into the recommendation criteria. In this sense, this reinforces how technology can actively shape consumer behaviors and promote sustainability within the fashion ecosystem.

I then explored a European study done by the Doctoral School of Security Sciences, which, according to Edit Csanák (2020), discusses how fashion, inherently forward-looking, has quickly integrated AI to analyze trends, anticipate consumer demands, and streamline various operations. This rapid digital integration, part of the industry's broader shift toward Industry 4.0

and 5.0, highlights a growing dependency on advanced technology. Yet, despite AI's clear advantages, such as trend prediction, customization, and waste reduction, it also poses several challenges, one such being the aforementioned paradox that emerges from AI's use: while it provides the potential to reduce environmental impact through sustainable fabric choices and zero-waste design processes, unchecked application can unintentionally promote faster production cycles, thus exacerbating issues related to fast fashion. Csanák further suggests that AI-driven design, despite its efficiency, often lacks the deep aesthetic and cultural sensitivity inherent in human-driven creativity, raising questions about the future of design authenticity. This stresses the importance of using AI not as a replacement for human creativity, but as a tool to enhance and support sustainable and innovative practices within fashion design.

Finally, a recent study published in the Proceedings on Engineering Sciences investigates the transformative role of machine learning (ML) in promoting sustainable innovation within the apparel industry. Ujjawal et al. (2024) state that ML technologies significantly contribute to sustainability by enabling apparel companies to source eco-friendly materials, reduce waste, enhance energy efficiency, and increase transparency throughout the supply chain. They emphasize how data-driven insights gained through ML facilitate more informed and environmentally conscious decision-making in apparel design and production. Furthermore, their survey results highlight the critical role of eco-literacy (understanding ecological concepts and their environmental consequences) in influencing the successful adoption of ML-based sustainable practices among designers. The researchers also emphasize the "Theory of Planned Behavior" (TPB) to explain how attitudes, subjective norms, and perceived behavioral control shape designers' intentions towards adopting sustainable practices facilitated by ML. Additionally, Ujjawal et al. call for increased collaboration among businesses, governments, and

consumers to enhance the implementation and acceptance of sustainable innovations. Overall, their findings provide concrete evidence stressing ML's positive impact on advancing sustainable practices within the apparel industry.

Positive Applications

The research done in this paper leads me to conclude that machine learning does play a positive role in promoting a more sustainable atmosphere within the fashion industry. As stated previously, the analytical framework of technological momentum emphasizes that technology is initially flexible and easily shaped by societal influences but eventually becomes more rigid as it becomes ingrained in our social structures (Bakker, 2018). In the context of fashion sustainability, machine learning is currently in the more "flexible" stage. Each article examined above provides concrete evidence of companies that are actively shaping these technologies to align with societal goals like environmental consciousness and sustainable consumer practices. One specific example includes H&M's supply chain management AI integration, a popular apparel company that partnered with Google to create a centralized data management platform with machine learning capabilities (AI Expert Network, 2023). Google and H&M demonstrate quickly adapting to societal demands for more efficient process flow, with the new platform having been shown to help in predictive analysis for fashion trends and informing retailers of the most effective buying strategy, contributing to waste reduction and more sustainable decisions from retailers. Reporting via H&M suggests that AI has positively impacted both the company's supply chain efficiency and the customer's experience, as well as promoted the general awareness of sustainable consumption.

Similarly, Stella McCartney's luxury clothing brand has greatly evolved in response to consumer outcry for transparency and accountability in sustainability. Since 2012, McCartney's company has utilized the Environmental Profit and Loss (EP&L) tool, which measures the environmental impacts throughout its entire supply chain, from raw materials to the final selling stage. This innovative approach assesses six critical areas: greenhouse gas emissions, water use, water pollution, land use, air pollution, and waste. The insights provided by EP&L allowed Stella McCartney to identify specific high-impact areas, such as the significant environmental burden of its cashmere products. Consequently, the brand shifted to using re-engineered cashmere yarn, which reduced its environmental impact from 42% to 11% within two years. Moreover, like H&M, Stella McCartney partnered with Google in 2019, allowing for Google Cloud data collection and machine learning analyses of the supply chain processes.

Sarah Thompson, Nike's Head of Sustainable Design, also talks about AI's dual benefits: "AI is not just accelerating the design process—it's helping us make better, more sustainable choices from the very beginning." She states that Nike's AI systems rapidly assess hundreds of material combinations and their environmental impacts within minutes, tasks that would otherwise take designers weeks or even months. Largely thanks to the implementation of AI in product design, Nike has successfully reduced the carbon footprint of its latest product lines by 30% (Sahm Capital, 2025). This rapid integration of AI-driven design principles, largely prompted by societal pressures for sustainability, highlights how technological systems can mold to society's demands. Companies such as these not only reduce their carbon footprint by using these technological solutions, but they also set an important precedent for others—normalizing the use of more advanced techniques to cut down on environmental harm within the fashion industry.

Risks and Limitations

Although AI has this unique potential to drive impactful change in improving the environment, it should also be noted that AI and machine learning cannot be relied upon solely in making big decisions surrounding these initiatives. Humans are, ultimately, at the core of every decision AI is programmed to make, shaping AI behaviors and inherently determining the consequences of their deployment. Technological momentum warns that as these AI-driven systems solidify into industry practices, their flexibility weakens, becoming increasingly resistant to change. AI-powered personalization tools, for example, offer hyper-customized shopping experiences designed to enhance consumer satisfaction and engagement. However, these systems inadvertently risk promoting overconsumption, as consumers are continually exposed to precisely targeted recommendations encouraging frequent purchases. Such overconsumption may then become ingrained in fashion's culture, ultimately reinforcing the pattern rather than mitigating it.

