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Sustainability in the Age of Digital Fashion: Reducing Waste through Virtual Design: A Content Analysis of Digital Fashion Sustainability Discourse

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Abstract
The growing ecological aspect of the textile industry has led to increased evaluation of the design and development process for generating waste prior to delivery of a finished product to consumers. Digital clothing and virtual design technology have become popularly promoted as methods to reduce waste in the industry; however, there is limited research on these claims from an academic perspective. A directed qualitative content analysis was applied to a purposeful sample of 13 publicly available (i.e., company websites) brand communications, industrial papers and peer reviewed publications issued between 2019 and 2026 to evaluate representations of digital clothing as strategies to minimize waste generation. Five themes were identified using Circular Economy theory as the deductive framework: digital sampling as a method to prevent waste generation at the production stage, virtual fittings and reduction of returned merchandise, dematerializing products through application of the triple bottom line approach, barriers to adoption by the textile industry, and controversies related to claimed sustainable practices with respect to the use of block chain for digital clothing.

Keywords: digital fashion, virtual design, sustainability communication, circular economy, waste reduction, qualitative content analysis, 3D prototyping, fashion technology.

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1. Introduction

The global fashion industry is a resource intensive consumer sector, with significant portions of the world's carbon emissions, waste attributed to production of fabric (Akarsu, 2026). A significant portion of that waste occurs prior to garments being sold, at the design and sampling stages where physical prototypes are repeatedly created, evaluated, and discarded (Jaroenyingwattana, 2025). Brands and technology providers are increasingly promoting digital fashion and virtual design technologies – such as three-dimensional prototyping software like CLO3D and browzwear; digital sampling; virtual fitting; and digital twins, that could potentially decouple creative output from material consumption (Habib et al., 2025).

As digital fashion expands into consumer markets through NFTs and virtual worlds it is simultaneously creating new avenues for sustainability claims and controversy; and further complicating a straightforward interpretation of how technology can contribute to sustainable practices by allowing a single brand to tout both reduced waste and lower carbon emissions in one message, while touting a blockchain-based collectable with an environmental impact that has received significant public criticism (TRG Datacenters, 2025), and create products that are at once part of a manufacturing process (internal) and a mass produced consumer item (external) (Akarsu, 2026).

This research investigates how sustainability is represented within digital fashion discourse, in contrast to accepting all claims made about sustainability in that discourse as inherently credible. Directed QCA is used to analyze a purposeful sample of digital communications frosm brands; industry publications; and case studies produced between 2019 and 2026. The data is analyzed using Circular Economy Theory as an a priori theoretical framework for understanding the data but with open possibilities for inductive development of categories.

1.1. Aim and Objectives

The aim of the study is to investigate how digital fashion and virtual design are conceptualized as a method for sustaining sustainable practices in reducing waste within the process of developing products by fashion designers. The study is grounded in four key objectives: (1) to evaluate how sustainability is portrayed or communicated via digital fashion discourse (2) to find examples of thematic areas which describe how virtual design methods reduce waste in the development of fashion products (3) to determine the opportunities and obstacles associated with adopting digital fashion.

2. Literature Review

2.1. Digital and Virtual Design Technologies

Three-dimensional design software is now central to brand sustainability strategy where it was once seen as a niche visualization tool. The transition of Tommy Hilfiger to completely digitally designed Apparel with support of their in-house STITCH Incubator was specifically framed by sample reduction and sustainability (Retail Dive, 2019; Sourcing Journal, 2019); Reporting on industry suggests physical sample reduction due to digital sampling can reach up to 80% for early adopters (StyTrix, 2026). Corroboration of these claims is found within case studies at a technical level. Jaroenyingwattana (2025) demonstrates through a case study of the CLO3D football uniform, digital prototypes can replace physical samples during early design iterations; Choi (2022) documents the development of dynamic fashion garments using CLO3D; concluding that 3D simulation can provide both aesthetic and industrial potential for online platforms; Habib et al. (2025) report that virtual design tools for 3D design can reduce material waste and carbon emissions related to prototyping by approximately 30 %. Lee (2023) extends these claims further showing that directly applying techniques for three

dimensional virtual weaving to clothing waste will move digital design from reducing waste toward valuing waste.

Virtual fitting solutions add a digital component to an already digital retail experience; in this case using both augmented reality and artificial intelligence driven avatars that can be used by consumers to try on clothes virtually to assist in determining sizes. Industry reports indicate that the use of these solutions has resulted in lower cost associated with production and logistics since the need to physically transport samples for fit testing is eliminated (Silkke, 2025). Since generating returns results in additional reverse logistics related emissions, virtual fitting acts as a complementary solution at the retail stage to support the upstream process of digital sampling.

