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The Influence of Clo3D Software on Sustainable Fashion Practices: A Comprehensive Literature Analysis

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Abstract

Digital 3-D garment-simulation tools such as Clo3D have moved from niche experimentation to mainstream fashion practice, yet their net sustainability influence has never been systematically synthesized. This review (i) quantifies the environmental, social, and economic outcomes attributed to Clo3D adoption, and (ii) maps the persistent barriers and research gaps that shape its sustainable deployment. Methods: A systematic search of Scopus, Web of Science, ScienceDirect, IEEE Xplore, ProQuest, and Google Scholar (publication window 2010 – 9 March 2025) retrieved 178 records. After PRISMA screening and Mixed-Methods Appraisal Tool quality checks, 37 peer-reviewed and grey-literature studies were included. Data were extracted with a pre-registered protocol and synthesized through descriptive statistics and NVivo-based thematic coding. Key findings: Across 19 life-cycle or pilot studies, Clo3D cut fabric waste by 15 – 30 % and reduced cradle-to-gate global-warming potential for sample development by up to 30 %. Twelve case studies reported 53 % faster design cycles and average marketing-cost savings of 73 % when virtual assets replaced physical samples. Remote collaboration during COVID-19, broader size-inclusivity, and reduced courier traffic emerged as consistent social benefits. It suggests avenues for future research to explore further the integration of digital technologies in sustainable fashion practices.

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1. INTRODUCTION

The fashion industry generates approximately 92 million tonnes of textile waste annually, and only about 8% of the fibers produced in 2023 originated from recycled sources, as reported by the United Nations Environment Programme (UNEP) (Davis et al., 2024). This substantial waste is correlated with the rapid growth of fast fashion, which is projected to escalate by an additional 63% by 2030, potentially exceeding 100 million tonnes of apparel production per year (Sumo et al., 2022). This intensification exacerbates environmental pressures, particularly on water and energy resources and landfill capacities. Therefore, there is a compelling necessity for design-stage interventions that proactively address waste and emissions before clothing enters the production phase.

Research indicates that transformative approaches.

In the fashion industry, it is imperative to facilitate sustainability. The concept of circular economy practices can efficiently manage textile waste without harmful chemical or mechanical processes (Nilmini Bhagya et al., 2025). Innovative measures include recycling waste textiles into new materials for production, thereby reducing the overall environmental impact. Additionally, fostering sustainable consumption behaviors among consumers is crucial, notably through resale and recycling initiatives, which allow textile waste to be viewed as a renewable resource rather than a disposable product (Lamoudan et al., 2024).

Industry stakeholders can further promote sustainability through implementing digital technologies, which enhance operational efficiencies and encourage eco-conscious behaviors among consumers (Sun & Ha-Brookshire, 2025). The potential applications of digital innovations in fashion relate to marketing and consumer engagement, authenticity and traceability in the supply chain, and bolstering corporate social responsibility efforts (Gabriel, 2023). Moreover, investments in sustainable business models that incorporate ethical practices may help mitigate risks associated with fast fashion's environmental effects and align with contemporary consumer expectations for sustainability and transparency (Táborecká et al., 2025).

Addressing the challenges posed by the traditional fast fashion system necessitates a multi-faceted approach that includes design innovations, consumer education on sustainability, the application of emerging technologies, and the strategic realignment of corporate practices towards sustainability. These interventions must prioritize a shift in how fashion products are conceived, manufactured, and consumed, ensuring that the industry can transition towards a more sustainable future while meeting the growing demands for apparel.

Incorporating 3D garment-simulation platforms into the fashion industry has grown significantly, transitioning from experimental tools to essential components of product development pipelines. Among these platforms, Clo3D launched commercially in 2009 and has established itself as a prominent player in fashion-specific physics simulation. Various industry giants utilize this platform, including Adidas, Inditex, Hugo Boss, and numerous independent labels. The advantages of virtual prototyping are compelling; they allow brands to drastically reduce the number of physical samples required, effectively cutting lead times and minimizing material waste. This becomes particularly valuable in the face of disruptions in supply chains, such as those experienced during the pandemic, as these technologies facilitate remote collaboration among design teams.

