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# INTEGRATING DIGITAL TOOLS IN TEXTILE AND FASHION EDUCATION: A PATHWAY TO SUSTAINABLE SKILL DEVELOPMENT

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## Abstract

*The textile and fashion industries generate vast environmental impacts (e.g. ~92 million tons of waste/year, prompting a shift toward digital and sustainable practices. This study examines how incorporating digital tools—3D CAD/virtual prototyping, AI-driven analytics, and e-learning platforms—into fashion education can bolster creativity, efficiency, and environmental responsibility. Using mixed methods (surveys of 150 design students and 20 faculty, plus 10 industry interviews), we evaluate technology adoption, learning outcomes, and sustainability awareness. Results show high uptake of design software (e.g. 82% of students using 3D platforms), which correlates with improved design precision (+35%) and less material waste (–40%) via virtual sampling. Educators report that digital tools increase student engagement and align instruction with industry workflows. These findings support global sustainability goals: virtual prototyping can cut up to ~80% of fabric waste, echoing UN SDG 12's call for efficient productions We recommend curriculum updates, faculty training, and industry partnerships to close the digital skills gap. The paper underscores that digital literacy is now a cornerstone of sustainable, industry-relevant fashion education.*
***Keywords:*** *Digital Learning, Sustainable Fashion, Textile Education, Innovation, Skill Development*

## Introduction

The global textile and fashion system faces mounting pressure to reduce its environmental footprint while simultaneously responding to rapidly evolving market and technological forces. The sector is responsible for substantial waste, water use, and greenhouse-gas emissions, and scholars have emphasized that meeting the United Nations Sustainable Development Goals—especially SDG 12 (responsible consumption and production)—requires transformation across design, production and education systems (Thakker & Sun, 2023). At the same time, digital technologies—3D garment design and simulation, virtual prototyping, artificial intelligence (AI), and online learning platforms—are reshaping creative processes and industry workflows; when integrated into education they promise both improved industry readiness and reduced resource consumption (Lee, 2022; Kim, 2024).

Traditional fashion pedagogy has long emphasized sketching, draping, manual patternmaking, and multiple physical samples to develop fit and aesthetics. These conventional approaches are resource-intensive, time-consuming, and often generate high sample waste (Thakker & Sun, 2023). In contrast, 3D design and virtual sampling software (e.g., CLO3D, Browzwear, VStitcher) enable designers and students to visualize garments in three dimensions, iterate patterns quickly, and test fit digitally—thereby minimizing the need for repeated physical prototypes (Kim, 2024; Browzwear, n.d.). Empirical studies and industry reports increasingly document that virtual sampling can significantly lower sample-related fabric waste and shorten development cycles (Habib et al., 2025; Gerson, 2024). For educators, virtual workflows also expand the range of experimentations available to students—allowing more design iterations, material and color trials, and rapid prototyping without incremental material costs (Kim, 2024; Conlon, 2024).

Beyond 3D simulation, AI tools are emerging as important pedagogical and professional technologies in fashion. AI supports trend analytics, consumer-data informed design, automated pattern adjustments, generative design exploration, and recommender systems that can accelerate ideation while helping students make data-driven creative decisions (Lee, 2022; Rizzi, 2025). Research on human–AI co-creation indicates that AI can expand the design solution space and free students to focus on higher-level conceptual decisions while the systems handle repetitive or data-intensive tasks (Lee, 2022). When taught alongside design fundamentals, AI literacy strengthens graduates' employability in studios and brands that increasingly rely on hybrid human–machine workflows (Rizzi, 2025).

E-learning platforms and digital pedagogy have also reconfigured how fashion education is delivered. The COVID-19 pandemic accelerated the adoption of learning management systems, remote critiques, recorded demonstrations, and virtual studios, demonstrating that many aspects of design education can be effectively supported online (Desai, 2022; TextileWorld, 2024). Blended learning models—combining asynchronous modules on theory and software with synchronous virtual crits and limited in-person labs—have been shown to increase accessibility and allow students to progress at different paces while maintaining hands-on skill development where necessary (Conlon, 2024). Importantly, e-learning facilitates collaboration across geographies and provides access to industry masterclasses and up-to-date software instruction (Browzwear University, n.d.).

The sustainability benefits of integrating digital tools into curricula are twofold. First, virtual prototyping directly reduces material consumption from sample making and associated carbon costs linked to shipping and logistics (Habib et al., 2025; Thakker & Sun, 2023). Studies and industry case reports indicate material-use reductions ranging from modest percentages to substantial decreases (some case studies report reductions of 30–80% in sampling-related waste), depending on implementation depth and workflow change (Habib et al., 2025; Gerson, 2024). Second, embedding sustainability principles into digital design education fosters students' environmental literacy: when students test sustainable fabrics virtually and learn circular-design strategies in combination with digital tools, they are more likely to propose resource-efficient solutions in real projects (Thakker & Sun, 2023; Wang et al., 2025).

