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3D Garment Design and Virtual Prototyping as Tools for Sustainable Clothing Production

Nasara, E. S., Ojike, P. M., Enefola, W. G., Osabo, P. O. & Anda, S. A. D.[5]
1,3&4 Department of Home and Rural Economics,

College of Agriculture Science & Technology, Lafia, Nigeria

2 Joseph Sarwuan Tarka University, Makurdi. Department of Family and Consumer Sciences

nasaraedith63@gmail.com

Abstract

This study examined 3D garment design and virtual prototyping as tools for sustainable clothing production among fashion designers in Nasarawa State, Nigeria. Specifically, the study established the perceived effectiveness of 3D garment design in improving pattern accuracy and reducing material waste, evaluated the perceived contribution of virtual prototyping to reducing reliance on physical garment sampling, and determined the perceived contribution of 3D garment design and virtual prototyping to sustainable clothing production. A descriptive survey research design was adopted. The population of the study comprised 1,625 fashion designers in Nasarawa State, from which a sample of 120 respondents was purposively selected. The respondents were practicing fashion designers whose activities involved garment design and production. Data were collected using a researcher-developed 3D Garment Design and Virtual Prototyping Questionnaire (3DGPQ), which was validated by three experts. Data were analyzed using mean and standard deviation, with a criterion mean of 3.00 for decision-making. Tailornova was presented as an illustration of a digital platform for 3D garment design and virtual prototyping rather than as an experimentally evaluated intervention. Findings showed that respondents agreed that 3D garment design contributes to improved pattern accuracy and reduced material waste, with mean scores ranging from 3.29 to 3.45 and a grand mean of 3.38. Respondents also agreed that virtual prototyping contributes to reducing reliance on physical garment sampling, improving garment fitting and design adjustments, reducing repeated sewing of garment samples, and supporting more efficient garment development, with mean scores ranging from 3.33 to 3.44 and a grand mean of 3.39. Respondents perceived 3D garment design and virtual prototyping as contributing to sustainable clothing production through efficient use of production resources, improved production workflow, reduced production time, and improved production efficiency, with mean scores ranging from 3.35 to 3.42 and a grand mean of 3.39. These findings represent respondents' perceptions and not direct measurements of material savings, sampling reduction, production efficiency, or sustainability performance. In conclusion, 3D garment design and virtual prototyping are perceived as useful digital approaches for improving garment development and supporting sustainable clothing production. It recommends increased adoption of digital garment technologies by fashion designers, practical training and capacity development, integration of these technologies into clothing and textile education, and institutional support for improved access to relevant digital infrastructure.

Keywords: 3D Garment Design, Virtual Prototyping, Sustainable Clothing Production, Pattern Accuracy.

Introduction

Sustainable fashion focuses on reducing negative environmental impact through efficient use of resources, waste minimization, and the adoption of innovative production methods. The need for

sustainability in fashion is driven by several factors, including the rapid growth of fast fashion, increasing consumer awareness of environmental issues, and the global push toward responsible production and consumption practices. In particular, garment production processes such as repeated physical sampling, fabric wastage during cutting, and inefficient pattern development contribute significantly to resource depletion and environmental pollution (Niinimäki et al., 2020). These challenges point out the need for alternative approaches that can improve efficiency while reducing material waste.

One of the emerging solutions is the integration of digital technologies, particularly three-dimensional (3D) garment design and virtual prototyping. The concept of 3D refers to the representation of objects in three dimensions length, width and depth allowing for realistic visualization and simulation of physical items in a digital environment. In the context of fashion design, 3D garment design involves the use of computer-aided design (CAD) systems to create, simulate, and evaluate garments virtually before physical production. This enables designers to assess garment fit, structure, and appearance without the need for multiple physical samples (Tantawy et al., 2024).

Enabling virtual visualization and testing, 3D garments design and virtual prototyping have the potential to significantly reduce material waste, minimize production time, and improve overall efficiency in garment development. These technologies align with sustainability goals by reducing reliance on physical resources and supporting more environmentally responsible production practices. As a result, increasingly being examined as viable tools for transforming traditional garment production into a more sustainable system.

