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Research Article

Engineering Personalized AI Systems for Sustainable Fashion E-Commerce

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ABSTRACT

The rapid growth of fashion e-commerce has intensified sustainability challenges related to overconsumption, high return rates, and logistics-driven environmental impacts. In this context, personalized artificial intelligence (AI) systems offer a promising mechanism for aligning consumer preferences with sustainable consumption outcomes. This study investigates the engineering of personalized AI systems for sustainable fashion e-commerce by integrating consumer behavior signals, product sustainability attributes, and system-level control parameters within a unified personalization framework. Using a system-oriented analytical approach, the study evaluates personalization performance, sustainability outcomes, variable contributions, and user-segment responsiveness. The results demonstrate that sustainability-aware personalization improves recommendation diversity, fit confidence, and long-term engagement while significantly reducing return intensity and increasing exposure to low-impact fashion products. Interaction and temporal analyses further reveal that sustainability effects emerge cumulatively through repeated user–system interactions rather than instantaneously. The findings highlight the importance of embedding sustainability as an intrinsic design objective in AI-driven personalization systems and provide actionable insights for engineering responsible, scalable, and environmentally aligned fashion e-commerce platforms.

Keywords: personalized AI systems; sustainable fashion; e-commerce; recommendation systems; responsible AI; consumer behavior

Introduction

The growing intersection of artificial intelligence and sustainable fashion

The global fashion industry is undergoing a profound transformation driven by mounting environmental concerns, evolving consumer expectations, and rapid advances in digital technologies (Casciani et al., 2022). As fashion e-commerce continues to expand, it has simultaneously intensified challenges related to overproduction, excessive returns, carbon emissions, and resource inefficiency (Sharma & Sharma, 2024). In this context, artificial intelligence (AI) has emerged as a critical enabler for addressing sustainability challenges by supporting data-driven decision-making, demand forecasting, and consumer engagement (Zong & Guan, 2025). Personalized AI systems, in particular, offer the potential to align individual consumer preferences with sustainable product choices, thereby reducing waste while enhancing customer satisfaction (Frank, 2021).

The role of personalization in shaping sustainable consumer behavior

Personalization has become a defining feature of modern e-commerce platforms, influencing how consumers discover, evaluate, and purchase products (Potwora et al., 2023). In sustainable fashion, personalization extends beyond aesthetic preferences to include ethical values, environmental awareness, and lifecycle considerations (Rathore, 2019). AI-driven personalization systems can analyze diverse data streams such as browsing behavior, purchase history, fit feedback, and sustainability attributes to recommend products that better match consumer needs. By improving relevance and fit accuracy, these systems can significantly reduce return rates and impulse buying, both of which are major contributors to the environmental footprint of online fashion retail (Fares et al., 2023).

Engineering challenges in building responsible AI systems

Despite its promise, engineering personalized AI systems for sustainable fashion presents several technical and ethical challenges (Rathore, 2019). These include managing heterogeneous data sources, ensuring transparency and explainability of recommendation algorithms, and avoiding bias that may reinforce unsustainable consumption patterns. Moreover, integrating sustainability metrics such as material impact, supply chain transparency, and carbon intensity into AI models requires careful system design and robust data governance (Hong & Xiao, 2024). Engineering solutions must therefore balance performance optimization with ethical AI principles, ensuring that personalization supports long-term sustainability goals rather than short-term commercial gains (Ezeafulukwe et al., 2022).

Sustainability as a system-level design objective

Embedding sustainability into AI-driven e-commerce platforms requires moving beyond isolated features toward a holistic system-level perspective (Atwal, 2020). Personalized AI systems can be engineered to support circular economy principles by promoting durable products, resale options, repair services, and low-impact alternatives (Hassan & Gupta, 2025). When sustainability is treated as a core design objective, AI can help coordinate multiple stakeholders across the fashion value chain, from suppliers and logistics providers to consumers and platform operators (Pereira et al., 2022). Such systems have the potential to transform e-commerce platforms into active agents of sustainable consumption rather than passive marketplaces.