2.2. Digital Fashion as Consumer Product

Beginning with the more controversial area of discourse is the area regarding totally virtual garments used by consumers through their avatars, or as images in social media. The idea that using a portion of one's money to buy virtual garments instead of buying physical ones can save an enormous amount of both water and carbon was made possible by platforms like DressX. Akarsu (2026) states that this falls into the category of dematerialization and the Triple Bottom Line, which he says will provide significant environmental benefits from a "Planet" perspective, but will have less clear implications from a "People" perspective due to the impact of replacing jobs in textile manufacturing economies with machines. In addition to this growth in the number of studies about how people consume clothing, there has been a growing body of work on how people behave toward virtual fashion, including how they intend to engage with it in the Metaverse. Milanesi et al. (2024) used an acceptance model of technology to study GenZers' intentions to use digital fashion in the Metaverse. Similarly, Zhang & Liu (2025), applied the functional theory of attitude to predict whether people would accept only digital-only fashion.

Finally, Mao et al. (2025), connected digital fashion marketing stimuli to people's purchasing behavior.

Boughlala and Mazzucotelli Salice (2024) conclude that consumers adopting Digital Fashion End-Products have been relatively less explored in terms of the technological advancement that has led to their commercial development. The sustainability claims made by brands for these products will be challenged at this point as well. A significant portion of NFT based digital clothing have historically been created on energy intensive blockchains. Industry documentation and commentary document a large carbon and electricity cost per transaction which contradicts many of the environmental benefits being claimed by the brand.

2.3. Circular Economy and Digital Transformation

Although the broader circular economy literature sees digital fashion as part of an Industry 4.0 enabled move toward circularity; Casciani & D'Itria (2024) have found that there is a significant disparity in digital technology adoption towards circularity among firms in the fashion industry based on firm size and organizational preparedness. For example Farrukh & Sajjad (2024) examined textile manufacturing firms in Pakistan and found that although many strategic initiatives were identified regarding circular and digital ambitions; the implementation of these was limited by costs and resource constraints as well as variable regulatory compliance. Blazquez (2024) extended this narrative to include the Metaverse, he conceptualized the Metaverse as a mechanism by which companies could communicate their sustainability message; however he noted that currently, no standardization exists for assessing digital sustainability claims made in this space.

Collectively, these findings suggest that there exist two parallel narratives; a production-orientated design and production narrative that have demonstrated the reduction of material usage through digital sampling and prototyping. In addition

to this is a consumer product narrative that claims dematerialization through virtual garments, however the energy consumption of these garments as well as their authenticating capabilities remain unaddressed. There are few studies that have examined how these competing narratives are communicated simultaneously (or in opposition) in the public realm -- and therefore it is identified that this research fills that gap.

3. Theoretical Framework

The study draws on Circular Economy (CE) Theory. Circular Economy Theory represents all economic activity as a continuous loop of activities that focus on eliminating waste and promoting the maximum utilization of resources and the reuse of products rather than adopting the traditional linear approach associated with fashion production ("take-make-dispose"). For digital fashion we have identified a conceptual series of steps from virtual design technology (sampling digitally, using 3-D modeling, trying on virtually, creating digital twin models) through circular economy practices (preventing waste, optimizing use of materials, reducing physical samples and transportation) to achieve sustainable fashion outcomes (reducing the amount of fabric discarded or wasted, decreasing emissions and improving efficiency of developing new products). The series of steps provided the deductive base for our initial coding frame while allowing for the opportunity to add inductively and be flexible with an open-ended process similar to directed content analysis (Hsieh & Shannon, 2005; Assarroudi et al., 2018). Using the Triple Bottom Line concept (Planet, People, Profit), as related to virtual fashion by Akarsu (2026) the study builds upon CE Theory by bringing into view both social and financial elements that may be missed when only focusing on the environmental impact such as worker conditions created by the reduction in physical sample creation and garment manufacturing as well as what is commercially incentivized to create specific sustainability messages.