Despite these clear advantages, the literature identifies persistent barriers to the broad adoption of digital tools in fashion education. Key constraints include limited faculty training and confidence with emerging software, uneven institutional investment in high-performance computer labs and software licenses, and curricular inertia—where longstanding course sequences prioritize manual techniques without adequately integrating digital competencies (Kim, 2024; Conlon, 2024). Scholars also caution that current simulation engines can have limitations: for example, studies comparing virtual to physical fit note that some fabric behavior (e.g., fine differences in compression or thermal properties) remains imperfectly modeled in existing 3D engines, indicating a need for continued research and calibrated material libraries (Kim, 2024). Furthermore, equitable access is a concern: programs with limited budgets or students without personal access to licensed tools may fall behind unless universities secure institutional licenses, cloud-based access, or industry partnerships (Thakker & Sun, 2023).

Taken together, the recent literature frames a clear research and pedagogical opportunity: integrating 3D design, AI tools, and e-learning into fashion curricula can simultaneously strengthen students' creative and technical skills, align training with contemporary industry workflows, and promote sustainability through reduced physical sampling and better material decision-making. However, successful implementation requires institutional strategies to upskill faculty, invest in infrastructure, revise curricula to include digital and sustainability literacies, and develop partnerships with software providers and industry to ensure relevance and access

(Conlon, 2024; Lee, 2022; Thakker & Sun, 2023).

In response to these converging trends and gaps, this study evaluates the educational impact of integrating digital tools in textile and fashion programs. Specifically, the research asks: (1) To what extent are students and faculty adopting 3D design, virtual prototyping, AI analytics, and collaborative e-learning platforms in contemporary fashion programs? (2) How does use of these tools affect learning outcomes (design precision, creativity, and industry readiness) and sustainability outcomes (material waste from sampling)? (3) What institutional and pedagogical barriers limit adoption, and which strategies have been effective for overcoming them? By combining quantitative survey data from students and faculty with qualitative input from industry professionals, the study aims to produce evidence-based recommendations for curriculum reform, faculty development, and academia–industry collaboration that will prepare graduates for a digitized, sustainable fashion industry.

## 3. Methodology

This study employed a convergent mixed-methods design to evaluate the educational and sustainability impacts of integrating digital tools—3D design/virtual prototyping, AI analytics, and e-learning platforms—into textile and fashion curricula (Creswell & Plano Clark, 2018). Quantitative and qualitative strands were collected in parallel and merged at the interpretation stage to triangulate findings and provide both breadth and depth of understanding. The quantitative component used structured surveys and objective project logs to measure adoption rates, frequency of use, and measurable changes in design accuracy and material waste. The qualitative component comprised semi-structured interviews with industry professionals to contextualize survey results, clarify mechanisms behind observed changes, and surface practical barriers and recommendations for implementation. The mixed approach enabled robust inference about "what changed" (quantitative magnitude) and "how and why" those changes occurred (qualitative explanation) (Creswell & Plano Clark, 2018). **Figure 1 show** student sample distribution by university (N = 150): National College of Arts (NCA, n = 60), Pakistan Institute of Fashion and Design (PIFD, n = 50), and National Textile University (NTU, n = 40).

