Application of Traditional Anatolian Motifs to Knitted T-Shirts by DTG Digital Printing: Effects on Physical Performance, Color Fastness and QR-Based Cultural Heritage

Mustafa Uğur Lülecioğlu[1] , Gulfem Giriş[1], Duygu Akçit[1], Emine Dilara Koçak[2*]

[1]Boyner Büyük Mağazacılık A.Ş. Design and R&D Center Istanbul/Türkiye

[2]Marmara University, Technology Faculty, Textile Engineering Department, İstanbul, Türkiye

***Corresponding Author**

DOI: https://doi.org/10.51244/IJRSI.2026.1306000470

Received: 02 July 2026; Accepted: 07 July 2026; Published: 17 July 2026

ABSTRACT

Traditional Anatolian motifs represent an important component of Türkiye's intangible cultural heritage. However, their integration into contemporary textile products through digital production technologies has been limited, and the influence of digital printing on the physical performance of knitted fabrics has not been comprehensively investigated. This study aimed to evaluate the applicability of traditional Anatolian motifs to knitted T-shirts using Direct-to-Garment (DTG) digital printing technology while examining the effects of the printing process on fabric performance.

Three traditional motifs, namely Elibelinde, Bereket, and Bukağı, were digitally redesigned and printed onto women's T-shirts produced from three different knitted fabric structures: 100% cotton single jersey, 50% modal/50% cotton single jersey, and 100% modal rib knit. Fabric mass, thickness, dimensional stability, bursting strength and color fastness properties were determined before and after printing according to relevant ISO standards. The experimental results were statistically evaluated using one-way ANOVA and Tukey's HSD test ($p < 0.05$). In addition, QR codes were integrated into the garment labels to provide users with digital access to the historical and cultural background of each motif.

DTG printing caused only slight increases in fabric mass and thickness, while bursting strength decreased by approximately 1–2%. Dimensional stability remained within acceptable limits for all fabric groups. Color fastness ratings were generally between 4 and 5, indicating satisfactory resistance to washing, rubbing, water, perspiration and light exposure. Among the investigated materials, 100% modal rib knit exhibited the most stable physical performance after printing.

The findings demonstrate that DTG digital printing enables the successful application of traditional Anatolian motifs to knitted garments without significantly compromising fabric performance. Furthermore, integrating QR code technology into textile products provides an innovative approach for preserving and promoting cultural heritage through contemporary apparel.

Keywords: Direct-to-Garment (DTG), digital textile printing, Anatolian motifs, cultural heritage, knitted fabrics, color fastness, physical performance, QR code.

INTRODUCTIONS

The textile industry is undergoing a significant transformation driven by digitalization and sustainable manufacturing strategies, shifting from conventional mass production toward demand-driven, low-inventory production systems. In this context, digital textile printing technologies have emerged as an efficient manufacturing approach owing to their high print quality, design flexibility, and shortened production cycles. Compared with conventional printing techniques, digital printing significantly reduces water, energy, and

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

chemical consumption, thereby contributing to more sustainable textile manufacturing processes (Hoque et al., 2024; Glogar et al., 2025). Among these technologies, Direct-to-Garment (DTG) printing has gained considerable attention due to its capability to apply digital designs directly onto ready-made garments, making it particularly suitable for customized production and rapid product development in knitted apparel (Thakker & Sun, 2024). However, the DTG printing process, including fabric pre-treatment, pigment ink application, and thermal curing, may alter the structural and mechanical characteristics of knitted fabrics, such as fabric mass, thickness, dimensional stability, and bursting strength. Therefore, evaluating the physical performance of DTG-printed fabrics is essential for assessing product quality, durability, and industrial applicability (Glogar et al., 2022; Thakker & Sun, 2024).