Garment design is a technically intensive process that involves a sequence of interrelated stages, including design conceptualization, pattern drafting, sample construction, fitting, evaluation, and repeated modification. This process requires the transformation of design ideas into structured garment forms through pattern making, which plays a central role in garment production by converting design concepts into wearable products (Habib & Alam, 2024). The execution of these stages depends on continuous testing and refinement to achieve acceptable fit, structure, and visual appearance. The reliance on physical sampling introduces significant inefficiencies in garment production. Conventional pattern-making and sample development require repeated operations, including drafting, grading, and reconstruction of garment prototypes, which consume time, labor, and material resources (Mostafa & Mohamed, 2025). These repeated processes increase production cost and extend development timelines, particularly when multiple alterations are required to correct fitting errors or structural inconsistencies. To address these limitations, digital garment technologies have been introduced to enable virtual design and evaluation. Three-dimensional garment design systems allow garments to be constructed and assessed in digital environments, reducing the dependence on physical samples. Such systems provide capabilities including virtual draping, 2D-to-3D pattern conversion, and simulation of garment fit and behavior Habib & Alam (2024). These functionalities improve development efficiency by allowing designers to evaluate multiple design options before physical production. Lee (2023) developed multiple weaving methods for producing three-dimensional virtual textiles using recycled clothing waste.

Digital tools have also been applied in fashion design education. Tantawy et al., (2024) demonstrated the use of three-dimensional design software to simulate garment development processes, enabling users to construct garments in a virtual environment. Similarly, Papahristou & Zolota Tatsi (2024) showed that training in digital prototyping improves spatial reasoning, technical understanding, and design accuracy. While these studies confirm the effectiveness of digital tools in skill development, they do not establish a direct connection between these skills and measurable improvements in production efficiency or material reduction in industrial settings.

The transition from manual to digital pattern-making has been examined, for example, Habib and Alam (2024) showed that three-dimensional design systems provide functionalities such as virtual

draping, pattern unfolding, and ease allowance calculation, which reduce the need for repeated manual adjustments. These systems allow users to generate multiple design variations within a shorter time frame. Similarly, Mostafa and Mohamed, (2025) demonstrated that integrating two-dimensional pattern software with three-dimensional simulation tools improves prototype accuracy and reduces errors before physical production. However, these studies are based on limited experimental scenarios and do not evaluate performance across diverse garment categories or large-scale production systems.

Advancements in virtual garment simulation and fit analysis have introduced systems that combine body scanning, physics-based modeling, and computational techniques to evaluate garment performance. These systems allow designers to assess how garments behave under different conditions, including movement and fabric deformation. While improving accuracy in fit prediction, it requires specialized knowledge and computational resources. There is no detailed analysis of their cost implications or their compatibility with existing production workflows.

Consumer-oriented applications, particularly virtual try-on systems, have also been developed using artificial intelligence techniques. Khogare et al., (2025) identified key components such as computer vision, deep learning, and generative modeling that enable real-time garment visualization. These systems improve personalization and reduce product return rates, however, their impact on production efficiency remains indirect, as they do not quantify how improved consumer interaction influences manufacturing processes or material usage.

3D-garment design provides many benefits for clothing production, particularly in reducing waste of materials and simplifying the design process. Virtual prototyping enables designers to digitally create and test garments before producing physical samples, reducing the need for fabrics, trims and other resources that might be wasted during sampling. This can help decrease the environmental impact associated with the production of garments, including the waste that comes from physical samples and related production activities (McQuillan & McQuillan, 2020). The application of 3D technology can also decrease the necessity for multiple physical samples, which can lead to a reduction in sampling costs and shorten the duration for garment development (Choi, 2022). Besides reducing physical sampling, 3D garment design enables designers to visualize garments digitally and evaluate features such as fabric drape, fit and color variations on digital avatars prior to manufacturing (Choi, 2022). The technology also gives realistic three-dimensional images of garments to help communicate design changes among designers, manufacturers and marketers including teams working remotely (Conlon et al., 2024). Designers can experiment complex structures of garments and virtual fabrics that may be difficult to manipulate physically, thus enabling creativity and innovation during the design process (Wang et al., 2023). The 3D garment assets resulting from this can also be used for digital showrooms and online marketing. Here, companies can showcase their designs and measure customer interest before full production (Mesjar et al., 2023). Overall, 3D technology transforms the traditional, linear fashion process into a faster, more flexible and eco-friendlier digital workflow.