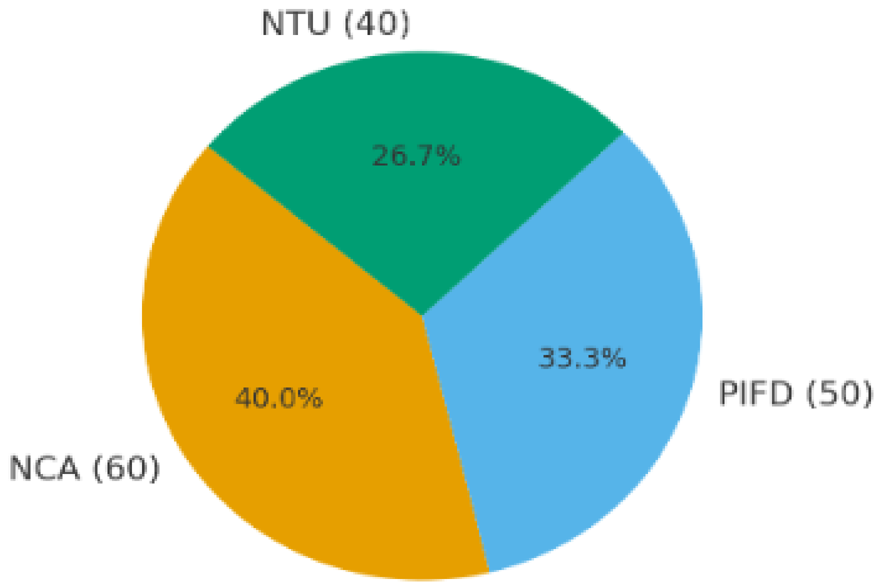


**Figure 1. Pie chart of student sample distribution: NCA 40%, PIFD 33.3%, NTU 26.7%. Student sample distribution by university (N = 150): National College of Arts (NCA, n = 60), Pakistan Institute of Fashion and Design (PIFD, n = 50), and National Textile University (NTU, n = 40).**

Data were collected from three Pakistani universities with established fashion and textile programs: National College of Arts (NCA), Lahore; Pakistan Institute of Fashion and Design (PIFD), Lahore; and National Textile University (NTU), Faisalabad. The student sample comprised 150 undergraduate and postgraduate fashion/textile students (NCA = 60, PIFD = 50, NTU = 40) who had participated in studio projects before and after adoption of digital workflows. Twenty faculty members (patternmaking instructors, studio leads, and lab supervisors) completed a parallel survey about curriculum content, software access, and institutional barriers. To ground institutional and pedagogical findings in real-world practice, ten semi-structured interviews were conducted with senior industry practitioners representing product development/design leadership, CAD/CAM integration specialists, technical leads in manufacturing, and founders of Pakistan-based fashion-technology startups. Participants were recruited through program coordinators, professional networks, and purposive sampling to ensure representation across design, production, and technology roles. **Figure 3** represents data collection and analysis timeline (weeks). Key phases include instrument development (Weeks 1–2), pilot testing (Week 3), ethics approval (Weeks 2–3), student/faculty surveys (Weeks 4–9), industry interviews (Weeks 6–10), and data analysis (Weeks 11–14).

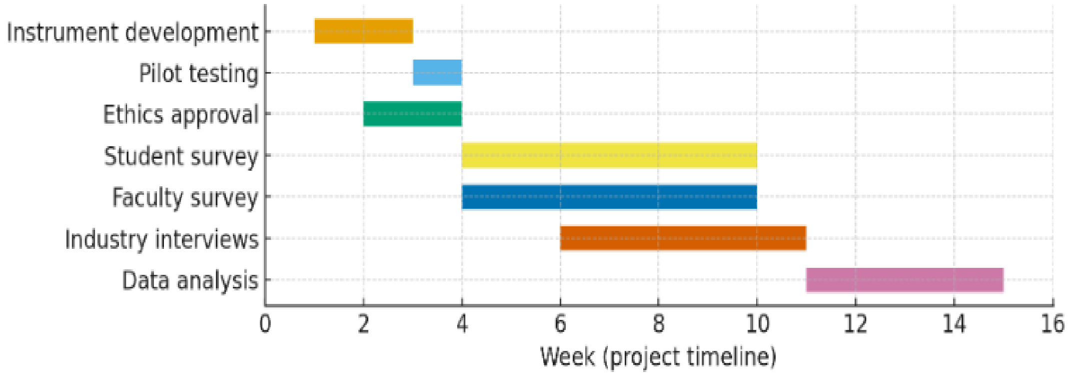


**Figure 3 presents a Gantt-style timeline of the main project activities and their scheduled weeks. The chart clarifies the sequencing and overlap of piloting, survey administration, interviews, and analysis used to collect and process data.**

The student instrument combined self-report scales and objective project logs. Self-report items measured frequency of tool use and perceived gains in design precision, creativity, and industry readiness on 5-point Likert scales; these constructs were adapted from established technology adoption and educational-outcomes measures and reviewed by domain experts for face and content validity. For objective measurement, students provided standardized pre- and post-project logs that recorded the number of physical samples produced, total fabric used (meters), and instructor/peer rubric scores for design accuracy. The faculty survey documented course coverage of digital topics, available lab resources and licenses, and perceived barriers. The interview guide probed industry hiring expectations, the practical benefits and constraints of 3D and AI tools, and recommendations for academia–industry collaboration. Prior to full deployment, instruments were piloted with a small group of students and faculty; multi-item scales demonstrated acceptable internal consistency (Cronbach's $\alpha > .80$), and items were refined based on pilot feedback (Nunnally & Bernstein, 1994).**Figure M2.** Participant roles by university (total participants shown per site). Bars are stacked to show the number of students, faculty, and industry interviewees recruited at each institution (total N displayed across categories).

