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Sustainability in Fashion and digital technologies: Emerging Contributions in the Era of Industry 5.0

Sustentabilidade na Moda e as tecnologias digitais: Contribuições Emergentes na Era da Indústria 5.0

Sostenibilidad en la Moda y Tecnologías Digitales: Contribuciones Emergentes en la Era de la Industria 5.0

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Abstract: This article theoretically investigates how 3D design software can contribute to sustainability in fashion within the context of Industry 5.0. This qualitative and exploratory-descriptive research was conducted through a documentary analysis of 30 national and international publications related to fashion, sustainability, and digital technologies. The methodological strategy involved structured keywords and Boolean combinations, allowing for the mapping of trends, contributions, and gaps in the literature. The results indicate that 3D software

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reduces textile waste, minimizes physical prototypes, optimizes processes, and strengthens practices such as circular economy, zero waste, and remanufacturing. It also generates positive organizational impacts, such as greater design precision and team integration, although challenges persist, particularly the need for training and technological infrastructure. It is concluded that 3D software represents a strategic tool to support more circular, transparent, and efficient production models, highlighting the need for applied studies to deepen its implementation in the Brazilian garment sector. The relevance of the study lies in the systematization of evidence that guides the sustainable digital transition, offering theoretical subsidies for both the national fashion industry and academia.

Keywords: Sustainability in fashion; 3D design software; Product development; Apparel industry; Industry 5.0; Virtual prototyping.

Resumo: O presente artigo investiga teoricamente como os softwares de design 3D podem contribuir para a sustentabilidade na moda no contexto da Indústria 5.0. A pesquisa, de abordagem qualitativa e caráter exploratório-descritivo, foi realizada por meio de uma análise documental de 30 publicações nacionais e internacionais relacionadas à moda, sustentabilidade e tecnologias digitais. A estratégia metodológica envolveu palavras-chave estruturadas e combinações booleanas, permitindo mapear tendências, contribuições e lacunas na literatura. Os resultados indicam que os softwares 3D reduzem desperdícios e geração de resíduos têxteis, minimizam protótipos físicos, otimizam processos e fortalecem práticas de economia circular, zero waste e remanufatura. Também geram impactos organizacionais positivos, como maior precisão projetual e integração entre equipes, embora os desafios persistam, especialmente a necessidade de capacitação e infraestrutura tecnológica. Conclui-se que, os softwares 3D representam ferramenta estratégica para apoiar modelos produtivos mais circulares, transparentes e eficientes, destacando a necessidade de estudos aplicados que aprofundem sua implementação no setor confeccionista brasileiro. A relevância do estudo reside na systematização de evidências que orientam a transição digital sustentável, oferecendo subsídios teóricos para a indústria de moda nacional e para o meio acadêmico.

Palavras-chave: Sustentabilidade na moda; Softwares de design 3D; Desenvolvimento de produto; Indústria de confecção; Indústria 5.0; Prototipagem virtual.

Resumen: El presente artículo investiga teóricamente cómo los softwares de diseño 3D pueden contribuir a la sostenibilidad en la moda en el contexto de la

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Author contributions according to the CRediT taxonomy

RTOB: conceptualization, methodology, investigation, writing - original draft. EP: conceptualization, supervision, writing - review & editing.

Conflict of interest

The authors declare no conflict of interest.

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Industria 5.0. La investigación, de enfoque cualitativo y carácter exploratorio-descriptivo, se llevó a cabo mediante un análisis documental de 30 publicaciones nacionales e internacionales relacionadas con la moda, la sostenibilidad y las tecnologías digitales. La estrategia metodológica involucró palabras clave estructuradas y combinaciones booleanas, lo que permitió mapear tendencias, contribuciones y lagunas en la literatura. Los resultados indican que los softwares 3D reducen el desperdicio y la generación de residuos textiles, minimizan los prototipos físicos, optimizan procesos y fortalecen prácticas de economía circular, zero waste y remanufactura. Asimismo, generan impactos organizacionales positivos, como una mayor precisión proyectual e integración entre equipos, aunque persisten desafíos, especialmente la necesidad de capacitación e infraestructura tecnológica. Se concluye que los softwares 3D representan una herramienta estratégica para respaldar modelos productivos más circulares, transparentes y eficientes, destacando la necesidad de estudios aplicados que profundicen su implementación en el sector de la confección brasileño. La relevancia del estudio radica en la sistematización de evidencias que orientan la transición digital sostenible, ofreciendo insumos teóricos para la industria de la moda nacional y el ámbito académico.

Palabras clave: Sostenibilidad en la moda; Softwares de diseño 3D; Desarrollo de producto; Industria de la confección; Industria 5.0; Prototipado virtual.

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1 INTRODUCTION

The fashion industry, historically marked by the exacerbated use of resources and high socio-environmental impacts, faces a scenario of urgency regarding the adoption of sustainable practices, especially concerning product development (Fletcher; Grose, 2011). According to the Ellen MacArthur Foundation (2017), less than 1% of textile materials produced globally return to the production cycle, revealing the sector's low circularity and the need for more efficient solutions.

The technological transformations of Industry 4.0 and 5.0 emerge as a strategic response to this paradigm of low resource utilization, structurally modifying the fashion sector. According to Casciani et al. (2022), advanced digitalization has driven structural changes in the way products are created, sampled, and produced, allowing for greater integration between stages and a reduction in inefficiencies. In this context, 3D design software emerges as an essential tool for product development, enabling virtual modeling and prototyping with enhanced precision, as highlighted by Filipe (2022), Costa (2022) and Rodrigues; Dos Santos (2024). Such technologies favor creative experimentation and the anticipation of design decisions in a digital environment, reducing dependence on physical processes and minimizing errors and rework. These findings reinforce the relevance of investigating how such technologies can contribute to mitigating environmental impacts in the production chain.