With the rapid advancement of digital textile printing technologies, consumer demand has expanded beyond functional and aesthetic product attributes toward basic apparel incorporating culturally distinctive designs. This trend has created new opportunities for integrating traditional cultural elements into contemporary textile products through digital manufacturing technologies. Anatolia, which has hosted numerous civilizations throughout history, possesses a rich textile heritage characterized by a wide variety of traditional motifs carrying symbolic meanings. These motifs have gradually evolved from being used exclusively in traditional handicrafts and decorative objects to being incorporated into contemporary textile and apparel products. Their application to everyday garments contributes to the preservation and transmission of the cultural identity of past civilizations to future generations.

Traditional Anatolian motifs are not merely decorative design elements but also visual communication symbols reflecting the social structure, beliefs, family values, and lifestyle of the communities in which they originated (Güven 2025; Hatipoglu, S. U. 2024). Consequently, integrating these motifs into modern textile products through digital printing technologies represents not only an aesthetic design approach but also an effective strategy for promoting cultural sustainability and enhancing the visibility of intangible cultural heritage in contemporary apparel.

The Elibelinde, Bereket, and Bukağı motifs selected in this study are among the most representative symbols of traditional Anatolian textile art. The Elibelinde motif symbolizes femininity, motherhood, fertility, and productivity, whereas the Bereket motif represents abundance, family unity, and the continuity of life. The Bukağı motif symbolizes unity, loyalty, and social solidarity (Guven S., 2025). Traditionally, these motifs have been extensively used in Anatolian carpets, kilims, and other handwoven textiles. However, their application in contemporary apparel products has remained largely limited to aesthetic and decorative purposes. Recent advances in digital textile printing technologies provide new opportunities for reproducing traditional motifs on textile surfaces with high printing resolution, superior color accuracy, and excellent production repeatability. Consequently, these traditional motifs can evolve beyond decorative elements into functional design components that facilitate the sustainable transmission of cultural heritage through contemporary textile products (Glogar et al., 2025).

Previous studies on digital textile printing have primarily focused on print quality, ink formulations, color management, process optimization, and sustainable manufacturing (Glogar et al., 2022; Rainert, K. T et al., 2024; Thakker & Sun, 2024). In contrast, studies investigating the application of traditional Anatolian motifs to knitted apparel using Direct-to-Garment (DTG) digital printing, together with the evaluation of their effects on the physical performance and color fastness of knitted fabrics, remain scarce. Furthermore, the integration of QR code-based digital content into textile products as a tool for communicating the historical and cultural significance of traditional motifs has received very limited attention in the current literature. Therefore, interdisciplinary research integrating digital textile manufacturing technologies with cultural heritage preservation is required to develop innovative textile products that simultaneously satisfy technical performance requirements and contribute to the sustainable preservation of intangible cultural heritage.

In this study, the traditional Anatolian motifs Elibelinde, Bereket, and Bukağı were digitally redesigned and transferred onto women's T-shirts manufactured from three different knitted fabric structures using Direct-to-Garment (DTG) digital printing technology. The influence of the DTG printing process on fabric mass, thickness, dimensional stability, bursting strength, and color fastness was systematically investigated through comparative analyses conducted before and after printing. In addition, a QR code-based digital labeling system was integrated

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

into the garments to provide users with direct access to the historical and symbolic meanings of the selected motifs. The proposed approach presents an innovative textile product model that integrates digital textile printing, technical performance evaluation, and cultural heritage preservation, contributing to the sustainable dissemination of traditional Anatolian motifs through contemporary knitted apparel.

EXPEREMENTALS

2.1 Materials and Methods

2.1.1 Materials

Three types of short-sleeved white women's T-shirts, manufactured from knitted fabrics commonly used in casual apparel, were selected as the experimental materials. The garments were produced from 100% cotton single jersey (160 g/m²), 50% modal/50% cotton single jersey (180 g/m²), and 100% modal rib knit (210 g/m²) fabrics. These fabric structures were intentionally selected due to their different fiber compositions and knitted constructions, allowing a comparative evaluation of the effects of Direct-to-Garment (DTG) digital printing on the physical performance and durability of knitted fabrics. Three traditional Anatolian motifs—Elibelinde, Bereket, and Bukağı—were selected as the design elements because they symbolically represent femininity, fertility, productivity, family unity, and social solidarity in Anatolian textile culture (Figure 1).