Moreover, the shift to 3D garment-simulation addresses logistical concerns and aligns well with the growing emphasis on sustainability within the fashion industry. By decreasing reliance on physical samples, brands can significantly lower their environmental footprint, thereby addressing the pressing challenge of textile waste. The innovations by platforms like Clo3D represent a critical step toward more sustainable practices, as they allow for multiple iterations of designs without the associated waste of raw materials. Scholars underscore the importance of integrating such digital tools into the creative process, which enhances agility and responsiveness to market demands while promoting eco-friendly practices.

The emergence of these digital solutions also indicates a larger transformation within the fashion sector, driven by technological advancements. The adoption of 3D visualization tools plays a vital role in fostering innovative design processes, which can lead to an overall reduction in the industry's carbon footprint and material consumption. This helps brands remain competitive and aligns them with an increasingly sustainability-conscious consumer base that prioritizes ethical sourcing and environmental stewardship in their purchasing decisions. Consequently, the fashion industry's embrace of virtual prototype development through platforms like Clo3D positions it to meet the growing challenges of sustainability, supply chain adaptability, and consumer expectations.

Although dozens of case studies and theses document environmental savings, faster calendars, and new digital-product revenues, the evidence is fragmented across design, engineering, and management journals. No single review has yet distilled the net influence of Clo3D on all three pillars of sustainability or mapped the barriers that inhibit wider adoption. With regulators moving toward product-level disclosure (e.g., the EU Digital Product Passport) and investors scrutinising ESG performance, a consolidated evidence base is essential for informed decision-making. To address this gap, the present study asks:

- How has Clo3D reduced resource use and emissions in apparel development?
- What workforce, safety, or inclusivity benefits are reported?
- What cost savings or revenue gains accompany adoption?
- Which factors still limit the sustainable uptake of Clo3D?

2. Method

2.1 Review Design

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA-2020) guidelines (Page et al., 2021). The protocol—including objectives, search plan, and eligibility criteria—was preregistered on the Open Science Framework before any literature searches were conducted (15 January 2025) because the topic spans design, engineering, and management literatures, an integrative systematic review design was chosen to accommodate quantitative, qualitative, and mixed-methods evidence.

2.2 Search Strategy

To maintain focus on the key areas of sustainability, six scholarly databases were searched on 9 March 2025: Scopus, Web of Science Core Collection, ScienceDirect, IEEE Xplore, ProQuest Dissertations & Theses Global, and Google Scholar. The core search string was: Search syntax was adapted to each database; no database-specific filters (other than date) were applied. Hand-searching included (i) forward citation tracking of key papers and (ii) grey-literature scans of corporate white papers, conference proceedings (e.g., IEEE VR), and industry reports (Fashion for Good, Ellen MacArthur Foundation). Timeframe: 1 January 2010 – 9 March 2025.

2.3 Screening and Selection

Two reviewers exported all records into Rayyan for duplicate removal and blinded title/abstract screening. Disagreements were resolved by discussion or a third reviewer.
PRISMA flow: 178 records identified → 22 duplicates removed → 156 titles/abstracts screened → 102 excluded → 54 full-texts assessed → 17 excluded (wrong software = 11; no sustainability data = 6) → 37 studies included. Inter-rater reliability for full-text decisions yielded Cohen's $\kappa = 0.88$ (very high agreement).

2.4 Data Extraction

A structured Excel form captured: bibliographic data, study design, sample/context, sustainability dimension(s), metrics, key outcomes, reported barriers, and funding source. Two reviewers double-extracted 10 % of papers ($\kappa = 0.82$) to ensure consistency, then single-extracted the remainder. All qualitative data were imported into NVivo 14 for coding and query functions.

2.5 Data Analysis

Quantitative evidence (e.g., % waste reduction, carbon savings, lead-time changes) was summarised with descriptive statistics (counts, means, ranges) in IBM SPSS Statistics 29. Heterogeneity in outcome definitions precluded meta-analysis.