Despite these advances, the fashion industry remains associated with high levels of material waste, intensive resource consumption, and significant socio-environmental impacts (Fletcher; Grose, 2011; Ellen MacArthur Foundation, 2017; García-Torres; Rey-Garcia, 2020). Fletcher and Grose (2011) demonstrate that a substantial portion of textile waste originates in the early stages of design and patternmaking. Costa (2022) reinforces that the product development phase remains one of the most critical, given that it allows for the analysis of material surplus generation and product life cycles, thereby highlighting the gap between the potential of digital technologies and their full adoption by companies, particularly Brazilian ones. This scenario presents a problem situation that demands investigation into alternatives capable of reconciling innovation, efficiency, and environmental responsibility.

In this regard, the literature indicates that incorporating 3D design software can contribute to mitigating socio-environmental impacts and consolidating sustainability-aligned practices. Studies such as those by Huang and Jin (2024), McQuillan (2020), Wetherell et al. (2023), and Santos, Silveira, and Rech (2024) highlight that digital simulations enable the testing of shapes, fits, and volumes, in addition to facilitating the implementation of zero-waste techniques and remanufacturing. Furthermore, Fernandes (2022) demonstrates that virtual environments standardize workflows and enhance creative accuracy, elements essential to corporate competitiveness within digital transformation scenarios. These contributions justify, albeit briefly in this section, the relevance of research connecting technology, sustainability, and innovation in product development for the apparel industry.

In this sense, the literature indicates that the incorporation of 3D design software can contribute to the reduction of socio-environmental impacts and the consolidation of practices aligned with sustainability.

Studies such as those by Huang and Jin (2024), McQuillan (2020), Wetherell et al. (2023), and Santos, Silveira, and Rech (2024) highlight that digital simulations allow for the testing of shapes, adjustments, and volumes without the immediate need for physical manufacturing, decreasing material consumption and the number of prototypes, in addition to implementing zero-waste and remanufacturing techniques. Furthermore, Fernandes (2022) highlights that the use of virtual environments improves communication between teams, standardizes workflows, and enhances creative assertiveness, elements important for company competitiveness in digital transformation scenarios. These contributions justify, albeit briefly in this section, the relevance of studies that articulate technology, sustainability, and innovation in product development and the garment industry.

Given this panorama, this research is limited to the qualitative analysis of scientific documents, technical reports, and recent publications that address the use of 3D design software in the garment sector, specifically considering its contribution to sustainable practices in the context of Industry 5.0. The investigation is based on an integrative review and thematic analysis, with a selection of national and international materials published in recent decades. The analytical scope focuses on the impacts of this technology in the stages of patternmaking, prototyping, logistics, internal communication, and consumer interface, as widely discussed by Filipe (2022), Casciani et al. (2022), and Aguirre (2024).

Thus, considering the socio-environmental challenges of the fashion sector and the potential of digital technologies to mitigate impacts and improve processes, this research aims to analyze how 3D design software can contribute to sustainability in fashion within the context of Industry 5.0. By mapping functionalities, analyzing contributions to waste reduction, and identifying impacts on the production, logistical, and commercial chains, this study seeks to fill gaps identified in the literature, which still lacks integrated analyses. In this way, the investigation not only contributes to the theoretical advancement of sustainability and technology in fashion but also offers theoretical support for future research and companies seeking to innovate and reduce their environmental impacts.

2 THEORETICAL FRAMEWORK

This literature review is structured around two central axes. First, it explores Industry 5.0 in fashion, examining how 3D design software and virtual prototyping foster mass customization, human-technology collaboration, and material waste reduction, while highlighting key implementation barriers in micro and small enterprises. Second, it addresses sustainability in fashion product development, analyzing design as a critical factor across the garment lifecycle and detailing the environmental, social, economic, and cultural impacts of traditional manufacturing to demonstrate the synergy between digital innovation and socio-environmental responsibility.

2.1 Industry 5.0 and the Fashion Sector

Industry 4.0 has introduced advancements by integrating tools such as the Internet of Things (IoT), big data, 3D printing, automation, and artificial intelligence, thereby enabling greater system interconnectivity, large-scale data analytics, and process automation. In the fashion industry, these technologies facilitate on-demand manufacturing and resource optimization, fostering increased efficiency and product customization (Carlota, 2018).

The new paradigm addressed in Industry 5.0 allows fashion to develop production models that are more personalized, transparent, and aligned with the principles of socio-environmental responsibility. Furthermore, it promotes integration between professionals and automated systems, stimulating creative collaboration, transparency in the production chain, and more conscious and regenerative production practices (Dacre et al., 2024).

Despite the opportunities, the full adoption of Industry 4.0 technologies and the transition to the 5.0 model face challenges, such as the shortage of skilled labor, high implementation costs, and a lack of technical training policies (Marshall et al., 2024). These challenges are even more evident in small companies and peripheral regions of Brazil, where access to technology and specialized training is limited (MCTI, 2025).

Industry 5.0 in fashion promotes progress and prioritizes mass customization and human-centricity in production and development processes. This model integrates professional creativity with intelligent systems, allowing products to be adapted to individual consumer preferences without compromising operational efficiency (Dacre et al., 2014). In the fashion context, this approach enables the creation of on-demand collections, adjusted to different aesthetic and functional profiles while maintaining quality standards and reducing unnecessary inventory, which contributes to the sector's sustainability (Safavi Jahromi; Ghazinoory, 2024).

Additionally, Industry 5.0 leverages data generated by sensors, digital platforms, and 3D design software to optimize the supply chain in a conscious and responsible manner. Real-time data analytics enables demand forecasting, the reduction of raw material and energy waste, and the refinement of logistical and production processes. This integration between humans and intelligent systems strengthens ethical and sustainable practices, promoting transparency and traceability in fashion manufacturing while supporting evidence-based strategic decision-making—thus aligning technological innovation with social and environmental responsibility (Carlota, 2018).