Going along with this, the cost of training these advanced AI models is not free. While digital prototyping and generative design techniques positively accelerate innovation, their complex underlying computational processes are often extremely environmentally costly. Training large-scale machine learning models, like Google's Gemini, for example, requires significant financial investment and energy consumption, with training alone costing between $30 million to $191 million according to Forbes (Buchholz, 2024). And, once companies have begun using these technologies, it becomes increasingly difficult to shift away from them without having to significantly restructure operations or risk financial loss. Thus, designers and

engineers must be aware of this tradeoff and make a conscious effort to balance the allure of innovative capabilities with a more responsible use of resources.

Lastly, biases unintentionally built into AI algorithms through their training data can end up supporting these unsustainable behaviors. For example, if training data disproportionately includes popular yet environmentally harmful products like fast fashion items, algorithms might unintentionally amplify these trends by recommending them more frequently, which not only encourages increased consumption but also moves us further away from our sustainability goals. To prevent this, we must regularly evaluate and correct algorithmic biases, keeping human judgment involved to ensure AI recommendations stay aligned with sustainable objectives. By technological momentum, a point will come where technology dictates practices rather than society dictating how technology develops. And, at this point, society's ability to easily correct the negative environmental outcomes will be meager at best.

Industry Outlook and Adoption Challenges

Looking forward, technological momentum can help point out the main AI-related adoption challenges the fashion industry faces. In analyzing the attitudes of consumers and the fashion industry during this early, flexible stage, a survey conducted by the consulting firm McKinsey & Company (2022) found that "67 percent [of respondents] consider the use of sustainable materials to be an important purchasing factor, and 63 percent consider a brand's promotion of sustainability in the same way." The conversation around sustainability is increasing, but not quite as rapidly as its environmental demand. By embracing the idea of sustainability and encouraging brands to promote it with direct incentives to their business model, the industry can better align with consumer expectations while simultaneously improving

the environment. In a 2022 McKinsey Global Survey on AI, 43% of surveyed companies that have adopted AI were actively using the technology to optimize sustainability efforts, and 40% were working to reduce the environmental impact of their AI use (McKinsey & Company, 2022). One significant application of AI in a variety of industries, along with fashion, is in demand forecasting, where it analyzes vast datasets to predict consumer preferences accurately. This precision allows brands to align production closely with actual demand, thereby reducing overproduction. Notably, H&M's Sustainability Director Sarah Chen states that AI-driven demand forecasting has led to a 20-30% reduction in overproduction, directly addressing the issue of waste in the fashion sector (Sahm Capital, 2025).

Furthermore, AI's integration into supply chain management has yielded substantial benefits, with McKinsey & Company reporting that fashion brands leveraging AI for supply chain management have achieved a 15% improvement in inventory efficiency and a 10% reduction in carbon emissions (Alicke et al., 2021). These improvements not only enhance operational efficiency but also contribute to environmental sustainability by minimizing unnecessary production and associated emissions. Despite these advancements, there remain gaps in the widespread implementation of AI-driven sustainability initiatives. Challenges persist, hindering some companies from adopting these technologies, such as high initial investment costs, technological integration complexities, and a shortage of skilled personnel. Addressing these issues is crucial for broader industry adoption and maximizing the potential of AI to drive sustainable practices (Balchandani et al., 2024). Likewise, encouraging more widespread standards, government policies, and transparent consumer interaction will ensure that as these technologies gain momentum, they promote sustainable practices.

Conclusion

The research presented in this paper highlights the complex yet promising potential of machine learning to address sustainability challenges within the fashion industry. Throughout this paper, I have discovered evidence proving machine learning's ability to enhance supply chain management, optimize material selection, and significantly reduce waste through precise and intelligent demand forecasting. Concrete examples from industry leaders such as H&M, Stella McCartney, and Nike emphasize the genuine benefits that AI-driven technologies can offer, demonstrating their ability to create meaningful, lasting improvements in environmental well-being and consumer transparency.

However, while there is significant promise of machine learning driving sustainability, the integration of these advanced technologies is not without considerable challenges. Hyper-personalized AI algorithms, for one, although beneficial for enhancing consumer experience and operational efficiency, often inadvertently fuel overconsumption by encouraging frequent and unnecessary purchases. This, although unintentional, undermines sustainability goals by prolonging fast fashion consumption cycles. Additionally, the substantial energy consumption and financial investments involved in training advanced machine learning models present another layer of ethical and environmental concerns. Compounding these challenges are biases that can be unintentionally embedded in AI systems through their training datasets, which can potentially amplify unsustainable consumer behaviors by disproportionately promoting environmentally harmful products.

Looking ahead, there is still a lot to be explored in the realm of fashion, technology, and sustainability. Future work should focus on developing clear guidelines for responsibly using machine learning in fashion, ensuring these advanced tools do not inadvertently perpetuate

harmful practices. Collaborations among designers, tech developers, environmental experts, and policymakers are vital to building frameworks that standardize sustainable practices within the industry. Moreover, it could be extremely constructive to investigate methods for reducing the environmental footprint of these AI training processes themselves, ensuring that innovation never comes at the expense of environmental obligations.

Ultimately, the effectiveness of machine learning in fashion sustainability hinges on intentional use and thoughtful oversight. We must continuously evaluate and refine these technologies, being intentional by actively working to correct biases and ensure alignment with our broader environmental values. With careful, collaborative efforts, machine learning and artificial intelligence can truly become a meaningful force for sustainable change, helping the fashion industry balance innovation with positive, long-term ecological responsibility.

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