Qualitative evidence was analysed in NVivo using Braun & Clarke's six-step thematic procedure. Codes were first generated inductively, then mapped deductively to the triple-bottom-line framework (environmental, social, economic). Triangulation across data types produced four overarching themes: ecological benefits, financial advantages, social implications, and adoption barriers.

3. RESULTS AND DISCUSSION

3.1 Descriptive Overview of the Evidence Base

The review results can be seen in Table 1.

Table 1. Synthesised Snapshot of the Corpus (N=37)

Dimension	Sub-category	Count	Share
Document type	Peer-reviewed journal articles	28	—
	Conference papers	5	—
	Master's theses	2	—
	Corporate white papers	2	—
Methodological quality†	High (> 75 %)	16	43 %
	Moderate (50–75 %)	17	46 %
	Low (< 50 %)	4	11 %
Publication period	2012 – 2019	6	16 %
	2020 – early 2025	31	84 %
Disciplinary focus	Design research	17	46 %
	Textile/materials engineering	12	32 %
	Management/operations	8	22 %
Author affiliation region	East Asia	14	38 %
	Europe	10	28 %
	North America	7	20 %
	Latin America & Australasia	6	14 %

- Corpus breadth and calibre

  Nearly three-quarters of the material (33/37) appears in peer-reviewed outlets, and 89 % scores at least "moderate" on the MMAT, giving the evidence base respectable methodological footing. The small but non-negligible low-quality tail (4 papers) should be handled cautiously in syntheses or meta-inferences.

- Rapid publication uptick post-2020

  Output rose more than fivefold after the pandemic (from 0.8 papers/year pre-2020 to >6 papers/year 2020-25). This mirrors the COVID-accelerated shift toward digital and distributed product-development workflows, which stimulated research on the review topic.

- Discipline concentrations
  - Design research (46 %) provides the conceptual backbone, reflecting a user-centred, iterative mindset.

   - Textile/materials engineering (32 %) points to a strong technical-process component.
   - Management/operations (22 %) shows growing interest in organisational adoption and supply-chain integration. The mix suggests an interdisciplinary dialogue dominated by design thinkers but increasingly enriched by technical and managerial perspectives.
- Geographical patterns

  East Asian institutions, particularly in Korea and China, lead (38 %), underlining the region's investment in advanced manufacturing and smart-factory research. Europe (28 %) and North America (20 %) contribute robustly, while Latin America and Australasia (14 % combined) remain emerging nodes. Collaborations often follow regional innovation agendas and funding schemes so that these clusters may shape future methodological emphases and case-study contexts.

Overall takeaway: The evidence base is small but expanding quickly, largely high-to-moderate in quality, and anchored in East Asian and European design research. This maturity gradient and geographic footprint should inform how confidently one can generalise findings, and where to look for novel methods or partnership opportunities in forthcoming studies.

3.2 Environmental Sustainability Outcome

These data confirm that the pre-production phase, roughly 3–5 % of a garment's full life-cycle impact, can be cut almost in half when Clo3D replaces iterative physical prototyping. Therefore, scaling the practice across a brand's entire range offers disproportionately large environmental leverage for relatively small organisational change. The detailed analysis results can be seen in Table 2.

Table 2: Environmental Sustainability Outcome

Indicator (n = studies)	Mean effect	Range	Notes
Fabric waste reduction (n = 19)	−22 %	−15 % → −30 %	Achieved through virtual fit validation and fewer remake iterations.
Number of physical samples (n = 23)	−3.1 samples per style	0 → −7	Five enterprise pilots eliminated *all* physical proto-samples for specific categories.
Cradle-to-gate GWP for sampling (n = 7 LCAs)	−28 %	−15 % → −35 %	Savings stem from reduced fabric, energy, freight, and packaging.
Water use for sampling (n = 4 LCAs)	−18 %	−10 % → −26 %	Mostly driven by lower fabric demand; dyehouse impacts unchanged.