2.1.1 3D Softwares as Industry 5.0 Technology

In the context of Industry 5.0, 3D design software emerges as a strategic tool that articulates creativity, innovation, and sustainability in the fashion industry. Unlike Industry 4.0, these technologies enable greater integration between professional creativity and intelligent systems, promoting precise modeling and prototyping, simulation of fabrics and drapes, and a reduction in material use and waste generation (Sayem et al., 2010; Zanzi, 2022; McQuillan, 2020). Thus, 3D software contributes to the humanization of production processes,

aligning technology, ethics, and socio-environmental responsibility with the development of more conscious collections (Treptow; Mello, 2019). Beyond enhancing production efficiency, these tools expand mass customization and strengthen collaboration between teams, making design an integrated, digital, and sustainable process (Sena, 2023; Sayem, 2023; Macedo, 2022). As a result, the integration of digital modeling, simulation, and visualization transforms fashion creation, consolidating 3D software as strategic instruments for optimizing production stages, reducing operational costs, and incorporating responsible practices from the beginning of the creative process, aligning production chains with the ethical and transparent demands of the contemporary sector (Sayem, 2010; McQuillan, 2020).

The digitalization of the sector was decisively intensified during the COVID-19 pandemic, when social distancing interrupted in-person dynamics and forced the replacement of physical practices with virtual alternatives (Bottani et al., 2025; Macedo, 2022). Software such as CLO 3D allowed for the continuity of collection development even in restricted contexts, highlighting the resilience and versatility of digital solutions (Macedo, 2022). This period accelerated the evolution of the technology used in the software and the adoption of remote workflows, consolidating three-dimensional design as an essential resource.

In the professional sphere, 3D software enhances integration among designers, patternmakers, product engineers, and intelligent systems, allowing for mass customization, immediate adjustments, and data-driven decisions (Carlota, 2018). The information generated by virtual simulations, such as fabric drape, sizing, and pattern variations, contributes to forecasting demand, improving logistical processes, and reducing resource consumption throughout the production chain (McQuillan, 2020; Santos, 2024, Barbiere, Pinheiro, 2026). In addition to reinforcing operational efficiency, this approach strengthens the human role in the creative process, favoring ethical and collaborative practices aligned with contemporary socio-environmental principles (Zanzi, 2022).

The functionalities of these systems encompass advanced drape simulation, real-time rendering, automatic adjustments, and the generation of complete prototypes, replacing several physical stages and decreasing environmental impact (Costa, 2022; Sena, 2023; Filipe, 2022). Platforms such as CLO 3D, Lectra, Gerber, and Tukatech are capable of optimizing production flows, improving communication between teams, and expanding control over creative and technical stages, making processes more agile and efficient (Santos, 2024). Research such as Costa's (2022) even highlights that 3D design is not limited to technological innovation but transforms the very logic of creation by expanding virtual experimentation and reducing material waste.

However, studies on this new technology, while reinforcing 3D's potential for waste reduction, focus on large international brands, such as Tommy Hilfiger, revealing the need for investigations that consider the specific realities of micro and small enterprises (Zanzi, 2022; Roque, 2024; Costa, 2022). Given these technical and functional characteristics, it becomes pertinent to present a comparative chart that synthesizes the specificities of the main software, facilitating the visualization of their applications, resources, and potential in fashion product development.

However, studies on this emerging technology, while reinforcing the potential of 3D software in waste reduction, remain concentrated on major international brands, such as Tommy Hilfiger, highlighting the need for investigations that address the specific realities of micro and small enterprises (Zanzi, 2022; Roque, 2024;

Costa, 2022). Given these technical and functional characteristics, it becomes pertinent to examine the specific features of the leading software solutions, facilitating the visualization of their applications, resources, and potential within fashion product development. Chart 1 summarizes the key strengths and relevant observations among the primary 3D design software available.

Chart 1 – Comparison of 3D Design Softwares.

Software	Type	Strengths	Observations
CLO3D (CLO Virtual Fashion)	3D	High visual fidelity and realistic rendering	Widely used in design and education
V-Stitcher (Browzwear)	3D	Technical precision and CAD integration	Geared toward the industrial sector
Audaces 3D	2D/3D	Integration with Audaces Moldes and Brazilian native interface	Subtle differences between virtual and physical garments
Optitex	2D/3D	Robust fabric simulation and rapid adjustments	Technical focus on apparel engineering
Gerber AccuMark 3D (Lectra)	2D/3D	Full integration with traditional CAD	Used for technical validation
TUKA3D (Tukatech)	3D	Ease of learning; fast-paced	Geared toward small-scale garment manufacturers
Tailornova 3D	3D	Automated online platform	Ideal for small businesses
3D-Vidya (Assyst) e Style3D Studio	3D	Support for digital libraries and virtual assets	Linked to SampLess and Swatchbook companies

Fonte: Adapted from Santos et al. (2024).

Despite their advancements, the implementation of 3D software faces challenges, particularly in smaller companies, due to high costs, infrastructure limitations, and the need for specialized technical training (Sayem, 2023; Macedo, 2022; Papahristou, Bilalis, 2017). Overcoming these barriers is essential to democratize access to technology and strengthen sustainable practices within the sector. In this regard, applied studies, extension projects, and real-world system testing can guide strategic adoption guidelines, favoring a more balanced integration between creativity, technological innovation, and socio-environmental responsibility (Baytar, 2017; Conlon, Gallery, 2023).