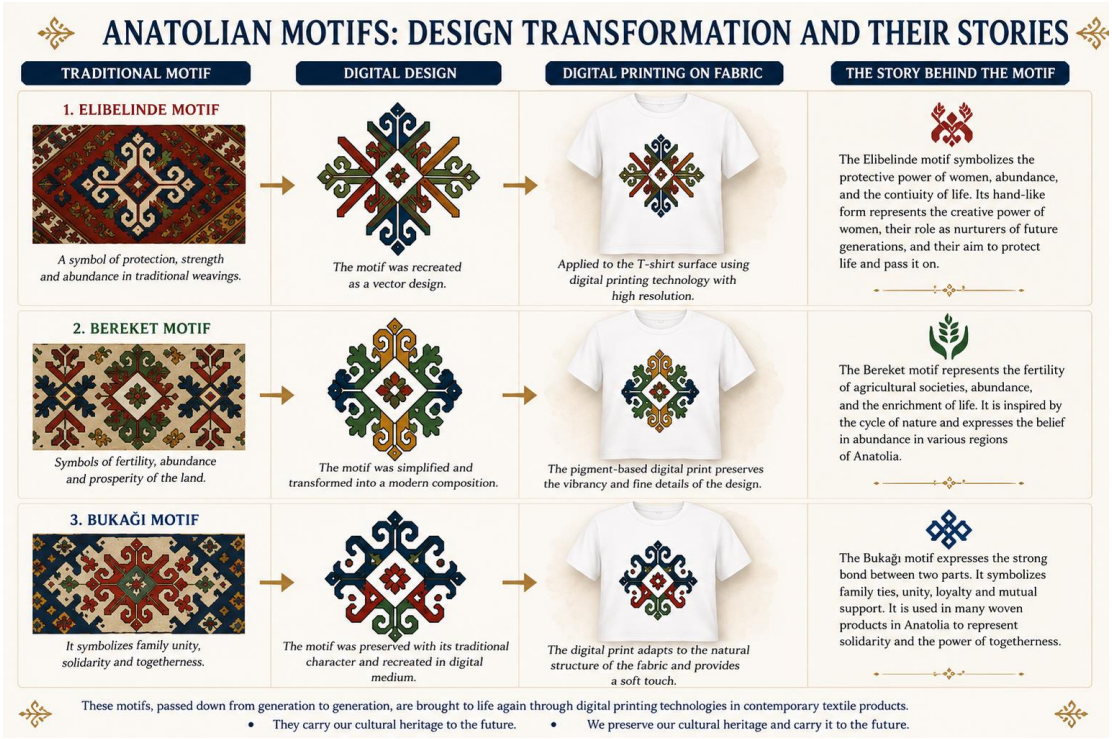

Figure 1. Digital transformation of traditional Anatolian motifs and their cultural significance.

2.1.2. Motif Design and Digital Textile Printing

The selected Anatolian motifs were digitally reconstructed as vector graphics using Adobe Illustrator CC. To ensure high printing quality and accurate color reproduction, the designs were converted into TIFF format using the CMYK color mode. While preserving the characteristic geometric features of the original motifs, line thickness, proportions, and overall composition were optimized to suit contemporary women's apparel.

The prepared designs were printed directly onto the front surface of the T-shirts using a Brother GTX Pro Direct-to-Garment (DTG) digital textile printer with DuPont™ Artistri® pigment-based textile inks. Printing was performed at a resolution of 1200 × 1200 dpi within an effective print area of approximately 200 × 250 mm, and identical printing parameters were maintained for all specimens to ensure process consistency. Since light-coloured fabrics were used, no white under base layer was applied. Prior to printing, all samples were treated

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

with a DTG-compatible pre-treatment solution to enhance pigment fixation and color fastness. Following printing, the specimens were thermally cured at 160 °C for 180 s to promote permanent bonding of the pigment-binder system to the fiber structure. Before physical and color fastness testing, all printed samples were conditioned for 24 h under standard atmospheric conditions (20 ± 2 °C and 65 ± 4% relative humidity) in accordance with TS EN ISO 139.