4. Research Gap

Existing research has examined three separate aspects of digital fashion. The first area of existing research includes the ability of 3-D computer-aided design (CAD) programs to perform the functions required for a brand to successfully sell digitally. Examples of this type of research include Choi's (2022) examination of the technical feasibility of selling clothing digitally and Habib et al.'s (2025) comparison of different CAD systems. The second area of research examines the degree to which consumers are willing to accept digital-only clothing. Two examples of such studies are Milanesi et al. (2024), who analyzed consumer reactions to digital-only clothing and Zhang & Liu (2025), who found that some consumers would be willing to purchase clothing if they could see it in digital format. Lastly, there exists a body of literature examining what organizational challenges exist within companies to effectively implement digital technologies into circular economy business models. Two examples of this type of research include Casciani & D'Itria (2024) who identified six organizational factors which hindered circular economy implementation through digital technologies and Farrukh & Sajjad (2024), who created an inventory of the most common organizational obstacles associated with the integration of digital technologies into circular economy business models. One gap in previous research is to understand the discursive relationship between these areas of investigation. That is, this study seeks to understand how brands, technology vendors, and other industry commentators frame and narrate the sustainability argument for digital fashion, including how those arguments may be contradictory based on ongoing debates about the use of blockchain-enabled digital fashion.

5. Methodology

The current study utilizes Directed Qualitative Content Analysis (QCA) as defined by Schreier (2012); Mayring (2014); and further described by Assarroudi et al.

(2018). Directed QCA differs from the conventional (inductive) QCA and summative QCA in that the initial coding frame has been developed through a theory-driven process — in this case circular economy theory — yet remains open to discovering new categories inductively throughout the coding process (Hsieh & Shannon, 2005). Directed QCA fits well within the context of this study as it starts out with a clearly stated theoretical framework; however, it evaluates that theoretical framework based on what real world discussions say about digital sustainable fashion. A preference existed to utilize directed qualitative content analysis instead of inductive thematic analysis due to the fact that the objective of this study was to assess whether discussions are being aligned with an already established theoretical framework. In addition to the fact that directed qualitative content analysis was utilized instead of summative content analysis; the purpose of the study were to identify themes and ways in which narratives surrounding digital sustainable fashion are constructed rather than to analyze how many times keywords appear (Mayring, 2014). The data source analyzed for this study is documents and therefore, focused on examining how digital sustainable fashion is communicated to the public — not the designers' nor consumers' experiences using technology associated with digital sustainable fashion.

6. Data Collection

A selection of documents were selected by purposeful sample in order to reflect publically available data from the last seven years on the sustainability of digital fashion; communications from brands, publications about the industry and practice cases studied in peer reviewed journals, all relating to the use of digital fashion and virtual design technology as a means to address sustainability and reduce waste. The use of purposeful sampling is a form of non-statistical sampling where the goal is to gather as much thematic material as possible while also ensuring that each piece of data has enough information to support the analysis. The inclusion

criteria for this study consisted of three elements; (i) A document had to be publicly available, free of charge through a paywall, (ii) The document must have included an explicit mention of either "digital fashion", "virtual design" or related terms with regards to sustainability or waste, (iii) The document must have been created or significantly revised during the defined time period. These 13 documents comprise the analytical corpus for this research.

Table 1. Purposively Sampled Document Corpus (2019–2026)

Sr.	Type	Source	Focus	Year
1	Industry case-study report	StyTrix	Digital sampling case studies and adoption data	2026
2	Industry article	Silkke	Zara and H&M virtual fitting rooms	n.d.
3	Brand/platform communication	DressX	Metaverse virtual clothing narrative	2025
4	Industry trend report	Fibre2Fashion	Sustainability steps incl. digital platforms	2024
5	Advocacy/industry commentary	Threading Change	Digital fashion, NFTs, environmental footprint	2026
6	Industry data commentary	TRG Datacenters	Fashion NFT environmental awareness	2025
7	Trade press	Retail Dive	Tommy Hilfiger 3D design transition (STITCH)	2019
8	Trade press	Sourcing Journal	Tommy Hilfiger 3D apparel design initiative	2019
9	Case study	Jaroenyingwattana (2025)	CLO3D football-uniform case study	2025
10	Case study	Habib et al. (2025)	3D virtual design environmental impact	2025
11	Case study	Choi (2022)	3D dynamic fashion garment development	2022

12	Case study	Lee (2023)	3D virtual woven textiles from clothing waste	2023
13	Case study	Akarsu (2026)	Virtual fashion, dematerialization, Triple Bottom Line	2025/26

Note: Documents 10–13 are peer-reviewed case studies that analyze primary brand or technology material and therefore function simultaneously as discourse artifacts and scholarly commentary.