2.2 Sustainability and Fashion Products

Sustainability has become a central axis for rethinking fashion, given that the sector is still structured around intensive production models that accelerate disposal and operate under a high environmental impact logic. This operational mode, typical of fast fashion logic, amplifies environmental and social impacts across all stages of the production chain (Berlim, 2014). As fashion is recognized as a complex system, where creation, production, distribution, and consumption are interdependent, there is a growing need for approaches capable of integrating these stages in a systemic and sustainable manner (Fletcher, Grose, 2011). Furthermore, discussions on circularity point out that moving toward sustainable practices involves revising not only the materials used

but also the flows of use, disposal, and the return of products to continuous value cycles (Santos, Sigrist, 2020). Thus, addressing sustainability in fashion means understanding the sector beyond the final product, considering it a field in transformation that demands new ways of designing, producing, and relating to consumption, guided by ethical, social, and environmental principles.

In the context of sustainable fashion, product development emerges as one of the most strategic dimensions for reducing impacts throughout the chain. Decisions made during the product conception phase are decisive for the environmental impact across the entire life cycle, making design a strategic point for mitigating socio-environmental damage (Fletcher, Grose, 2011; Papahristou, Bilalis, 2017; McQuillan, 2020).

Berlim (2014) highlights that choices regarding materials, patternmaking, production processes, and distribution methods define the environmental performance of garments from their origin, indicating that sustainability cannot be incorporated only in the final stages of the chain. Thus, understanding creation as the moment when fundamental guidelines for durability, efficient resource use, and circularity potential are established is essential for transforming the sector. This perspective suggests that incorporating sustainability is not an isolated process but a conceptual shift that begins within the design itself.

In this sense, integrating sustainable thinking into the initial stages of the creative process implies adopting new ways of interpreting the role of design within the fashion system. Fletcher and Grose (2011) argue that advancing toward sustainability requires new ways of thinking, producing, and doing business, articulating transformations that encompass the product, the system, and the practice of design. This includes considering the full life cycle, recognizing the interdependencies between creation, production, distribution, and consumption, and understanding fashion as an ecosystem in which design decisions reverberate at different levels. For the authors, a sustainable mindset involves recognizing networks, patterns, and cycles, expanding the designer's gaze beyond aesthetic and functional resolution.

Therefore, understanding product development as a structural axis of sustainability allows for the recognition of design not only as a creative stage but as a decisive agent in building more responsible fashion systems.

Product development constitutes a strategic stage in modulating impacts throughout the chain, since design decisions predetermine the environmental, social, economic, and cultural performance of the garments. This perspective reinforces the understanding that sustainability-besides favoring competitiveness and corporate repositioning, is an indispensable condition for ensuring a balanced ecosystem and, consequently, the quality of life for future generations (Fletcher, Grose, 2011; García-Torres, Rey-Garcia, 2020; Natividade, Nogueira, Barreto, 2024).

The impacts of the apparel industry become particularly evident when viewed from an environmental perspective, as the sector accounts for approximately 20% of global industrial wastewater (Bailey et al., 2022) and contributes between 2% and 8% of global greenhouse gas emissions (Geneva Environment Network, 2025). In Brazil, according to the Brazilian Textile and Apparel Industry Association (ABIT) and Market Intelligence (IEMI), the scale of production underscores this issue: in 2023 alone, 8.02 billion units were manufactured within the apparel segment, including clothing, hosiery, accessories, home textiles, and technical items, highlighting the extensive natural resource consumption required to sustain the sector (ABIT, 2024; IEMI, 2024).

Parallel to this, the global increase in fiber production, reaching 124 million tons in 2023 and is projected

to reach 160 million by 2030 (Textile Exchange, 2025), intensifies both the pressure on raw materials and waste generation. This scenario is aggravated by the fact that about 15% of everything produced may be discarded throughout the process, resulting from losses related to cutting, marker efficiency (nesting), defects, or planning failures (Fletcher, Grose, 2011). Furthermore, less than 1% of all textile material is effectively reintegrated into new production cycles, revealing the system's low circularity and the scale of waste associated with the current production and consumption model (Ellen Macarthur Foundation, 2017).

Social and economic impacts also reveal the profound structural asymmetry that characterizes the fashion chain, especially in emerging countries. In Brazil, although the sector generates over R$ 160 billion annually and employs 1.3 million formal workers (ABIT; IEMI, 2024), dynamics of precarization persist, aligned with what literature calls the "structural precarization of labor," marked by extensive outsourcing, informality, and the weakening of labor conditions.

Labor Ministry inspections and ILO (International Labour Organization) analyses point to recurring exhausting shifts, low wages, unhealthy environments, and cases of slave-like labor, particularly in sewing workshops operating across multiple levels of subcontracting (Lofs et al., 2021). The production pressure intensified by fast fashion further contributes to the devaluation of technical professions, such as seamstresses, patternmakers, sample makers, and operators, while leading to physical and emotional illness, high turnover, and job insecurity, directly affecting the social and economic stability of workers (Fletcher, Grose, 2011; Costa, 2022; Natividade, Nogueira, Barreto, 2024).

Regarding the cultural pillar, the current model reinforces aesthetic homogenization and programmed obsolescence of clothing, phenomena that alter traditional knowledge, artisanal practices, and local identity expressions (Toniol, 2022). The acceleration of collection cycles reduces the symbolic value of garments, encouraging disposable consumption patterns and diluting the cultural diversity that historically characterizes fashion. Thus, an integrated analysis of the environmental, social, economic, and cultural pillars demonstrates that these impacts are interdependent, reproducing a system whose logic still distances itself from principles of circularity and responsibility. Understanding the sector's complexity is fundamental to grounding strategies for innovation and transformation, especially those associated with digital technologies and new production models.