2.1.3. QR Code-Based Cultural Content Design

As shown in Figure 2, a QR code-based digital labelling system was integrated into the garment labels to provide users with direct access, via mobile devices, to a dedicated digital information platform. The platform presents the historical background, symbolic meanings, regional distribution, and design stories of the selected Anatolian motifs. The QR code was incorporated as a functional component of the apparel, extending the role of digital textile printing beyond decorative surface design. This integrated approach combines DTG digital printing with digital information technologies to facilitate the sustainable dissemination of Anatolian cultural heritage while improving user engagement and adding cultural value to contemporary knitted apparel.

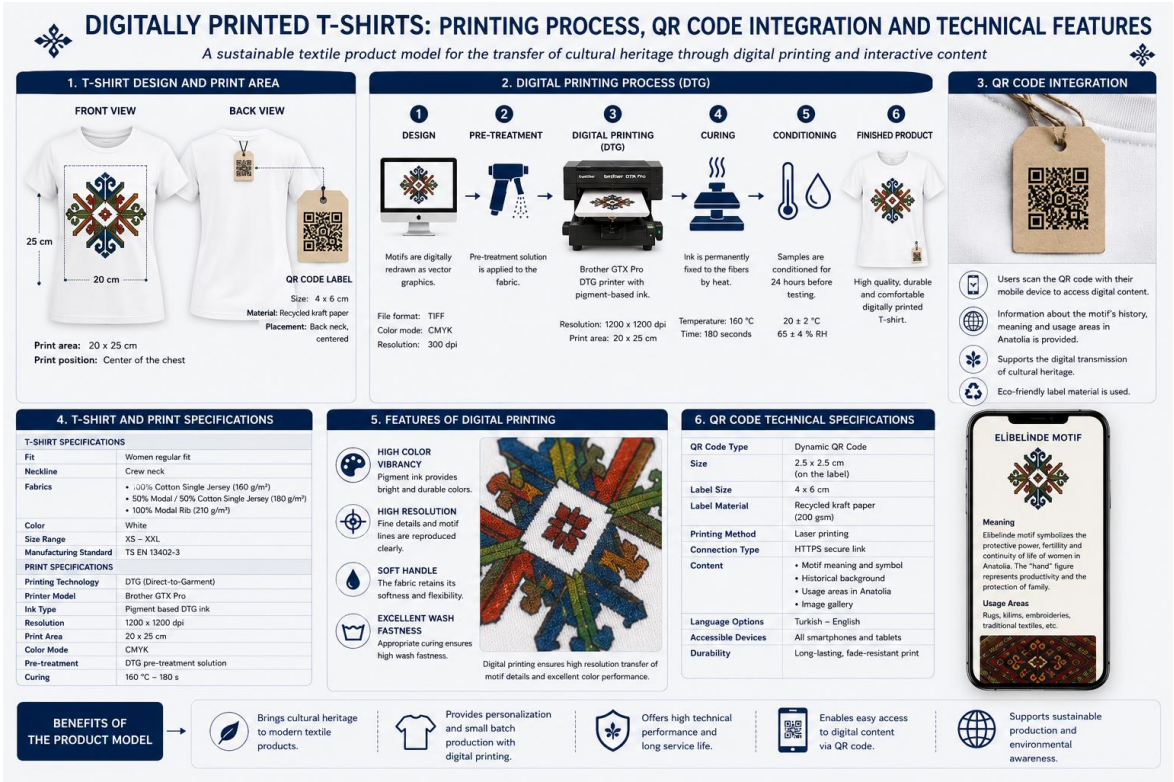

Figure 2. Product development workflow of the DTG-printed knitted T-shirt with QR code-based cultural content integration.