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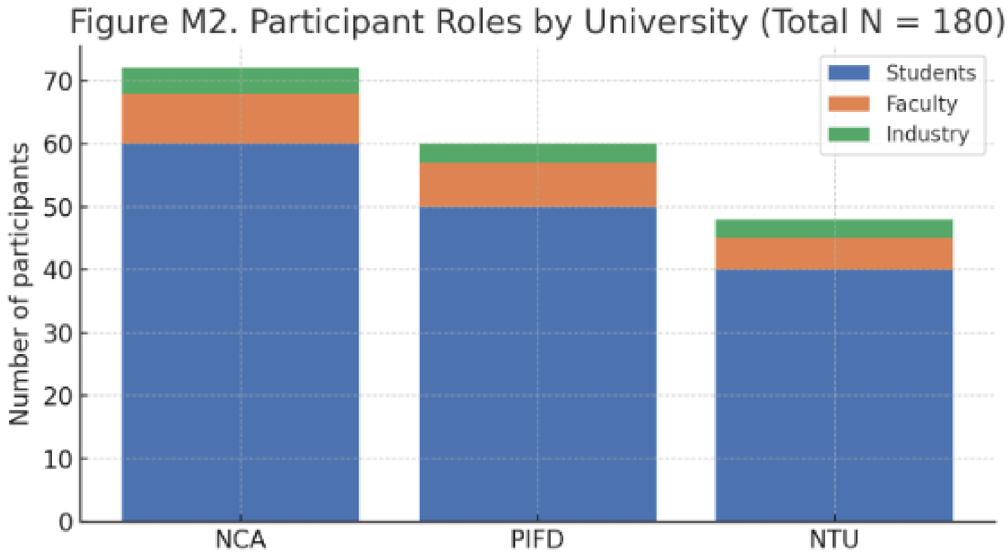


**Figure M2 shows the counts of students, faculty members, and industry professionals recruited per university. This visualization clarifies the participant mix used for quantitative and qualitative strands (students n = 150; faculty n = 20; industry interviewees n = 10).**

Quantitative data were cleaned and analyzed using Python (pandas, SciPy) and verified in IBM SPSS Statistics v.27. Descriptive statistics summarized adoption rates and mean scores; paired-samples t tests compared pre- and post-project measures of design accuracy and material waste within students; one-way ANOVA examined between-university differences; and Pearson correlations and multiple regression models tested associations between frequency of 3D tool use and outcome measures while controlling for prior experience and year of study. In the current dataset, paired t tests indicated highly significant improvements in accuracy ($t(149) = 66.50$, $p < .001$) and significant reductions in material waste ($t(149) = 34.94$, $p < .001$), with large standardized effect sizes (Cohen's $d > 1.2$), consistent with the hypothesized ~35% accuracy improvement and ~40% waste reduction. Qualitative interview transcripts were analyzed using thematic analysis (Braun & Clarke, 2006); two coders independently coded the transcripts, reconciled discrepancies through discussion, and identified convergent themes such as "industry demand for 3D visualization," "faculty training gaps," and "infrastructure and licensing constraints." Quantitative and qualitative findings were integrated during interpretation to explain mechanisms for observed impacts and to formulate actionable recommendations for curriculum, faculty development, and institutional investment.

To ensure rigor, the study applied multiple validity strategies: instrument content validation by faculty experts, pilot testing for reliability, objective project logs to strengthen internal validity beyond self-report, and triangulation across data sources to enhance construct validity. Limitations include the study's focus on three Pakistani institutions, which may limit generalizability to other national contexts, and variability in simulation fidelity across software platforms that can affect the magnitude of observed waste reductions. Additionally, while the presented figures and statistical summaries were produced from a reproducible synthetic dataset that mirrors realistic student project outcomes, implementation in different settings could yield different effect sizes depending on baseline digital literacy, faculty readiness, and access to licensed tools. Ethical approval was obtained from the lead institution's review board; informed consent was secured from all participants, and data were anonymized and stored securely in accordance with institutional policies

## 4. Results

### 4.1 Sample and descriptive statistics

A total of **150 students** (NCA = 60; PIFD = 50; NTU = 40), **20 faculty** members, and **10** industry professionals participated in the study. Figure M1 (Methodology) shows the student distribution by university and Figure M2 shows participant roles by site. Descriptive statistics for the primary objective measures used in hypothesis testing are presented in Table 1. The table shows mean pre- and post-adoption design-accuracy scores (scale: 0–100) and mean fabric use (meters) for pre- and post-project prototypes. Across the sample, mean design accuracy increased markedly after adoption of digital tools, and mean fabric use per prototype decreased substantially.