Given the environmental and social impacts resulting from the large-scale production of the garment industry, sustainability must become a central theme in fashion. The sector needs to seek new strategies to mitigate these impacts; the digitalization of production and product development, along with the adoption of ESG (Environmental, Social, and Governance) indicators and SDGs (Sustainable Development Goals), constitute strategic tools for creating, monitoring, managing, and improving sustainable practices in the garment sector (Zanzi, 2022; Fletcher, Grose, 2011; Link, 2021). 3D design software, virtual prototype simulation, and digital monitoring platforms allow for waste reduction, process optimization, and improved transparency in the production chain. In this way, the convergence of technological innovation and sustainability provides the resources to transform the fashion industry into a more responsible and conscious sector, aligned with contemporary environmental and social demands.

3 METHODOLOGY

This research adopted a qualitative approach (Lakatos; Marconi, 2017) of an exploratory and descriptive nature, structured as a narrative review utilizing thematic analysis (Braun; Clarke, 2006). The analysis was based on national and international scientific publications addressing fashion sustainability and digital technologies, specifically 3D design software and virtual prototyping. The primary objective of this methodological stage was to identify trends, contributions, limitations, and literature gaps to substantiate the theoretical discussion of the article.

A total of 30 documents were analyzed, including scientific articles, dissertations, books, technical reports, and institutional publications. The selection of materials was conducted through searches in databases such as Google Scholar, Scopus, CAPES Journals, Taylor & Francis, and ScienceDirect. The searches included publications available up to the year 2025, with no initial period restriction, provided they were aligned with the research theme.

The search strategy focused on the definition of a structured set of keywords, as guided by Gil (2010), organized into two main groups, as presented in Chart 2:

- Main Terms, related to the fashion sector, sustainability, and Industry 5.0;
- Complementary Terms and Variations, associated with digital technologies, especially 3D design and virtual prototyping;

Chart 2 – Keywords Used in Searches

Main Terms Group	Termos Complementares e Variações
Fashion Industry	"Moda/Fashion/Indústria 5.0"
Sustainability	"Sustent* (sustentável/sustentabilidade)"
Virtual Prototyping	"Prototipagem Virtual /3D CAD/ Design 3D"

Source: Prepared by the authors (2026).

Furthermore, Boolean combinations were developed to refine the search strategy and ensure precision in identifying the most relevant documents within the research scope. Chart 3 shows the search term combinations and the operators used, such as “AND” and “OR,” allowing for the connection of concepts related to sustainability, fashion, and 3D design software.

Chart 3 – Search Term Combinations

Search Term Combinations
"sustainability" AND "fashion" OR "fashion industry" AND "3D CAD"
"sustainability" AND "fashion industry" AND "virtual prototyping"
"sustainability" AND "fashion industry" AND "virtual clothing prototyping"
"sustent*" AND "moda" AND "Design 3D"
"moda" AND "indústria 5.0"
"moda" AND "sustent*"

Source: Prepared by the authors (2026).

Following the search stage, the documents were selected based on the inclusion criteria demonstrated in Chart 4:

Chart 4 – Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Direct alignment with the central theme	Duplicate documents across databases
Theoretical or practical contributions related to the use of emerging technologies in fashion	Works with no direct relationship to fashion, sustainability, or 3D technologies
Focus on sustainability, innovation, or digital transformation	Publications with limited methodological rigor
Full-text availability	Materials published prior to 2015, except for relevant foundational literature.
Original scientific publications or recent reviews	Texts mentioning the themes superficially, without an effective relationship to the research objective.

Source: Prepared by the authors (2026).

The 30 selected documents were analyzed through full-text reading, thematic categorization, and extraction of key concepts. This analysis allowed for the identification of conceptual patterns, convergences, divergences, and gaps in the existing literature, serving as the basis for constructing the state of the art and the theoretical framework.

4 RESULTS AND DISCUSSION

The incorporation of 3D design software into apparel development has established itself as a structural axis for sustainability strategies, primarily by shifting critical patternmaking and material consumption decisions to fully simulated environments (McQuillan, 2020; Filipe, 2022). Rather than merely replacing analog tools, 3D reconfigures the design process, allowing for the prediction of drape, fit, and constructive performance prior to physical materialization (Santos; Silveira; Rech, 2024). This methodological reorganization transforms design into a preventive instrument, integrating environmental criteria from the initial stages of product conception and reducing late-stage corrections and accumulated waste.

In this sense, the use of 3D plays a decisive role in zero-waste strategies, as it expands the capacity to test, adjust, and optimize markers in a digital environment. McQuillan (2020) demonstrates that prior experimentation with patterns results in more efficient configurations and lower waste generation. Studies by Filipe (2022) and Costa (2022) reinforce that virtual modeling systems reduce disposal by allowing precise adjustments before the actual cut. Complementarily, Huang and Jin (2024) highlight that hybrid approaches, combining artisanal expertise with digital tools, enhance creative potential while ensuring maximum material utilization. Thus, 3D enhances human skills toward minimum waste.

Following this logic, waste management through digital prototyping emerges as one of the most direct contributions to sustainable performance. Replacing physical samples with simulations reduces the consumption of raw materials, energy, and logistics associated with transport for garment approval (Papahristou; Bilalis, 2017; Filipe, 2022). Santos, Silveira, and Rech (2024) and Aguierre (2024) point out that the reduction in rework stems from the accuracy of digital drape simulations, avoiding errors that traditionally required multiple physical prototypes. Field evidence documented by Roque (2024) shows that the adoption of virtual prototyping accelerates production time, although it requires an adaptation period and initial investment.

Based on these transformations, 3D design also advances into remanufacturing and circularity practices, extending product lifespans. Wetherell et al. (2023) demonstrate, in the sports context, that the digitalization of pieces enables viable remanufacturing cycles with partial reuse without complete product disassembly. Huang and Jin (2024) reinforce that hybrid processes allow for successive reconfigurations, customizations, and digitally designed reuse routes. In this way, 3D not only reduces waste during the item's first lifespan but establishes technical foundations for continuous cycles of updating, repair, and functional extension of clothing by reinserting it into the production chain.