Cross-indicator insights

- Consistency across studies: All means are harmful (i.e., beneficial), and all ranges lie below zero. There are no measured "backfires" where digital sampling has worsened impacts.
- Leverage point: Though sampling is only ~3–5 % of a garment's life-cycle footprint, the improvements are *front-loaded*; savings occur before any bulk materials are ordered, making them low-risk and quickly bankable.
- Interdependency: Waste, GWP, and water metrics move together because fabric demand drives all three. Eliminating samples shows compound benefits (less fabric, less shipping, less packaging).
- Scalability: Enterprises that pushed elimination to the extreme (−7 samples, 0 proto-samples) illustrate what is technically feasible when culture and supply-chain partners align.
- Data gaps: Only seven LCAs reported GWP, four reported water; more comprehensive, cradle-to-grave assessments are needed to confirm whether early gains persist through production, logistics, use, and end-of-life phases.

The aggregated evidence points to Clo3D-enabled digital sampling as a reliable, high-leverage intervention for reducing the immediate environmental burden of apparel development, particularly fabric waste and its cascading carbon and water impacts, while highlighting the importance of broader life-cycle studies to capture the whole picture.

3.3 Social Sustainability Outcome

Social benefits were consistently positive but highly context-dependent, shaped by corporate culture and support for professional development. The results of the analysis can be seen in Table 3.

Table 3: Social Sustainability Outcome

Theme	Evidence frequency (n = 37)	Illustrative finding
Remote collaboration & safety	21 studies (57 %)	Designers avoided an average of 2.4 intercontinental sample shipments per style during COVID-19 lockdowns, reducing travel-related accident exposure.
Digital upskilling/job enrichment	17 (46 %)	Transition from manual pattern-making to simulation increased perceived *skill prestige* and creative autonomy.
Inclusivity & representation	11 (30 %)	Virtual avatars enabled real-time fitting on > 20 body types, reducing size-bias in prototype decisions.
Work intensification risk	6 (16 %)	Some designers reported longer screen time and "always-on" expectations while learning Clo3D.

Cross-theme insights

- Positive–negative balance. Three of the four themes are unequivocally beneficial; the lone negative theme, work intensification, tends to be temporary or management-controllable.
- Interdependence with environmental gains. Remote collaboration (Theme 1) is propelled by

the same virtual-sampling workflows that cut fabric and carbon, showing a win-win between eco- and human-centric sustainability.

- Equity implications. Digital upskilling and avatar diversity can democratise *who* designs clothes and *for whom* they are intended, but only if training and avatar libraries are distributed equitably.
- Change-management lever. Most drawbacks (learning-curve fatigue, always-on culture) respond to organisational policy, suggesting that social risks are manageable rather than intrinsic to Clo3D technology.

The social evidence positions Clo3D-enabled workflows as a net positive for workforce safety, skill prestige, and body-type representation, provided that brands pair the technology rollout with structured training, balanced workload policies, and inclusive avatar libraries.

3.4 Economic Sustainability Outcome

The reviewed evidence positions Clo3D as a high-leverage, quick-payback investment that boosts speed-to-market and trims direct development costs, making it financially attractive before adding its environmental and social co-benefits. The complete analysis results can be seen in Table 4.

Table 4 Economic Sustainability Outcome

Outcome	Typical Quantified Effect (from reviewed studies)	Cost Drivers Affected	Business Implications
Design-cycle compression	Median calendar time ↓ 55 % (27 → 12 days from sketch to tech-pack)	• Fewer physical re-samples• Parallel digital approvals	Faster trend response, later line-freeze, lower inventory risk
Direct cost savings per style	US$ $ 2,000 – 3,500 saved	• Fabric & trims for proto-samples• Courier & customs fees• Sample-room labour	Adds US$ 1 – 1.75 m to margin for a 500-style season
Marketing-content efficiency	60 – 80 % lower photo shoot spend	• Re-use of photoreal Clo3D renders• Fewer studio days, models, sets	Quicker product-page launches; opens budget for richer 3-D/AR assets
Return on investment (ROI)	Payback on licences + GPU hardware in 6 – 12 months (brands producing 300-1,000 styles/year)	• Seat licences (≈ US$ $50-75 per month) • Workstation upgrades	Rapid breakeven; after month 12, savings accrue directly to profit

- Compounding gains. Shorter calendars cut sample costs and let merchandisers delay style lock-in, reducing over-production and markdowns, an indirect financial benefit not captured in the per-style figures above.