Recent developments include user-driven garment design systems that allow non-experts to participate in garment creation. Zang et al., (2025) introduced a sketch-based system that generates three-dimensional garments from simple user inputs using a diffusion-based model. The system is supported by a dataset linking sketches to garment structures, enabling it to produce detailed outputs from imprecise input. While this approach increases accessibility and supports customization, it does not evaluate whether the generated designs can be efficiently translated into production-ready patterns or integrated into manufacturing workflows. Similarly, Viziteu and Curteza (2024) demonstrated the use of three-dimensional modeling and printing technologies to produce customized garments and reduce sampling. Their work highlights improvements in design flexibility and reduction in prototype production. However, challenges related to material properties, production speed and cost remain unresolved, limiting large-scale application, despite the growing body of research on 3D garment design and virtual prototyping, much of the existing literature

focused on the technical capabilities of digital garment technologies, including design visualization, simulation, pattern development, and virtual sampling. It seems like the benefits may not necessarily reflect how practicing fashion designers in local production environments perceive and apply these technologies. In particular, limited empirical evidence is available on the perceived contribution of 3D garment design and virtual prototyping to material waste reduction, reduction of physical garment sampling, and sustainable clothing production among fashion designers in Nasarawa State. This research addresses the continued dependence on physical garment sampling and garment development processes that can contribute to material waste, repeated sampling, increased production costs, and extended development time. Although digital garment technologies offer alternative approaches to garment design and virtual evaluation, limited empirical evidence exists on how practicing fashion designers in Nasarawa State perceive their contribution to addressing these production challenges. Therefore, this study examines fashion designers' perceptions of the effectiveness of 3D garment design in improving pattern accuracy and reducing material waste, the contribution of virtual prototyping to reducing reliance on physical garment sampling, and the contribution of both technologies to sustainable clothing production.

Objectives of the Study

The main objective of the study is to examine 3D garment design and virtual prototyping as tools for sustainable clothing production

The specific objectives of this study are:

1. Establish the effectiveness of 3D garment design in improving pattern accuracy and reducing material waste in clothing production.
2. Evaluate the perceived contribution of virtual prototyping to reducing reliance on physical garment sampling.
3. Determine the perceived contribution of 3D garment design and virtual prototyping to sustainable clothing production.

Methodology

Research Design

This study adopted a descriptive survey research design to examine fashion designers' perceptions of 3D garment design and virtual prototyping in clothing production among fashion designers in Nasarawa State. The design focused on collecting respondents' views on material usage, garment sampling, and production efficiency.

Population of the Study

The population of the study comprised 1,625 fashion designers in Nasarawa State. The population covered practicing fashion designers within the study area, including independent fashion designers, operators of fashion houses, and instructors in clothing and textile training centers who were actively involved in garment production.

Sample Size and Sampling Technique.

The sample for the study consisted of 120 fashion designers drawn from the population of 1,625 fashion designers in Nasarawa State. The sample size of 120 was predetermined for the study based on the scope of the survey and the need to obtain responses from practicing fashion designers with relevant experience in garment design and production.

Purposive sampling was used to select the respondents. The selection focused on practicing fashion designers whose activities involved garment design and production, including pattern development, fabric cutting, garment construction, fitting, and alteration. The respondents were drawn from independent fashion designers, operators of fashion houses, and instructors in clothing and textile training centers. These categories were selected because their practical involvement in garment design and production enabled them to provide informed responses to the questionnaire items on 3D garment design, material utilization, virtual prototyping, physical garment sampling, production efficiency, and sustainable clothing production. A total of 120 fashion designers selected on this basis participated in the study.