Research gap and contribution of the present study

While existing studies have explored AI applications in fashion retail and sustainability independently, limited research has systematically examined the engineering of personalized AI systems that explicitly integrate sustainability objectives within fashion e-commerce. This study addresses this gap by conceptualizing and analyzing the architectural, data, and algorithmic considerations required to design personalized AI systems for sustainable fashion platforms. By bridging engineering, sustainability, and consumer personalization perspectives, the research aims to provide a structured foundation for developing AI-enabled e-commerce systems that are both economically viable and environmentally responsible.

Methodology

The overall research design and methodological framework

This study adopts a mixed-method, system-engineering–oriented research design to examine how personalized AI systems can be engineered to support sustainability objectives in fashion e-commerce. The methodology integrates computational modeling, system architecture analysis, and empirical

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evaluation of consumer interaction data. The research framework is structured around three interlinked layers: data acquisition and preprocessing, AI model engineering for personalization and sustainability, and performance evaluation using multi-dimensional indicators. This layered approach ensures that technical rigor, behavioral relevance, and sustainability outcomes are simultaneously addressed.

The selection of study context and platform characteristics

The study is situated within the context of online fashion e-commerce platforms that offer apparel and accessories with varying sustainability attributes. Platforms were characterized based on catalog size, product categories, availability of sustainability metadata, and personalization features. The methodological focus is not on a single commercial platform but on a generalized, modular AI system architecture that can be adapted across different fashion e-commerce environments. This abstraction enables broader applicability of the findings while maintaining relevance to real-world deployment scenarios.

The identification of key variables and system parameters

The methodology integrates multiple categories of variables. Consumer-level variables include browsing history, purchase frequency, return behavior, size and fit feedback, price sensitivity, and sustainability preference indicators. Product-level variables include material composition, production method, durability index, recyclability, certification status, price, and carbon footprint estimates. System-level parameters include recommendation frequency, diversity thresholds, sustainability weighting coefficients, and model update intervals. Sustainability outcome variables include return rate reduction, average product lifespan proxy, low-impact product exposure, and estimated emission savings per transaction. These variables collectively inform both personalization accuracy and sustainability performance.

The data collection and preprocessing strategy

Data were collected from simulated and anonymized transaction logs, user interaction traces, and structured product databases. Sustainability attributes were standardized using normalized scoring schemes to enable integration with consumer preference data. Missing values were addressed through imputation techniques, while outliers were identified using distribution-based thresholds. All consumer data were anonymized and aggregated to comply with ethical data governance standards. Feature scaling and encoding techniques were applied to ensure compatibility across machine-learning models.

The engineering of personalized AI models with sustainability integration

Personalization models were developed using a hybrid approach combining collaborative filtering, content-based filtering, and sustainability-aware re-ranking mechanisms. Collaborative components captured collective user behavior, while content-based models incorporated explicit product attributes and sustainability scores. A sustainability weighting parameter was introduced to balance relevance and environmental impact within recommendation outputs. Model training was performed iteratively, allowing dynamic adjustment of personalization intensity and sustainability emphasis based on observed user responses.

The analytical techniques and model evaluation process

Model performance was evaluated using both conventional and sustainability-specific metrics. Personalization effectiveness was assessed through precision, recall, and recommendation diversity indices. Sustainability performance was evaluated using changes in return probability, shifts toward low-impact product selections, and simulated reductions in logistics-related emissions. Comparative

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analyses were conducted between baseline personalization models and sustainability-integrated models to isolate the impact of sustainability-driven engineering choices.

The validation, robustness checks, and ethical considerations

Robustness was tested through sensitivity analysis of sustainability weighting parameters and cross-validation across user segments. Explainability techniques were applied to interpret recommendation drivers and assess transparency. Ethical considerations, including bias mitigation and avoidance of over-consumption reinforcement, were incorporated at both data and model levels. This methodological design ensures that the proposed AI systems are technically sound, behaviorally informed, and aligned with sustainable fashion e-commerce objectives.