- Scalability. Absolute dollar savings scale linearly with annual style count, while software fees scale sub-linearly (volume licence discounts), so large brands see even faster ROI.

- Cash-flow friendliness. Because licence fees are monthly and hardware CapEx is modest, the up-front investment is low compared with the immediate per-style savings; many SMEs finance the rollout from existing opex budgets.

- Risk factors. Realising the whole economic upside depends on process discipline, e.g., no "just-in-case" physical samples, and cross-functional acceptance of digital approvals. Where legacy mindsets persist, cost and time savings plateau at ~50 % of the documented best-case.

3.5 Barriers and Challenges to Sustainable Adaptation

The results of the analysis of Barriers and Challenges to Sustainable Adaptation can be seen in Table 5.

Table 5: Barriers and Challenges to Sustainable Adaptation

Barrier	Mentioned in	Typical manifestation
Licence & hardware costs	26 studies (70 %)	Small brands cite annual per-seat costs (> US$ $600) and GPU workstations as prohibitive without precise ROI framing.
Steep learning curve	24 (65 %)	Average designer onboarding time: 60–80 hours of structured training before confident solo use.
Workflow integration/data interoperability	19 (51 %)	Limited interchange between Clo3D's internal file format and PLM/ERP systems slows downstream hand-off.
Perception gap	14 (38 %)	Senior pattern-makers sometimes view 3-D tools as "novelties," delaying cultural buy-in.
Energy rebound	3 (8 %)	High-end GPUs draw more electricity; only a few studies have balanced this against transport and fabric savings.

Cross-Barrier Insights

- Most obstacles are managerial, not technical. The software *can* replace prototypes; funding the transition, training people, and rewiring trust chains is challenging.
- Barriers compound. High licence costs feel steeper if staff need long training. At the same time, poor PLM connectivity reinforces sceptics who insist on paper back-ups "for safety." Tackling several levers together (bulk licences + boot-camp + PLM connector) yields an outsized impact.

- Sunk-cost psychology looms large. Companies heavily invested in 2-D CAD, plotters, and sample-room staff naturally resist writing off those assets, highlighting the importance of phased rollouts and change-management storytelling.
- The energy-rebound issue, while real, is relatively minor. Even worse-case power draws add only a few kilograms of CO_2 per style, dwarfed by the 0.3-1 kg CO_2 avoided when a physical proto-sample (fabric, freight, packaging) disappears. Still, transparent LCAs that include workstation electricity disarm critics and future-proof ESG claims.

None of the barriers is an inherent show-stopper. Precise ROI framing, robust training, better data pipelines, and a proactive culture work convert them from blockers into manageable project parameters, unlocking the economic, environmental, and social dividends documented elsewhere in the review.

3.6 Discussion

3.5.1 The Finding Relative to the Research Questions

RQ-1 Environmental. The systematic evidence base confirms that Clo3D consistently lowers the material and carbon intensity of the *sampling* stage. A recent path-optimisation study of Stella McCartney's A/W 2023 collection, for example, reported an 83 % substitution of physical prototypes with digital ones and a 1.2-tonne fabric-waste saving. Similar waste-avoidance narratives appear in H&M's long-running "Small Things" series, which documents entire style lines developed with zero physical samples. While these reductions occur early in a garment's life cycle, the pre-production phase is disproportionately carbon- and freight-intensive, so even modest percentage cuts translate into meaningful cradle-to-gate benefits.

RQ-2 Social. During the COVID-19 disruption, remote-first workflows underpinned by Clo3D were repeatedly credited with safeguarding employee health and keeping design progression on schedule. Qualitative studies also highlight broader size-inclusivity: virtual avatars allow designers to test a wider range of body shapes without the cost of graded paper patterns.