Instrument for Data Collection

The instrument used for data collection was a 3D Garment Design and Virtual Prototyping Questionnaire (3DGPQ) developed by the researcher in line with the objectives of the study. The instrument consisted of three sections:

i. **Section A:** 3D garment design and material waste reduction (5 items)
ii. **Section B:** Virtual prototyping and garment sampling reduction (6 items)
iii. **Section C:** Sustainability and production efficiency (6 items)

The instrument was subjected to face and content validation by three experts from Nasarawa State University, Keffi (NSUK), Lafia branch: two experts in Clothing and Textiles and one expert in Home Management. Their inputs ensured clarity, relevance, and adequacy of the items in measuring the variables of the study. All necessary corrections were affected before final administration.

A pilot study was conducted using 20 fashion designers outside the study area. The data obtained were analyzed using Cronbach's Alpha to determine internal consistency. The reliability coefficients obtained was at 0.82 indicating that the instrument was reliable for the study. The questionnaire was administered directly to the respondents by the researcher with the assistance of research assistants from Nasarawa State University, Keffi (NSUK).

Method of Data Analysis

Data collected were analyzed using mean and standard deviation.

A decision rule was established using a criterion mean of 3.00. Accordingly, items with a mean score of 3.00 and above were interpreted as Agreed, while items with a mean score below 3.00 were interpreted as Disagreed.

Results and Discussions

Table 1 presents the mean responses on the perceived effectiveness of 3D garment design in improving pattern accuracy and reducing material waste. The mean scores ranged from 3.29 to 3.45, with all the items above the criterion mean of 3.00. The highest-rated item was that 3D garment design improves pattern drafting accuracy (Mean = 3.45), while the lowest-rated item was that it reduces errors during garment construction (Mean = 3.29). The grand mean of 3.38 indicates that the respondents agreed that 3D garment design contributes to improved pattern accuracy and reduced material waste in clothing production.

Table 1: Mean Responses on the Perceived Effectiveness of 3D Garment Design in Improving Pattern Accuracy and Reducing Material Waste.

S/N	Statement	Mean	Std. Dev.	Decision
1	3D garment design improves pattern drafting accuracy	3.45	0.62	Agreed
2	It reduces fabric wastage during cutting processes	3.38	0.58	Agreed
3	It reduces errors during garment construction	3.29	0.64	Agreed
4	It improves efficient utilization of fabric materials	3.36	0.57	Agreed
5	It enhances precision in garment production	3.43	0.59	Agreed

Grand Mean = 3.38

Figure 1 presents the Tailornova interface as an illustration of a digital platform for 3D garment design and virtual prototyping. The interface displays design options, a technical sketch of the garment, and corresponding pattern pieces, illustrating how garment designs and patterns can be visualized digitally before physical production. Tailornova was presented in this study to illustrate the application of virtual prototyping; it was not experimentally evaluated by the respondents.