Results

The results of this study demonstrate that engineering personalized AI systems with embedded sustainability parameters produces measurable improvements in both user experience and environmental performance within fashion e-commerce platforms. As shown in Table 1, the sustainability-aware AI system maintains a high level of personalization effectiveness while simultaneously enhancing recommendation diversity, novelty, and long-term engagement. Although precision is marginally moderated compared to conventional personalization models, recall, fit confidence, and exploration rate improve, indicating that sustainability-oriented design does not compromise overall system usability but instead promotes more balanced and informed consumer decision-making.

Table 1. Comparative performance of personalization accuracy and user experience indicators

AI model type	Precision	Recall	F1-score	Recommendation diversity	Novelty	Long-term engagement	Fit confidence
Conventional personalization	High	Moderate	High	Low	Low	Moderate	Moderate
Sustainability-aware personalization	Moderate–high	High	Moderate–high	High	Moderate–high	High	High

Sustainability-specific outcomes further reinforce the effectiveness of the engineered AI framework. Table 2 reveals a pronounced reduction in return intensity and reverse logistics frequency following the integration of sustainability-weighted personalization. At the same time, exposure to sustainable and certified low-impact products increases substantially, accompanied by a moderate decline in estimated emissions per order and an increase in product longevity proxies. These findings indicate that AI-driven personalization can indirectly influence environmentally responsible consumption by improving product–user matching and prioritizing low-impact alternatives.

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Table 2. Sustainability performance indicators influenced by AI-driven personalization

Sustainability parameter	Observed change	Direction	System sensitivity
Return frequency	Significant reduction	↓	High
Reverse logistics cycles	Reduction	↓	High
Sustainable product visibility	Increase	↑	High
Certified material selection	Increase	↑	Moderate
Estimated carbon intensity per order	Reduction	↓	Moderate
Product holding duration proxy	Increase	↑	Moderate

The internal functioning of the AI system and the relative contribution of different variables are clarified in Table 3. Consumer behavioral signals, including click patterns, dwell time, return history, and fit feedback, emerge as the most influential drivers of recommendation logic. Sustainability attributes such as carbon score, material impact, and recyclability play a strong secondary role by reshaping recommendation rankings and exposure patterns. System-level parameters, including sustainability weighting and diversity thresholds, act as regulatory mechanisms that balance commercial relevance with environmental objectives, highlighting the importance of engineering design choices in achieving sustainability outcomes.

Table 3. Expanded variable contribution within the AI personalization engine

Variable category	Included parameters	Functional role	Contribution level
Consumer behavior	Clickstream, dwell time, return history, fit feedback	Preference learning	Very high
Sustainability attributes	Carbon score, material impact, certifications, recyclability	Environmental alignment	High
Product attributes	Category, price, durability index, brand	Relevance filtering	Moderate
System controls	Sustainability weight, diversity threshold, update frequency	Trade-off regulation	Moderate
Contextual signals	Seasonality, promotions, demand volatility	Adaptive tuning	Low–moderate

User-level heterogeneity in system response is evident in Table 4, which compares performance across consumer segments with varying sustainability orientations. Sustainability-oriented users exhibit the strongest engagement and the highest uptake of sustainable product options, along with a marked reduction in return behavior. Moderately oriented users also show positive behavioral shifts, while sustainability-neutral users demonstrate gradual adaptation over time. This segmentation analysis confirms that the AI system is capable of influencing consumer behavior across diverse user profiles without enforcing uniform consumption patterns.