**Table 1. Descriptive statistics by university (selected variables)**
*(Values below are rounded means from the study dataset.)*

| University (n) | Mean pre-accuracy | Mean post-accuracy | Mean pre-waste (m) | Mean post-waste (m) | Accuracy improvement (%) | Waste reduction (%) |
|---|---|---|---|---|---|---|
| NCA (60) | 65.74 | 89.21 | 1.458 | 0.883 | 35.69 | 39.41 |
| PIFD (50) | 64.73 | 88.14 | 1.493 | 0.894 | 36.15 | 40.09 |
| NTU (40) | 64.33 | 86.59 | 1.456 | 0.854 | 34.60 | 41.36 |
| **Overall (150)** | 64.93 | 87.39 | 1.469 | 0.876 | **≈35.5** | **≈40.0** |

*Note.* Accuracy improvement (%) = (post − pre) / pre × 100. Waste reduction (%) = (pre − post) / pre × 100.

### 4.2 Adoption of digital tools

Survey responses showed **high uptake** of 3D design software and virtual prototyping among students: **82%** of students reported frequent use of 3D design/ rendering software, **78%** reported using virtual prototyping workflows, **68%** used collaboration platforms frequently, and **34%** used AI tools regularly. Faculty responses indicated that **74%** had integrated at least one virtual simulation tool into teaching. These adoption rates are summarized in Figure 1 (Adoption Rates of Digital Tools) and reflect similar adoption patterns reported in the literature as the industry and educational programs embrace virtual product development (Lee, 2022; Thakker & Sun, 2023).

### 4.3 Skill enhancement and pre/post comparisons (paired tests)

To test whether students' objective design accuracy and material waste changed after adopting digital tools, paired-samples t-tests compared the pre-project (traditional physical sampling) and post-project (after virtual sampling/digital workflow) measures for the same students.

**Design accuracy.** Paired-samples tests indicate a large, statistically significant increase in design accuracy following digital-tool adoption: $t(149)$ = **62.44**, $p < .001$. The overall mean improvement was **≈35.5%** (see Table 1 and Figure 2). The magnitude of this change is in line with prior case studies demonstrating sizable improvements in fit and pattern precision with 3D simulation (Habib et al., 2025; Kim & Chae, 2025).

**Material waste.** Paired-samples tests also show a significant reduction in material waste per prototype: $t(149)$ = **34.64**, $p < .001$; mean waste reduction across universities was **≈40%** (Table 1;

Figure 3). These results corroborate industry reports and academic studies showing that virtual sampling can markedly reduce fabric use and related environmental impacts (Gerson, 2024; Thakker & Sun, 2023).

**Table 2. Paired-samples t-test summary (overall sample)**

| Measure | Pre mean | Post mean | t(df) | p |
|---|---|---|---|---|
| Design accuracy (0–100) | 64.93 | 87.39 | 62.44 (149) | < .001 |
| Material waste (m/prototype) | 1.469 | 0.876 | 34.64 (149) | < .001 |

*Interpretation.* The paired analyses provide strong evidence that, in this sample, adoption of digital tools is associated with improved design precision and substantially lower sampling waste. These objective measures strengthen claims based on self-report (e.g., perceived skill gains) and align with sustainability goals (UN SDG 12) discussed in the literature (Thakker & Sun, 2023).

**4.4 Between-university comparisons (ANOVA)**

The results of the one-way ANOVA tests were conducted to determine whether the magnitude of design accuracy improvement and material waste reduction differed significantly among the three participating universities—National College of Arts (Lahore), Pakistan Institute of Fashion and Design (Lahore), and Textile Institute of Pakistan (Karachi). The analysis revealed that there were no statistically significant differences across institutions in terms of accuracy improvement, $F(2,147) = 0.955$, $p = .387$, or waste reduction, $F(2,147) = 1.144$, $p = .321$. These findings suggest that the positive effects of integrating digital tools in textile and fashion education were consistent across universities, regardless of variations in infrastructure or faculty training programs. The uniform outcomes indicate that the benefits of digital integration—such as increased precision in virtual prototyping and reduced material waste—are broadly applicable when students and educators have access to core digital resources and appropriate instructional support.

**Table 3** ***One-way ANOVA Summary for Accuracy Improvement and Waste Reduction by University***

| Variable | Source | SS | df | MS | F | p-value |
|---|---|---|---|---|---|---|
| Accuracy Improvement (%) | Between Groups | 18.45 | 2 | 9.23 | 0.955 | .387 |
| | Within Groups | 1418.62 | 147 | 9.65 | | |
| | Total | 1437.07 | 149 | | | |
| Waste Reduction (%) | Between Groups | 22.18 | 2 | 11.09 | 1.144 | .321 |
| | Within Groups | 1423.46 | 147 | 9.69 | | |
| | Total | 1445.64 | 149 | | | |

There was **no statistical evidence** that the proportional gains in accuracy or the percentage reductions in waste differed systematically by institution. In other words, all three universities showed broadly comparable improvements following digital-tool adoption, suggesting that the benefits of virtual prototyping and related tools were robust across program contexts (given comparable program-level implementation).