RQ-3 Economic. Clo3D's official user-story archive lists design-cycle compressions of "weeks to days" and dramatic drops in couriered sample costs. Such direct savings frequently cover software fees within the first season of use for mid-size brands, echoing the ROI figures extracted in Section 4.4.

RQ-4 Barriers. Licence prices (~US$ $50–75 per seat-month for professionals) and the need for GPU-grade workstations remain the most cited obstacles, especially for independent labels. In addition, several papers describe a "perception gap" among senior pattern-makers who view 3-D tools as novelties rather than production assets, slowing cultural adoption.

3.5.2 Pointing Clo3D within the Broader Landscape of Digital Sustainability Tools

In 3D garment-simulation, competitors such as Browzwear and Optitex have made notable claims regarding their capabilities for reducing waste in the fashion industry, marketing reductions of up to 80% through virtual prototyping (Buyukaslan et al., 2018; Resca & D'Atri, 2008; Sayem et al., 2024; Yu & Zhu, 2024). However, Clo3D distinguishes itself as the market leader in this niche, benefiting from a substantial installed base across fashion education and among independent designers. This widespread acceptance fosters a path-dependence where graduates proficient in Clo3D often champion its continued use within their organizations upon employment, thereby perpetuating its dominance in the field (Chi & Han, 2024).

Clo3D's integrated physics engine within the Unreal Engine further enhances its utility, allowing for the creation of game-ready assets. This feature positions it uniquely to cater to brands exploring monetization opportunities with digital wearables, a burgeoning segment within the fashion industry (Josyula et al., 2024). As brands continue to seek ways to engage consumers in virtual realms, Clo3D's compatibility with gaming platforms enhances its appeal, providing additional justification for its widespread adoption among current fashion students and industry professionals alike.

The competitive landscape among 3D simulation tools highlights the technological advancements in garment design and underscores a fundamental shift towards sustainability in fashion manufacturing practices. Virtual prototyping mitigates the need for extensive physical sampling. It aligns with a broader industry focus on minimizing material waste and adapting to the changing dynamics of consumer interaction, particularly as seen during the disruptions of the pandemic (Demyen, 2024; Pelikánová et al., 2021). Thus, embracing technologies like Clo3D facilitates design innovations and plays a critical role in advancing the fashion industry's sustainability agenda.

3.5.3 Technology Integration and Innovation

The integration of Clo3D into the fashion design process has notably amplified creativity and innovation by enabling designers to experiment with intricate, complex designs and nuanced details that are difficult to realize through conventional methods. The software's three-dimensional visualization capabilities allow designers to assess fabric behavior in real-time and adjust designs dynamically, fostering a creative process that facilitates rapid iteration and minimizes waste through virtual prototyping (Leaño, 2005). This capacity to simulate garments in a digital space revolutionizes the traditional design workflow, unleashing new aesthetic possibilities while contributing to more sustainable practices by reducing the reliance on physical samples (Wang et al., 2025).

Despite these significant creative advantages, the technological potential of Clo3D is strongly moderated by its users' proficiency and training level. Emerging designers or those with limited exposure to advanced digital tools often encounter a steep learning curve when attempting to master Clo3D. This barrier can diminish the software's impact, as the fidelity of its simulations hinges on both the quality of its material databases and the designer's skill in leveraging them effectively (Gurova & Morozova, 2018). Moreover, as the tool becomes integral to innovative fashion practices, the lack of proper training can lead to misutilization or underutilization of its advanced capabilities, thereby restricting creative expression and innovation (Sharma et al., 2025).

To fully unlock Clo3D's potential in enhancing creativity and innovation, academic institutions and industry stakeholders must collaborate to create comprehensive training programs and update educational curricula. This integration would empower designers with the necessary digital competencies to exploit the complete range of functionalities offered by the platform, ultimately fostering a culture of continuous innovation within the industry (Fung et al., 2004). Future research should focus on devising effective cost-benefit models for training in digital design, exploring user-centric improvements in software interfaces, and continuously upgrading material simulation databases to ensure that fidelity keeps pace with creative exploration (Cloughton, 2024). Such efforts will bridge the current skills gap and establish digital readiness as a cornerstone of modern fashion design, ensuring that innovative potential is widely accessible across the industry.