2.1.4. Statistical Analysis

All experimental measurements were performed in five replicates, and the results are presented as mean ± standard deviation. One-way analysis of variance (ANOVA) was employed to evaluate the effect of fabric type on the physical performance and color fastness properties. Statistical analyses were conducted using IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), and statistical significance was established at $p < 0.05$.

RESULTS

3.1. Effect of DTG Digital Printing on Fabric Mass

Following DTG digital printing, an increase in fabric mass was observed for all knitted fabric groups (Figure 3). One-way analysis of variance (ANOVA) revealed that fabric type had a statistically significant effect on the

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post-printing fabric mass ($F = 36.84$, $p < 0.001$). Tukey's HSD multiple comparison test further demonstrated significant differences among all three fabric groups ($p < 0.05$).

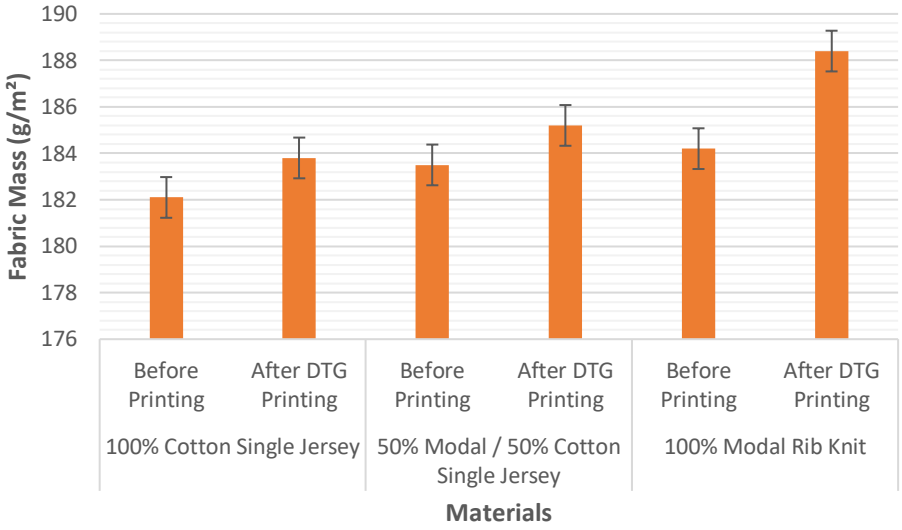

Figure 3. Effect of DTG digital printing on the fabric mass of knitted T-shirts.

The greatest increase in fabric mass was recorded for the 100% modal rib knit fabric, followed by the 50% modal/50% cotton single jersey and 100% cotton single jersey fabrics. This increase can be attributed to the additional mass introduced by the DTG pre-treatment solution and the pigment–binder layer deposited on the fabric surface during printing. Furthermore, the combined effect of the modal fiber composition and the rib knit structure is considered to enhance the retention of the pre-treatment chemicals and pigment ink compared with the single jersey fabrics. Similar increases in fabric mass following pigment-based DTG printing have been reported in previous studies (Glogar et al., 2022; Hoque 2021). Nevertheless, the observed increase remained within approximately 1–2% for all fabric groups, indicating that the DTG printing process had only a minor influence on the structural characteristics of the knitted fabrics while maintaining their suitability for apparel applications.

3.2. Effect of DTG Digital Printing on Fabric Thickness

Following DTG digital printing, a slight increase in fabric thickness was observed for all knitted fabric groups (Figure 4). The fabric thickness increased from 0.61 to 0.64 mm for the 100% cotton single jersey, from 0.62 to 0.65 mm for the 50% modal/50% cotton single jersey, and from 0.68 to 0.71 mm for the 100% modal rib knit fabric