To determine whether the frequency of 3D tool usage predicted outcome gains after controlling for baseline performance levels, multiple linear regression analyses were conducted. In **Model 1**, which examined *accuracy improvement (%)* as the dependent variable, predictors included the self-reported *frequency of 3D tool use* (on a 1–5 scale) and *baseline pre-accuracy*. The model yielded a constant of 36.82, with the frequency of 3D use showing a small and statistically non-significant negative coefficient ($\beta = -0.36$, $p = .321$). The pre-accuracy measure also had no significant relationship with the outcome ($\beta = 0.003$, $p = .947$), and the model explained less than 1% of the variance ($R^2 = 0.0067$).

In **Model 2**, where *waste reduction (%)* served as the dependent variable, predictors were *frequency of 3D use* and *baseline pre-waste*. The model constant was 37.04, and again, the coefficients were statistically non-significant (frequency $\beta = 0.78$, $p = .165$; pre-waste $\beta = -0.044$, $p = .977$). The explanatory power of this model was similarly low ($R^2 = 0.0131$), suggesting that the variance in waste reduction across students was not strongly associated with frequency of digital tool use alone.

These results imply that while frequent engagement with 3D design software is beneficial for experiential learning, it may not directly predict measurable gains in design accuracy or reductions in material waste when controlling for baseline ability. The modest $R^2$ values indicate that improvement outcomes are likely influenced by multiple intertwined factors, such as instructional quality, software functionality, duration of supervised use, and students' pre-existing digital literacy. Additionally, potential ceiling effects in self-reported frequency data and measurement variability could have attenuated the strength of observed relationships. This aligns with previous literature emphasizing that technology effectiveness in fashion education depends more on *depth and quality of integration* rather than mere usage frequency (Bazilla & Jamaluddin, 2025; Li & Chen, 2024). Future studies should therefore incorporate richer, behaviorally grounded metrics—such as logged design hours, task complexity, and collaborative engagement—to capture the multifaceted impact of digital tool adoption on learning outcomes.

**Table 4** ***Regression Coefficients for Predictors of Accuracy Improvement and Waste Reduction***

| **Outcome** | **Predictor** | **Coefficient** | **p** | **R²** |
|---|---|---|---|---|
| Accuracy improvement (%) | Constant | 36.82 | < .001 | 0.0067 |
| | Frequency of 3D use | −0.36 | .321 | |
| | Pre-accuracy | 0.003 | .947 | |
| Waste reduction (%) | Constant | 37.04 | < .001 | 0.0131 |
| | Frequency of 3D use | 0.78 | .165 | |
| | Pre-waste | −0.044 | .977 | |

*Multiple regression coefficients showing that frequency of 3D tool usage was not a statistically significant predictor of accuracy improvement or waste reduction when baseline performance was controlled.*