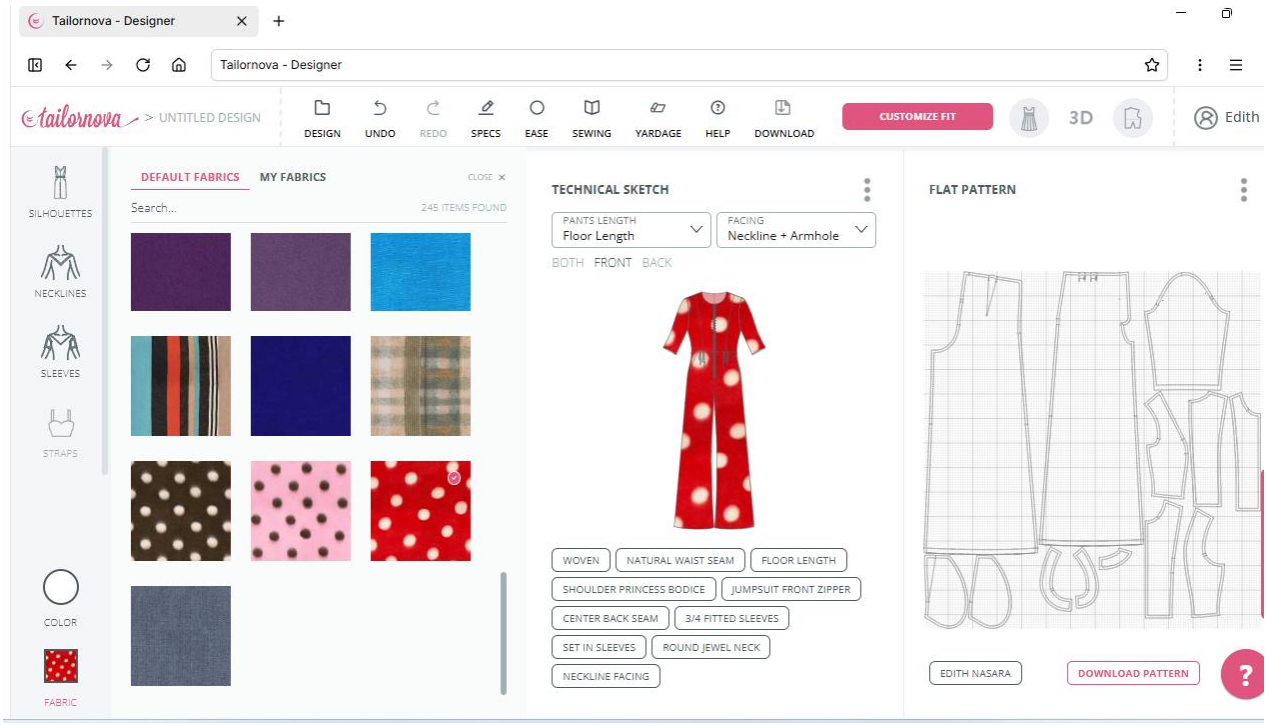


Table 2 presents the respondents' perceptions of the contribution of virtual prototyping to reducing reliance on physical garment sampling. The mean scores ranged from 3.33 to 3.44, with all the items above the criterion mean of 3.00. The highest-rated item was that virtual prototyping saves time during garment development (Mean = 3.44), while the lowest-rated item was that it reduces repeated sewing of garment samples (Mean = 3.33). The grand mean of 3.39 indicates that the respondents agreed that virtual prototyping contributes to reducing reliance on physical garment sampling and supports garment fitting, design adjustment, time saving, and reduced material costs during garment development. These findings represent the respondents' perceptions and not direct measurements of reductions in physical samples, production time, sampling costs, or materials used.

Table 2: Mean Responses on the Perceived Contribution of Virtual Prototyping to Reducing Reliance on Physical Garment Sampling

S/N	Statements	Mean	Std. Dev.	Decision
1	Virtual prototyping reduces the need for physical garment samples	3.41	0.55	Agreed
2	It improves garment fitting before production	3.36	0.61	Agreed
3	It reduces repeated sewing of garment samples	3.33	0.59	Agreed
4	It saves time during garment development	3.44	0.57	Agreed
5	It improves design adjustments before production	3.39	0.60	Agreed

6	It reduces the cost of materials used for garment sampling	3.42	0.56	Agreed

Grand mean = 3.39

Table 3 presents the respondents' perceptions of the contribution of 3D garment design and virtual prototyping to sustainable clothing production. The mean scores ranged from 3.35 to 3.42, with all the items above the criterion mean of 3.00. The highest-rated item was the efficient use of production resources (Mean = 3.42), while the lowest-rated item was the reduction of environmental waste in clothing production (Mean = 3.35). The grand mean of 3.39 indicates that the respondents agreed that 3D garment design and virtual prototyping contribute to sustainable clothing production through efficient use of production resources, improved production workflow, reduced production time, and improved production efficiency. These findings represent the respondents' perceptions of the contribution of these technologies and not direct measurements of sustainability performance.