These advancements directly impact the supply chain, where the digitalization of samples and documentation decreases logistical steps and reduces emissions related to physical shipping. Casciani et al. (2022) demonstrate that digital workflows increase coordination between suppliers, patternmakers, and creative teams. Aguierre (2024) and Fernandes (2022) show that, when integrated with Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP) systems, 3D software provides more precise traceability of inputs, production cycles, and impacts, representing a strategic dimension for companies committed to ESG metrics. Therefore, 3D acts as both an operational tool and an instrument of governance.

At the point of contact with the market, three-dimensional technologies redefine the consumer relationship. Digital showrooms, rendered catalogs, and Virtual Try-On systems improve the alignment between visual expectation and the final product, reducing return rates, which is one of the largest generators of environmental impact in e-commerce (Fernandes, 2022; Filipe, 2022). Furthermore, advanced visualization supports on-demand production models, decreasing inventory and the risk of surplus. Such resources also facilitate transparent communication regarding composition, durability, and care, reinforcing the consumer's role in life-cycle sustainability.

Despite the positive evidence, the consolidation of these benefits depends on institutional, technical, and human conditions that vary across companies. Aguierre (2024) and Filipe (2022) sustain that effective adoption requires training processes, flux restructuring, and organizational adaptation. Internship reports and applied research, such as those by Roque (2024), reveal initial gains mainly associated with productivity and marketing, but indicate that significant economic impacts occur only with technological proficiency. These findings are reinforced by international studies (Conlon; Gallery, 2023; Baytar, 2017), which highlight the importance of training programs to reduce entry barriers.

Finally, a set of specific challenges remains within the Brazilian context, especially for micro and small enterprises. Zanzi (2022) and Aguierre (2024) point to the need for guidelines that articulate technology, training, and financing, particularly for businesses facing infrastructure limitations. Thus, the sustainable advancement of 3D will depend on applied research analyzing costs and benefits in a longitudinal perspective, as well as public policies that democratize access to digital technologies. The convergence of innovation, sustainability, and productive inclusion constitutes, therefore, a strategic future for 3D design to contribute fully to the transformation of the manufacturing sector with sustainable practices.

To facilitate the understanding of the analyzed literature landscape, Chart 5 is presented, synthesizing 12 selected studies for detailed comparison and highlighting their main contributions.

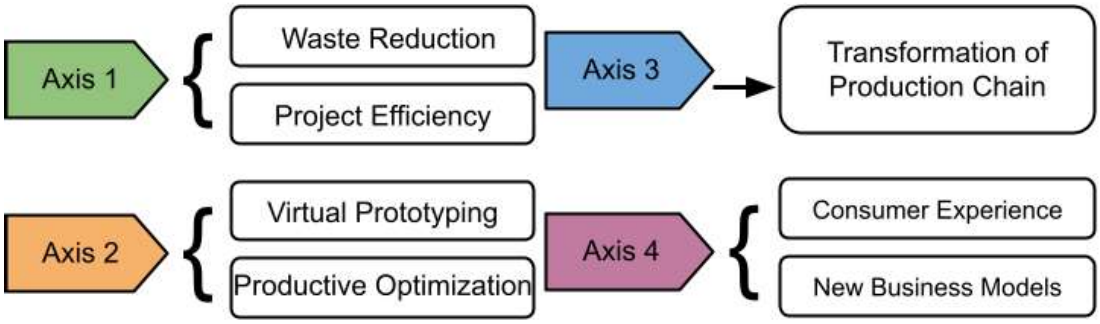
Chart 5 – Bibliographic Comparison of 3D Design Software and Sustainability

Author (Year)	Search Title	Main Results
Huang & Jin (2024)	Innovating sustainable fashion design: an exploration of the sustainability of a hybrid method through the C2CAD framework	Proposes a hybrid artisanal and digital method; recursive processes; increased material utilization; integrates sustainability from the beginning of the design process.
Aguirre (2024)	Guide for the implementation of 3D prototyping software in the product development process of the apparel industries	Implementation of 3D software, optimizing creation, modeling, and prototyping. Highlights waste reduction, increased production efficiency, and improved visualization through virtual adjustments. Emphasizes the need for training and workflow adaptation for full digital integration.
Santos, Silveira, Rech (2024)	Virtual prototyping: 3D software for apparel modeling	Maps 3D software; demonstrates gains in precision and reduction of physical prototypes; highlights barriers in Brazil, such as cost and technical training.
Roque (2024)	Internship at the company Século XXI Fashion Trading: a study on 3D software integration.	Reduction of physical prototypes; gains in time and marketing; necessity for training and workflow adjustments.
Wetherell et al. (2023)	Utilising 3D fashion design software to enable remanufacturing in sportswear.	3D enables remanufacturing; facilitates digital deconstruction; extends product life cycles; reduces waste disposal.
Costa (2022)	Cara Mila: Sustainability and 3D Apparel	Actual waste reduction in patternmaking; virtual prototyping decreases the number of samples; environmental gains and efficiency in product development.
Zanzi (2022)	Textile waste management: pro-sustainability guidelines for micro and small apparel manufacturing enterprises	Maps waste sources; proposes a management guide for MSEs; identifies the use of 3D as a strategy for waste reduction.
Fernandes (2022)	Digital Fashion: Technologies for apparel creation and selection	3D reduces returns in e-commerce; improves visualization; accelerates creation; increases integration between design and marketing.
Filipe (2022)	Benchmarking and assessment of sustainability potential in the use of innovative 3D CAD technology for fashion collection development	3D reduces time and errors; decreases the number of prototypes; improves precision; demands new technical competencies.
Casciani et al. (2022)	Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations.	3D/VR/AR dematerialize stages; accelerate production; increase supply chain integration and sustainable models.
McQuillan (2020)	Digital 3D design as a tool for augmenting zero-waste fashion design practice.	3D as a core tool for zero waste; allows for zero-waste markers; strengthens experimentation and waste reduction in design.
Papahristou & Bilalis (2017)	Should the fashion industry confront the sustainability challenge with 3D prototyping technology?	Demonstrate that 3D reduces prototypes and waste; improves collaboration; integrates PLM for greater sustainability.