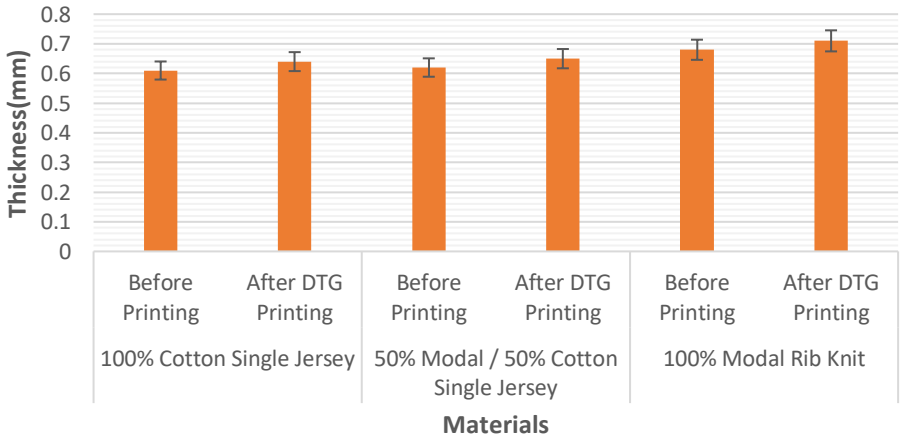

Figure 4. Effect of DTG digital printing on the fabric thickness of knitted T-shirts.

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One-way ANOVA revealed that fabric type had a statistically significant effect on the post-printing thickness values ($p < 0.05$). According to Tukey's HSD multiple comparison test, the 100% modal rib knit fabric exhibited significantly higher thickness than both single jersey fabrics ($p < 0.05$), whereas no significant difference was found between the 100% cotton and 50% modal/50% cotton single jersey fabrics ($p > 0.05$). The increase in thickness is attributed to the deposition of the DTG pre-treatment chemicals and the pigment–binder layer formed on the fabric surface during printing. Similar findings have been reported for pigment-based digital textile printing, where the formation of a thin polymer layer resulted in a slight increase in fabric thickness without adversely affecting the structural integrity of the fabric (Glogar et al., 2022; Thakker & Sun, 2024).

3.3. Effect of DTG Digital Printing on Lengthwise Dimensional Stability

The lengthwise dimensional stability results before and after DTG digital printing are presented in Figure 5. A slight increase in lengthwise shrinkage was observed for all knitted fabric groups after printing. The dimensional stability changed from −2.2% to −2.4% for the 100% cotton single jersey, from −2.0% to −2.2% for the 50% modal/50% cotton single jersey, and from −1.8% to −2.0% for the 100% modal rib knit fabric.

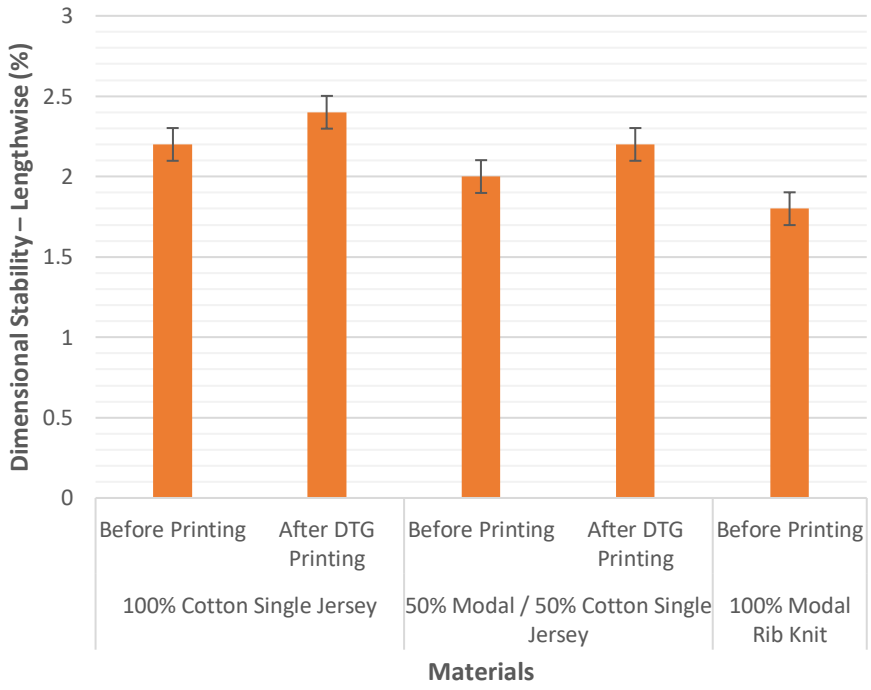

Figure 5. Lengthwise dimensional stability of knitted T-shirts before and after DTG digital printing.