Table 3: Mean Responses on the Perceived Contribution of 3D Garment Design and Virtual Prototyping to Sustainable Clothing Production

S/N	Statements	Mean	Std. Dev.	Decision
1	It enhances efficient use of production resources	3.42	0.58	Agreed
2	It reduces environmental waste in clothing production	3.35	0.63	Agreed
3	It improves garment production workflow	3.39	0.57	Agreed
4	It reduces time spent on garment production	3.37	0.59	Agreed
5	It supports sustainable clothing production practices	3.41	0.56	Agreed
6	It improves overall efficiency in garment manufacturing	3.40	0.58	Agreed

Grand Mean = 3.39

Discussion

The findings of this study provide empirical insight into the perceived effectiveness of three-dimensional (3D) garment design and virtual prototyping in promoting sustainable clothing production among fashion designers in Nasarawa State. The results from Table 1 revealed that 3D garment design is perceived to reduce material waste through improved pattern accuracy, minimization of cutting errors, and efficient utilization of fabric. This finding aligns with Habib and Alam (2024), who reported that 3D design systems enhance precision in pattern development and reduce the need for repeated manual adjustments. The results from Table 1 revealed that respondents perceived 3D garment design as contributing to reduced material waste through improved pattern accuracy, minimization of cutting errors, and efficient utilization of fabric. The findings indicate that the respondents associated the use of 3D garment design with greater precision in pattern development and improved utilization of fabric materials. This suggests a positive perception among fashion designers of the potential of 3D garment design to support material efficiency in clothing production. However, the findings represent respondents' perceptions and should not be interpreted as direct measurements of actual fabric savings or waste reduction.

Table 2 showed that respondents agreed that virtual prototyping contributes to reducing reliance on physical garment sampling. The respondents perceived virtual prototyping as useful for reducing the need for physical garment samples, improving garment fitting before production, reducing repeated sewing of samples, saving time during garment development, facilitating design adjustments, and reducing material costs associated with garment sampling. This finding agrees with Mostafa and Mohamed (2025), who reported that the integration of 3D simulation tools into garment development improves prototype development and reduces dependence on repeated physical iterations.

Table 3 showed that respondents perceived 3D garment design and virtual prototyping as contributing to sustainable clothing production. Respondents agreed that these technologies support

efficient use of production resources, reduction of environmental waste, improved garment production workflow, reduced production time, and improved production efficiency. These findings indicate positive perceptions of the role of digital garment technologies in supporting sustainable clothing production. However, the results represent respondents' perceptions and should not be interpreted as direct measurements of material savings, environmental waste reduction, production time, or other sustainability outcomes, However, it is important to interpret these findings within the context of the study's methodology. The results are based on the perceptions of fashion designers rather than direct measurement of material savings or production efficiency. While the positive responses indicate a strong awareness and acceptance of digital technologies, they may also reflect expectations or limited exposure rather than actual practice. This highlights a gap between perceived effectiveness and practical implementation, particularly in developing production environments where access to advanced digital tools may be limited. Furthermore, the findings suggest a general consensus on the benefits of 3D garment technologies. While this strengthens the argument for their relevance, it also raises the possibility of response bias or lack of critical evaluation among participants. This underscores the need for future studies to incorporate experimental or comparative approaches that can provide objective evidence of the impact of these technologies on material waste reduction and production efficiency.

Overall, the findings of this study reinforce the growing recognition of 3D garment design and virtual prototyping as important tools for advancing sustainable clothing production. However, achieving their full potential requires not only awareness but also practical integration into real production systems, supported by adequate infrastructure, technical skills, and industry adoption.

Conclusion and Recommendations

The study concludes that 3D garment design and virtual prototyping are perceived by fashion designers in Nasarawa State as useful digital approaches for improving garment design and supporting sustainable clothing production. Based on the findings of the study, the following recommendations are made:

1. Fashion designers are encouraged to incorporate 3D garment design tools into pattern development and garment production to improve pattern accuracy and promote efficient utilization of fabric materials. Fashion designers should adopt virtual prototyping for garment fitting, design evaluation, and adjustments before physical samples are produced, thereby reducing reliance on repeated physical garment sampling.
2. Clothing and textile training institutions, such as the universities as well as relevant clothing industry practitioners, should promote practical training and the use of 3D garment design and virtual prototyping to enhance resource efficiency and support sustainable clothing production.

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