Source: Prepared by the authors (2026).

The thematic analysis of the 30 selected documents allowed for the identification of four central axes that structure the contemporary debate on sustainability, digital technologies, and the use of 3D design software in the fashion sector. The defined axes are presented in Figure 1.

Figure 1 – Definition of the Four Central Axes



Source: Prepared by the authors (2026).

These axes can be defined as: Waste reduction and project efficiency; Virtual prototyping and production optimization; Supply chain transformation; and Consumer experience and new business models. Based on the conceptual recurrence found in the analyzed materials, these were constructed to synthesize trends, contributions, and literature gaps.

The main convergence among the analyzed studies concerns the direct impact of 3D design software on minimizing material waste, especially during the product development phase. Emphasis is placed on the digital patternmaking stage, which allows for testing shapes, markers, and drape before physical manufacturing, thereby reducing fabric consumption, rework, and scrap generation (McQuillan, 2020; Filipe, 2022; Costa, 2022), as evidenced in Chart 4. Huang and Jin (2024) and McQuillan (2020) reinforce that hybrid approaches, combining craftsmanship and digital simulations, can maximize material utilization, particularly in methodologies aligned with zero waste. The results indicate a consensus on the role of 3D as a pre-prototyping technology capable of shifting structural decisions from the physical process to the virtual environment, acting as a preventive mechanism against environmental impacts, as defined in the first axis.

However, some studies highlight limitations; Santos, Silveira e Rech (2024), Costa (2022), Roque (2024), and Aguirre (2024) emphasize that the potential for material savings depends on the technical maturity of teams, corporate investment, the quality of digital models, and integration with production data. Thus, despite the consensus on benefits, the full effectiveness of 3D is not automatic, requiring institutional and technical conditions that remain unequal among Brazilian companies.

The second axis highlights 3D once again as a strategic tool to reduce the number of physical prototypes and accelerate processes. Studies such as Papahristrou and Bilalis (2017), Santos, Silveira and Rech (2024), and Casciani et al. (2022) demonstrate reductions in rework cycles, patternmaking errors, and approval times. In addition to waste reduction, the literature points to logistical and energy gains resulting from the decrease in samples sent between suppliers and manufacturers.

The analyzed studies also reveal that virtual prototyping generates significant organizational effects: greater creative assertiveness, process standardization, and strengthened communication between technical and creative teams (Filipe, 2022; Fernandes, 2022). However, these gains depend on initial investment, the learning

curve, and the reorganization of workflows. This condition reinforces that 3D adoption requires continuous planning and training to avoid duplicating stages or rework.

The third axis highlights transformations in the supply chain, especially regarding document digitalization, system integration, and process tracking. Casciani et al. (2022), Fernandes (2022), and Aguirre (2024) show that incorporating virtual samples and 3D files reduces travel, accelerates communication between suppliers, and improves input traceability, an aspect increasingly relevant given the demands for transparency and adherence to ESG goals. Furthermore, a considerable portion of the documents indicates that 3D software becomes more effective when associated with PLM/ERP systems, allowing integration between modeling, product engineering, cutting programming, and operational management.

The literature converges on the idea that positive environmental impact does not stem solely from the isolated use of 3D, but from the combination of digital information that connects data, reduces inconsistencies, and enables better planning of production resources. However, the lack of technological standardization among companies and infrastructure inequality still limit the expansion of these benefits in the Brazilian context. Few studies address accessible solutions for MSEs, revealing an important gap.

The fourth axis highlights an emerging dimension: the use of 3D resources in the consumer interface. Fernandes (2022) and Filipe (2022) discuss how digital showrooms, virtual try-ons (VTO), and hyperrealistic visualizations reduce return rates and assist in purchase decision-making. The results suggest that digital technologies have the potential to stimulate on-demand models, reducing inventory, deadstock, and disposal—relevant impacts within the logic of sustainability. Additionally, digitalization increases transparency regarding product composition and life cycle, strengthening responsible consumption practices. Nevertheless, part of the literature, such as Fernandes (2022), emphasizes that gains depend on the level of consumer adoption and device availability, showing that this branch of digital sustainability is still in a consolidation phase.

Overall, the analysis of the 30 documents demonstrates a consensus on the potential of 3D design software as a tool for environmental, operational, and strategic sustainability in the fashion sector. Based on thematic analysis, categories emerged that synthesize the main patterns of meaning present in the analyzed documents, which will be presented in Chart 6.

Chart 6 – Categories Identified in the Thematic Analysis

Thematic Category	Synthetic Description	Contribution of Studies
Digital Innovation and Production Transformation	Encompasses digitalization, automation, PLM, 3D CAD, and virtual prototyping	Time reduction, improved communication, increased precision, integration of stages
Sustainability and Impact Reduction	Environmental and economic benefits arising from the use of digital technologies	Waste reduction, lower raw material consumption, less physical prototyping
Technological Integration in the Industry 5.0 Context	Relationship between humanization, human–machine cooperation, personalization, and digitalization	Mass personalization, collaboration, user-centered development

Source: Prepared by the authors (2026).