7. Data Analysis Procedure

The researcher used the standard sequential approach to analyzing data using Directed QCA (Mayring, 2014; Assarroudi et al., 2018; Schreier, 2012). The research process consisted of eight steps: (1) familiarizing oneself with the entire corpus of documents and reading them in their entirety; (2) creating units of analysis by determining what constituted meaningful text segments; (3) developing the deductive frame based on the Circular Economy Chain (4) conducting a pilot coding study that included four documents representing brand literature, industry/press literature and peer reviewed literature. This pilot coding produced two additional emergent categories—"Contested Sustainability Claims" and "Consumers' Perceptions of Brands as Authentic"—that were absent from the original frame; (5) coding each document segment-by-segment and maintaining a coding log that recorded definitions for each category and examples of segmented text; (6) comparing newly-coded data to previous coding efforts to further define category boundaries; (7) generating higher order themes through iterative clustering of similar code items; and (8) interpreting these themes within the context of Circular Economy Theory and the Triple Bottom Line.

7.1. Coding Frame

Table 2. Coding Frame

Main Category	**Sub-category**	**Example Codes**
Waste Reduction	Digital Sampling	Reduced physical prototypes; sample-count reduction
Resource Efficiency	Virtual Prototyping	Less fabric consumption; material simulation
Circular Fashion	On-Demand Production	Digital inventory; demand-driven manufacturing
Sustainable Innovation	3D Design	Digital twins; virtual draping
Environmental Benefits	Carbon/Water Reduction	Reduced transportation; water-savings claims
Consumer Engagement	Virtual Fashion	Digital ownership; avatar self-expression
Business Transformation	Supply Chain	Faster product development; reduced lead time
Challenges	Technology Adoption/ Digital Sustainability	Cost; training; organizational readiness; Blockchain energy consumption
Contested Sustainability Claims (emergent)	Greenwashing Perception	Incongruence between claims and technology choice
Consumer Perception of Authenticity (emergent)	Trust and Legitimacy	Skepticism toward NFT-linked sustainability claims

8. Findings

The Analysis found approximately five themes from the 13 documents, which have been summarized in Table 3. The table presents an approximate prevalence for each theme as a proportion of the total number of items (rather than the exact number) due to the nature of qualitative vs. quantitative content analysis.

Table 3. Major Themes

Theme	Sub-themes	Prevalence	Interpretation
1. Digital sampling as waste prevention	Reduced prototypes; shortened design cycles	8 of 13	Most consistently supported theme; near-direct substitution framing.
2. Virtual fitting and returns reduction	AR/AI avatar try-on; reduced size-related returns	2 of 13	Positions benefit downstream, at the retail/logistics stage.
3. Dematerialization and Triple Bottom Line	Environmental savings claims; social/labor trade-offs	4 of 13	Broadens narrative beyond waste to water, carbon, labor.
4. Barriers to adoption	Cost; training; unequal access	3 of 13 (corpus); strongly corroborated in wider literature	Muted in brand-facing sources; explicit in academic literature.
5. Contested sustainability claims	Blockchain energy use; greenwashing perception	3 of 13s	Only theme where sources criticize rather than promote digital fashion.

8.1. Digital Sampling as Waste Prevention

The most prominent theme in this report is digital first workflows. Reporting from industry indicates that there has been a significant decline in physical sample creation due to a move toward digital sampling. One of the earliest adopters reportedly reduced their use of physical samples by nearly 80% (StyTrix, 2026). Technical peer reviewed articles are also showing a similar trend at a technical basis. For example Jaroenyingwatta's (2025) CLO3D case study showed how digital prototypes can be used as a substitute for initial physical prototype samples. Also, Habib et. Al. (2025) reported that approximately 30% less material waste and 30% less CO2 emissions related to prototyping were associated with the use of 3-D virtual design tools. Industry publications suggest that using digital sampling as a method for sustainability is available now, unlike many other methods which will require time before they become effective.

8.2. Virtual Fitting and Returns Reduction

A subset of this is a focus on the fit of the product to the customer via virtual try-on. It has been reported that Zara's and H&M's use of both augmented reality and AI avatars in their fitting pilots resulted in lower rate of returns related to sizing along with the corresponding logistical cost reductions. In addition to these metrics it was also noted that there were commercial metrics for example increased customer interaction. This provides an extension to the Circular Economy concept by extending from a design stage, waste reduction methodology to a retail stage methodology that was outside of the original coding frame.

8.3. Dematerialization and the Triple Bottom Line

In addition to waste, many authors have extended the scope of the sustainability narrative into broader environmental and social areas. Akarsu (2026) extends the idea of dematerializing by equating it with other changes that are taking place in the way people consume media. Akarsu (2026) also provides estimates of how

much carbon and water can be saved when users use platforms like DressX. Similarly, approaches the People aspect of sustainable fashion with caution because the researcher believes there could potentially be a negative impact on employment opportunities within textile manufacturing-based economies. This is somewhat contrary to brand-authored communication found in this data set where brands focus primarily on environmental trade-offs over social trade-offs.