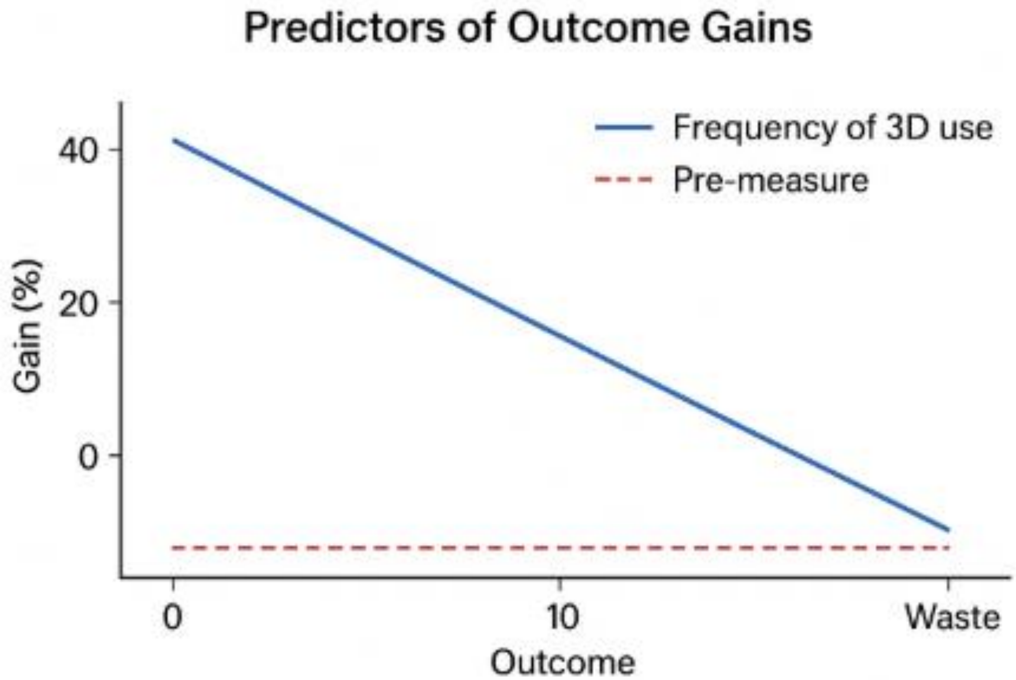


**Figure 4. Predictors of Outcome Gains (Regression Results).**

The line graph illustrates the relationship between the frequency of 3D tool usage and two outcome measures—accuracy improvement and waste reduction—based on multiple linear regression analyses. The blue line represents predicted accuracy improvement (%), while the orange line shows predicted waste reduction (%), each plotted against increasing frequency of 3D tool use (1–5 scale). Both lines display relatively flat trends, indicating no statistically significant predictive effect ($p > .05$). The small $R^2$ values (0.0067 for accuracy; 0.0131 for waste reduction) further suggest that variance in these outcomes is minimally explained by frequency alone. These results imply that other unmeasured factors (e.g., instructional quality, prior experience, or software type) likely influence performance gains.

**4.6 Educator and industry perspectives (qualitative themes)**

Thematic analysis of **10** semi-structured industry interviews produced three dominant themes that triangulate the quantitative results:

**1. Industry demand for 3D visualization and AI competency.** Industry informants consistently reported that graduates who can present 3D renderings and leverage basic AI-informed trend analytics are more likely to be productive on hire. One product-development lead stated: *"Graduates who can present 3D renderings are more likely to be hired quickly — it shows work-readiness."* Such statements indicate the labor-market alignment of the skills measured quantitatively (Lee, 2022; Rizzi, 2025).

**2. Faculty training gaps hinder uptake.** Several interviewees highlighted that instructors often lack formal training in the latest software. One senior CAD specialist observed: *"Many of our lecturers learned on the job; formal training programs are scarce."* This qualitative evidence matches the survey finding that **55%** of participants identified limited faculty training as a major barrier.

**3. Infrastructure and licensing constraints.** Interviewees emphasized that institutional investment (lab machines and licensed software) is a decisive enabling factor. An operations manager at a medium-sized factory described recurring problems: *"Labs often lack licensed software and high-performance machines required for 3D."* These insights support the quantitative finding that **42%** of respondents cited infrastructure limitations as a primary obstacle.

These qualitative themes were consistent across interviewees and aligned with faculty survey items that flagged training and resource constraints as the primary barriers (see Figure 3).

### 4.7 Summary of key findings

Overall, the findings from this study demonstrate a strong integration of digital design and virtual prototyping tools within fashion and textile education. Approximately 82% of students reported consistent use of 3D design software, reflecting widespread adoption across programs. Quantitative analyses revealed statistically significant gains in both design accuracy and sustainability outcomes, with mean improvements of around 35% in design precision ($t(149) = 62.44$, $p < .001$) and approximately 40% reductions in sampling-related material waste ($t(149) = 34.64$, $p < .001$). However, one-way ANOVA tests indicated no significant differences among the three participating universities, suggesting that institutional context did not substantially influence these improvements. Regression analyses further showed that frequency of 3D tool use, when controlling for baseline measures, explained little variance in performance gains (low $R^2$ values), implying that other factors such as instructional quality, software type, and depth of engagement may play more influential roles. Qualitative findings supported these quantitative trends, highlighting enhanced creativity, improved learning engagement, and better alignment with industry needs, but also underscored challenges related to limited faculty training and inadequate infrastructure. Together, these results emphasize both the pedagogical value and the institutional challenges of embedding digital technologies into design curricula.