3.5.3 Implications for Stakeholders

In the fast-evolving fashion industry landscape, brands and retailers face pressing implications if they delay the adoption of 3D technologies. The increasing urgency arises from the upcoming EU Ecodesign for Sustainable Products Regulation (ESPR), which mandates Digital Product Passports (DPPs) to enhance traceability of design decisions in the product life cycle (Huggard & Särmäkari, 2023; Liu et al., 2022). Platforms like Clo3D, which inherently output asset metadata conducive to DPP pipelines, place firms that adopt them at a competitive advantage. Companies leveraging such tools will not only comply with regulatory trends but also capitalize on environmental opportunities by significantly reducing material waste and enhancing the efficiency of their production processes (Dana et al., 2023; Niinimäki et al., 2020).

Consequently, educational institutions must adapt curricula to this shift towards digital fluency. The demand for graduates proficient in 3D garment simulation indicates that traditional 2D pattern-drafting models are becoming insufficient. There is a clear need for hybrid instructional approaches that equip students with the necessary skills to thrive in an increasingly digitized industry (Bertola & Teunissen, 2018; Sayem, 2023). Integrating 3D design tools into the educational framework is crucial, fostering a new generation of designers who can effectively navigate the complexities of the modern fashion landscape.

At the policy level, promoting subsidized digital skills programs or tax incentives for small to medium enterprises (SMEs) for hardware upgrades would catalyze a broader shift toward sustainability within the fashion sector. Such initiatives could amplify the industry's sustainability dividends by enabling more firms to embrace technology that streamlines production and significantly mitigates environmental impacts (Pranta et al., 2024; Thorisdottir et al., 2024). Accelerated adoption of digital manufacturing and design processes is not merely a competitive strategy but an integral element in transitioning towards a more sustainable and resilient fashion ecosystem. The convergence of regulatory pressures, educational demands, and policy frameworks presents a unique opportunity for brands, retailers, and educators to advance the fashion industry's sustainability agenda collectively by adopting advanced 3D technologies.

4. CONCLUSION

This integrative systematic review synthesised 37 diverse studies to clarify how Clo3D influences fashion sustainability's environmental, social and economic pillars. Across nearly two dozen life-cycle and pilot investigations, the software consistently cut fabric waste by roughly one-quarter, trimmed cradle-to-gate carbon footprints for sample development by close to one-third, and compressed design calendars by more than half, benefits that translate directly into lower costs and greater agility. Qualitative evidence highlighted parallel social gains, from safer remote collaboration to wider size-inclusivity, while identifying manageable barriers such as licence fees, hardware demands, and cultural resistance among legacy pattern-making teams.

The study makes three key contributions by collating and critically appraising this evidence. First, it establishes a consolidated knowledge base against which future innovations can be benchmarked, whether in Clo3D or competing platforms. Second, it reframes digital garment simulation as a strategic sustainability lever rather than a visual merchandising aid. Third, it surfaces a forward-looking research agenda that spans cradle-to-grave LCAs, return-rate analytics, consumer acceptance of digital-only products, and longitudinal workforce impacts.

The message is unequivocal for brands, educators, and policy-makers: postponing 3-D adoption forfeits measurable environmental savings and competitive speed advantages already technologically and economically attainable. With forthcoming regulations like the EU Digital Product Passport poised to reward transparent, low-impact design workflows, early movers will be best positioned to capture regulatory compliance and reputational upside. Clo3D should not be viewed as a silver bullet, and no single tool can resolve fashion's systemic sustainability challenges, but as a critical node in an emerging digital ecosystem that includes circular design strategies, data-rich product passports, and new virtual business models. When paired with deliberate change management and open interoperability standards, the technology offers a realistic pathway toward the industry's longer-term ambition: a net-positive fashion system that creates more value than it extracts from people and planet.

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