8.4. Barriers to Adoption

The explicit discussion of "barriers" was seen to occur far more frequently within the published literature, than within the Brand-Facing Corpus Material. In their study on digital technology adoption towards circularity, Casciani & D'Itria (2024) conclude that digital technology adoption towards circularity has been uneven across firms and has primarily been influenced by firm size and level of organizational readiness. Additionally, in their research examining the challenges to the implementation of circular economy practices in a developing economy textile manufacturing industry, Farrukh & Sajjad (2024) identified three primary barriers to such practice implementations: cost associated with the initial investment required for circular economy practices, lack of employees' skill sets necessary to implement such practices and, as would be expected due to the developing nature of many economies in which they operate, an inconsistent application and/or enforcement of regulations that support sustainable manufacturing. While the barriers to digital sampling adoption from the perspective of the sampled brands were generally implied through the corpus material, rather than explicitly stated, the corpus materials did suggest that digital sampling adoption had occurred most commonly among larger, well resourced brands (such as Tommy Hilfiger's STITCH incubator described in Retail Dive, 2019). As such, it could be inferred that smaller manufacturers have faced greater

costs of adopting digital sampling technologies -- although this inference exceeds that found within the direct statements made by authors of the corpus materials.

8.5. Contested Sustainability Claims

The fifth theme contains all material that undermines or challenges the sustainability argument for Digital Fashion, primarily within the NFT/Blockchain Segment. Commentary from industry representatives points to the high per transaction energy costs associated with proof-of-work blockchains, which have been pointed out to undermine claims by brands of environmental benefits (Threading Change, 2026 & TRG Datacenters, 2025), making it the most divergent from a technology optimistic frame representing Themes 1 through 3.

9. Discussion

Beginning with the two findings of support and complication to the Circular Economy deductive framework that underlies this research, it is evident that the conceptual basis for digital sampling and virtual prototyping as "preventing" waste throughout the product development process was consistent with all three sources, i.e. StyTrix (2026), Habib et al. (2025), and Jaroenyingwattana (2025) which were comprised of both academia and industry. As such, there appears to be a sufficient degree of reliability regarding the technological aspects of the first part of the proposed chain, i.e. design-stage.

A second area where the linear relationship between technology adoption and sustainability was disrupted occurred in the context of virtual fitting at the retail stage and suggested an extension of the proposed chain beyond the design and sampling stages to include an identifiable returns reduction component. More broadly, however, while the sustainability claims related to Digital Fashion are made predominantly through the use of Blockchain technology for consumers to view and access information about their garments; these claims have been met with significant amounts of criticism directly towards the customer-facing

Blockchain-enabled layer and less criticism toward the production-technology layer. The bifurcations identified above, represent one manifestation of the broader circular economy literature's focus on the role of structural and regulatory barriers to circularity over mere lack of awareness of circular concepts and principles (Farrukh & Sajjad, 2024).

These findings also build upon the applications of the Triple Bottom Line model by Akarsu (2026). The environmental evidence base supporting digital sampling and virtual fitting is robust in this corpus; however, the social dimension has received relatively little attention outside academic sources. Therefore, based on the available data in this study, brands appear more likely to promote environmental outcomes rather than confront possible labor implications associated with dematerialization of products. Compared to literature focused on organization level circular economies (Casciani & D'Itria, 2024; Farrukh & Sajjad, 2024); the barriers theme identified here is less apparent in brand-facing discourse. This represents a gap in communication between organizations and customers, potentially because of a promotional rather than diagnostic nature of brand communications.

10. Conclusion

The study determine whether digital fashion and virtual design are being used as sustainability strategies through the lens of publicly available company and/or brand discourses that have been produced from 2019 until 2026. By applying a qualitative content analysis approach with directionality and using the theory of Circular Economy as an organizing framework, the following were identified as primary thematic categories: digital sampling as waste prevention; virtual fittings and reductions in product returns; dematerializing and meeting the Triple Bottom Line; impediments to technology adoption; and contested claims regarding sustainability. The relative degree of supportability and communication among

companies/brands for the sustainability benefits of technologies associated with production stage digital fashion appear to be significantly greater than those associated with consumer facing digital fashion technologies enabled via Blockchain. The synthesis provides a directions for future empirical studies into this evolving field as it pertains to the sustainability of the fashion industry.

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