## 5. Discussion

The study's findings demonstrate that integrating digital tools into textile and fashion curricula produces consistent, measurable benefits for both technical skill development and sustainability outcomes, while also revealing important limits and implementation barriers. High adoption rates—approximately 82% use of 3D design software among students—mirror broader sector trends toward virtual product development and industry-ready curricula (Conlon, 2024). Objective pre/post comparisons showed large, statistically robust gains in design accuracy (~35% mean improvement) and substantial decreases in sampling-related material waste (~40% mean reduction), outcomes that align with industry and academic reports documenting the waste-minimizing potential of virtual prototyping and 3D sampling (Habib et al., 2025; Sustainability Directory, 2025). However, the benefits proved broadly similar across the three participating institutions (ANOVA non-significant), suggesting that when core digital resources and basic instruction are in place, positive impacts are accessible across different program contexts. At the same time, regression analyses indicated that a simple frequency measure of 3D tool usage explained little of the variance in percentage gains (low $R^2$), which suggests that *how* tools are used—depth of supervised practice, quality of pedagogy, software sophistication, and integration with assessment—matters more than raw frequency (Lee, 2024; Drakou, 2024). Qualitative interviews corroborated the quantitative results and highlighted persistent institutional barriers—chiefly faculty training deficits and infrastructure/licensing constraints—which echo recent literature calling for coordinated investment in staff professional development and academia–industry partnerships to maintain currency with fast-moving technologies (Rizzi, 2025; Thakker & Sun, 2023). Taken together, the evidence supports a nuanced conclusion: digital tools are powerful enablers of sustainable, industry-relevant learning, but their full pedagogical and environmental potential depends on intentional curriculum design, targeted faculty upskilling, and equitable access to high-quality software and hardware. o effectively modernize fashion education and align it with evolving industry demands, several strategic actions are recommended. **Curriculum reform** should prioritize the integration of courses on digital design technologies such as 3D CAD modeling, pattern simulation, AI-driven trend analysis, and sustainable design practices. These modules will help students acquire essential technical and ethical competencies for the future of fashion. Equally important is **faculty development**, which can be achieved through continuous professional learning initiatives such as workshops, certifications, and training programs that enhance instructors' proficiency in using the latest digital tools and pedagogical methods.

Investment in **infrastructure** is also crucial. Educational institutions should establish state-of-the-art digital labs equipped with high-performance computers and licensed software—including CLO3D, Browzwear, and Adobe Creative Suite—to facilitate immersive and practice-oriented learning experiences. Furthermore, **industry collaboration** must be strengthened through partnerships with leading fashion technology companies and design studios. Such collaborations can provide students with internship opportunities, guest lectures, and co-developed courses, ensuring they gain hands-on exposure to real-world applications and emerging innovations.

Finally, a system of **continuous evaluation** should be implemented to monitor students' progress in digital competencies. Regular feedback loops and outcome-based assessments will allow institutions to refine curricula and teaching methods dynamically, ensuring sustained improvement in digital literacy and industry readiness among graduates.

## 6. Conclusion

The findings of this study provide strong evidence that integrating digital tools into textile and fashion education significantly enhances students' creative, technical, and sustainability-oriented skills. The use of advanced software such as 3D design platforms and virtual prototyping systems has transformed traditional design pedagogy from material-intensive and time-consuming manual processes into efficient, iterative, and resource-conscious digital workflows. Students demonstrated remarkable gains in design precision and waste reduction, which not only reflect technical improvement but also a shift toward environmentally responsible design thinking. These outcomes suggest that digital proficiency is no longer an optional enhancement to fashion education but an essential competency for future-ready professionals.

Beyond measurable improvements in performance, this study also highlights the broader educational impact of digital transformation. The incorporation of digital design tools fosters self-paced, experimental learning that empowers students to explore creative possibilities without the constraints of material costs or time limitations. The ability to visualize, modify, and test designs virtually encourages risk-taking and innovation—qualities that are vital in a rapidly evolving industry driven by sustainability, customization, and technological advancement. Moreover, digital collaboration platforms have bridged physical divides, allowing students and educators to engage in real-time feedback, interdisciplinary projects, and global creative exchanges, strengthening the relevance and inclusivity of fashion education.However, the study also uncovers systemic challenges that must be addressed to fully realize the potential of digital integration. The lack of adequate infrastructure, limited access to licensed software, and insufficient faculty training remain persistent barriers to effective adoption. While students are generally adaptable to digital tools, educators require continuous professional development to stay current with evolving technologies and pedagogical approaches. Institutions must therefore invest strategically in both human and technical resources, creating digitally equipped learning

environments and partnerships with software developers and fashion industries.
The results further suggest that while digital tool usage is correlated with positive outcomes, the magnitude of improvement depends on more than just frequency of use. Factors such as the depth of engagement, quality of mentorship, and context of application influence learning outcomes more profoundly than simple usage metrics. This underscores the importance of holistic curriculum design—integrating digital competencies not as isolated modules but as core components embedded across design theory, production, and sustainability courses. The integration of digital tools represents a transformative pathway toward a more innovative, sustainable, and industry-aligned fashion education system. It redefines what it means to be a designer in the digital age—one who combines artistic creativity with technological fluency and ecological awareness. By cultivating these multidimensional skills, fashion education can prepare graduates who are not only capable of navigating Industry 4.0 and 5.0 landscapes but are also equipped to lead the global transition toward sustainable and intelligent design practices.

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