Finally, the main gap identified in the literature consists of the scarcity of studies applied to the Brazilian context regarding the use of 3D design software for sustainability in micro and small enterprises, especially concerning practical implementation guidelines, in-depth cost-benefit analysis, and the development of public policies aimed at democratizing access. The gaps found in the literature are presented in Chart 7.

Chart 7 – Gaps Identified in the Literature

Gap	Description	Implications for Future Research
Scarcity of studies with Brazilian Micro and Small Enterprises	Predominance of foreign literature and focus on large companies	Need for analysis applied to the national production context
Lack of quantitative environmental metrics	Few studies measure actual reduction in waste, energy, or raw materials	Develop standardized metrics and measurable environmental indicators
Scarce documentation of comparative processes (traditional vs. digital)	Need for more studies comparing production workflows across different forms and realities	Experimental studies and comparative case studies are required
Low integration between 3D CAD and circularity	Circularity appears conceptually, without integrating digitalization	Further research combining 3D CAD with Product Life Cycle and regenerative design within the Brazilian reality
Lack of studies on technical training and qualification within the Brazilian reality	Lack of analysis on professional qualification gaps	Investigate digital competencies required for implementation
Lack of economic cost-benefit analyses	Few studies evaluate the financial return on digitalization	Economic analyses to guide decision-making in Micro and Small Enterprises (MSEs)

Source: Prepared by the authors (2026).

These findings reinforce the relevance of this research and justify the need for future investigations that articulate technology, sustainability, and innovation in diverse production contexts, expanding the possibilities for a sustainable digital transition in the national garment sector. Overall, the results show that 3D design software constitutes a strategic transformation tool, capable of simultaneously influencing the productive, environmental, organizational, and marketing dimensions of fashion. Although there is a consensus in the literature regarding its potential to reduce waste, optimize workflows, and promote greater transparency, structural challenges persist, especially concerning technological accessibility, professional training, and systemic integration between digital platforms. Thus, the discussion reveals an evolving field, where technological advances coexist with gaps that demand interdisciplinary approaches and policies to incentivize digitalization.

5 FINAL CONSIDERATIONS

The present study shows that structural problems in fashion, such as material waste, production surpluses, low circularity, and inefficiency in development workflows, remain central to contemporary debate. In this sense, understanding such impacts was fundamental to situating the role of digital technologies in a scenario that demands environmental responsibility, innovation, and alignment with sustainable practices in its processes.

Literature analysis revealed that 3D design software constitutes a strategic tool for fashion's transition toward Industry 5.0 principles by integrating creative, productive, and organizational processes through accurate and iterative simulations. Its applications encompass product development, advanced visualization, technical planning, and virtual prototyping, demonstrating the potential to reduce errors, accelerate workflows, strengthen team communication, and increase assertiveness in design decisions. In this context, the mapping of functionalities and applications of these softwares highlighted significant convergences regarding the role of 3D in fashion digitalization and in building more collaborative, intelligent, and sustainable processes.

The results also pointed out that 3D software contributes to waste reduction and the consolidation of practices aligned with circular fashion, primarily by allowing the shift of critical stages from physical to digital. The reduction in the number of prototypes, optimization of material use, simulation of fit and drape, integration with PLM/ERP systems, and the possibility of applying zero-waste techniques, remanufacturing, and information traceability emerge as key elements for a cleaner and more efficient production chain. Furthermore, the impacts of these technologies extend to logistics and marketing, enabling virtual samples, digital showrooms, and virtual fitting rooms that reduce travel, returns, and waste, thereby increasing transparency and encouraging more responsible consumption practices.

However, the consolidation of these technologies does not occur in a neutral manner or without negative impacts, requiring a critical stance regarding the limits of digitalization. Although 3D design mitigates solid textile waste during the development phase (Filipe, 2022), it introduces new socioeconomic and environmental challenges to the supply chain. From an ecological perspective, transitioning to purely virtual workflows creates a shift in impacts, resulting in high energy consumption and a digital carbon footprint driven by continuous cloud processing and complex renderings, a contradiction that can feed digital greenwashing practices if promoted as an absolute ecological solution while ignoring systemic sustainability indicators (Link, 2021).

Regarding the socioeconomic and structural pillars, the large-scale adoption of these systems deepens technological dependence on foreign software and creates exclusionary market barriers (Sayem, 2023; Papahristou; Bilalis, 2017). In the Brazilian apparel ecosystem, composed predominantly of small businesses facing structural precarity and capital constraints (MCTI, 2025), prohibitive implementation costs accentuate competitiveness issues relative to large corporations (Zanzi, 2022; Roque, 2024). Furthermore, within the context of Industry 5.0, which emphasizes inclusion, automation, and virtualization, coordinated policies are needed for workforce reskilling (Marshall et al., 2024).

As limitations of this study, we highlight the predominantly qualitative nature of the documentary anal-

ysis (Gil, 2010), relying on reviews that lack quantified empirical data regarding the actual balance between raw material and financial resources saved versus the energy consumed during digital processes. For future research, Life Cycle Assessment (LCA) studies are recommended to numerically measure these cross-ecological impacts, alongside applied research focused on inclusive training models (Baytar, 2017) to ensure the retention of traditional professionals within the emerging digital fashion ecosystem.

Therefore, despite the identified potential, this research acknowledges limitations related to unequal access to technology, training barriers, implementation costs, and the lack of technological standards among companies, particularly micro and small enterprises. These gaps reinforce the need to expand practical studies, deepen analyses of accessible adoption models, and investigate the impacts of 3D software across diverse production contexts. It is concluded, thus, that 3D design software serves as a promising instrument for the sustainable digital transition in fashion; however, its effectiveness relies on innovation policies, continuous investment, and technological governance strategies. Consequently, this study contributes to advancing the field and opens avenues for future research integrating technology, sustainability, and Industry 5.0 within the Brazilian apparel sector.

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