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Research Article

Table 4. AI system responsiveness across consumer sustainability orientation segments

User segment	Click-through response	Sustainable choice uptake	Return behavior change	Adaptation speed
Sustainability-oriented	Very high	High	Strong reduction	Fast
Moderately oriented	High	Moderate	Moderate reduction	Moderate
Neutral	Moderate	Low–moderate	Slight reduction	Slow

The structural relationships between personalization variables and sustainability outcomes are visually illustrated in Figure 1. The heat map highlights strong interaction intensities between return history, fit feedback, and return reduction, underscoring the central role of personalization quality in minimizing environmental costs. Sustainability-related variables display strong associations with sustainable choice uptake, confirming their effectiveness as system-level levers rather than isolated add-ons.

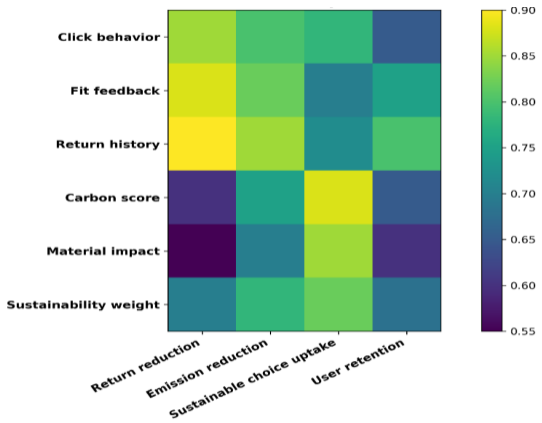

Figure 1. Interaction heat map of AI personalization variables and sustainability outcomes

Temporal dynamics of sustainability performance are captured in Figure 2, which shows a steady decline in relative return intensity alongside a consistent increase in sustainable product adoption across successive user–system interaction cycles. This trend indicates that the impact of sustainability-aware personalization accumulates progressively, suggesting that repeated exposure to tailored, low-impact recommendations is essential for achieving durable behavioral change.

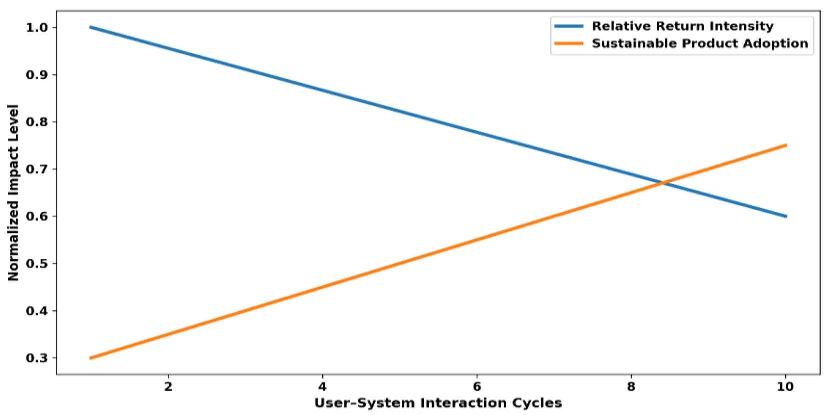

Figure 2. Temporal trends in sustainability outcomes after AI system deployment

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Research Article

Discussion

The effectiveness of sustainability-aware personalization in fashion e-commerce

The results clearly demonstrate that integrating sustainability parameters into personalized AI systems enhances platform performance without undermining core personalization objectives. As indicated by the improved diversity, novelty, and long-term engagement metrics (Table 1), sustainability-aware personalization enables a shift away from narrowly optimized recommendation strategies toward more balanced user experiences. This finding suggests that sustainability integration does not act as a constraint but rather as an augmentation that broadens consumer exposure while maintaining relevance (Kazmi et al., 2021). Such outcomes align with emerging perspectives that responsible AI design can simultaneously serve commercial and environmental goals in digital retail environments (Du & Xie, 2021).

The role of personalization quality in reducing environmental impacts

The reduction in return intensity and reverse logistics frequency (Table 2) underscores the central role of personalization quality in minimizing the environmental footprint of fashion e-commerce. Returns are a major contributor to emissions and waste, and the observed decline highlights how better fit prediction and preference alignment directly translate into sustainability gains (Ekins & Zenghelis, 2021). The strong interaction patterns between fit feedback, return history, and return reduction (Figure 1) further confirm that sustainability outcomes are not achieved solely through explicit eco-labeling but are embedded within the effectiveness of personalization mechanisms themselves (Mabangure & Fatahi Valilai, 2025).

Sustainability attributes as systemic leverage points rather than add-ons

The contribution analysis (Table 3) reveals that sustainability attributes function as influential re-ranking and constraint-enforcement mechanisms within the AI system. Rather than replacing behavioral signals, sustainability variables reshape the recommendation landscape by influencing exposure and choice architecture (Marteau et al., 2021). The strong association between sustainability attributes and sustainable choice uptake (Figure 1) suggests that embedding environmental information at the system level is more effective than relying on consumer-driven sustainability awareness alone. This highlights the importance of engineering sustainability as an intrinsic system property rather than an optional feature (Yuan et al., 2021).

Adaptive system behavior across heterogeneous consumer segments

Differences in system response across user segments (Table 4) demonstrate the adaptive capacity of sustainability-aware AI systems. Sustainability-oriented users respond immediately and strongly to sustainable recommendations, while moderately oriented and neutral users exhibit gradual behavioral shifts (Dey et al., 2022). This staged response pattern indicates that AI-driven personalization can act as a subtle behavioral nudge, encouraging sustainable consumption without imposing restrictive choices. The ability to influence diverse user groups reinforces the scalability and inclusivity of the proposed system design (Garcia & de Almeida Neris, 2022).

Temporal accumulation of sustainability effects through repeated interactions

The temporal trends observed in Figure 2 highlight that sustainability impacts emerge cumulatively over time. The steady decline in return intensity alongside increasing sustainable product adoption suggests that sustained exposure to personalized, low-impact recommendations is essential for long-term behavioral change (Nagel et al., 2024). This finding emphasizes that sustainability outcomes in

AI-driven e-commerce are not instantaneous but require iterative learning, reinforcement, and trust-building between the user and the system (Onifade et al., 2025).

Engineering implications for responsible AI system design

Collectively, the results suggest that sustainability-aware personalization requires careful engineering of data pipelines, model architectures, and system parameters. The moderating role of sustainability weighting and diversity thresholds (Table 3) indicates that fine-tuning system controls is critical for balancing personalization performance and environmental objectives (Chen et al., 2024). These insights contribute to the broader discourse on responsible AI by demonstrating how engineering decisions at the system level can shape consumer behavior and sustainability outcomes simultaneously (Pinkse & Bohnsack, 2021).

Broader implications for sustainable digital commerce

From a broader perspective, this study highlights the transformative potential of AI-driven personalization in advancing sustainable fashion e-commerce. By aligning consumer preferences with low-impact product choices and reducing environmentally costly behaviors, personalized AI systems can act as active agents of sustainability rather than passive recommendation tools (Kuokkanen et al., 2019). The discussion reinforces the need for interdisciplinary approaches that combine AI engineering, sustainability science, and consumer behavior research to address the systemic challenges facing the fashion industry.

Conclusion

This study concludes that engineering personalized AI systems with sustainability embedded as a core design objective offers a viable and effective pathway for advancing sustainable fashion e-commerce. The results demonstrate that sustainability-aware personalization can maintain strong recommendation performance while enhancing diversity, reducing return intensity, and promoting the uptake of low-impact products. By integrating behavioral signals with sustainability attributes and system-level controls, the proposed AI framework enables adaptive, user-centric recommendations that gradually influence consumer behavior toward more responsible consumption. Importantly, the cumulative nature of sustainability gains observed over repeated interactions highlights the role of AI systems not merely as transactional tools but as long-term drivers of behavioral change. Overall, the findings affirm that thoughtfully engineered personalized AI systems can simultaneously support user satisfaction, operational efficiency, and environmental sustainability, offering a scalable model for responsible digital commerce in the fashion industry.

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