One-way ANOVA indicated that fabric type had a statistically significant effect on the post-printing lengthwise dimensional stability ($p < 0.05$). Tukey's HSD multiple comparison test showed that the 100% modal rib knit fabric exhibited significantly lower shrinkage than both single jersey fabrics ($p < 0.05$), whereas no statistically significant difference was found between the 100% cotton and 50% modal/50% cotton single jersey fabrics ($p > 0.05$). The slight increase in shrinkage can be attributed to the combined effects of the pre-treatment, thermal curing, and relaxation processes applied during DTG printing. Similar observations have been reported for pigment-based digital textile printing, where thermal curing resulted in minor changes in the dimensional behaviour of knitted fabrics without adversely affecting their dimensional stability (Ujiie, 2020; Glogar et al., 2022).

3.4. Effect of DTG Digital Printing on Width Wise Dimensional Stability

The width wise dimensional stability results before and after DTG digital printing are presented in Figure 6. A slight increase in width wise shrinkage was observed for all knitted fabric groups following the printing process. The dimensional stability changed from −2.8% to −3.2% for the 100% cotton single jersey, from −2.5% to −2.7% for the 50% modal/50% cotton single jersey, and from −2.2% to −2.4% for the 100% modal rib knit fabric.

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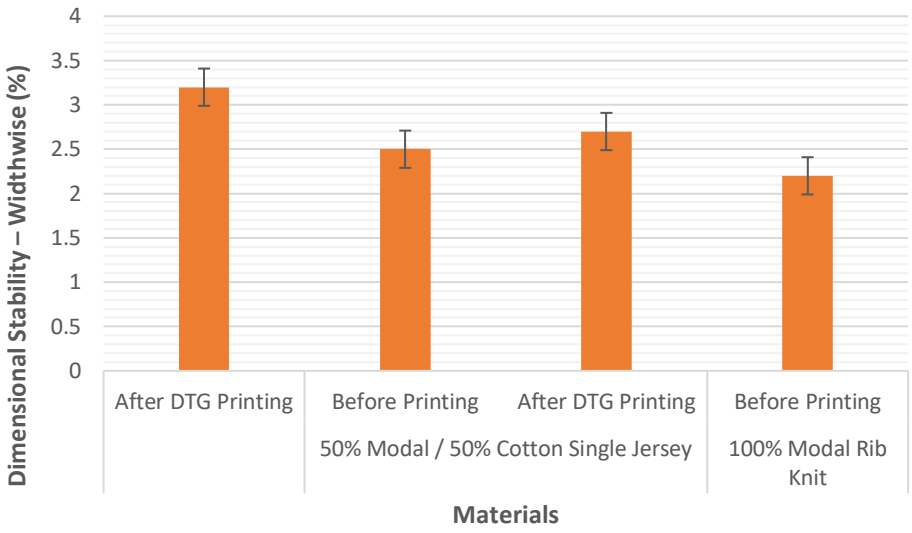

Figure 6. Effect of DTG digital printing on the widthwise dimensional stability of knitted T-shirts.

One-way ANOVA demonstrated that fabric type had a statistically significant effect on the post-printing widthwise dimensional stability ($p < 0.05$). According to Tukey's HSD multiple comparison test, the 100% cotton single jersey fabric exhibited significantly higher shrinkage than the 100% modal rib knit fabric ($p < 0.05$), while the 50% modal/50% cotton single jersey fabric showed intermediate behaviour and did not differ significantly from either group ($p > 0.05$). The lower shrinkage observed in the modal rib knit fabric is likely associated with the combined influence of its rib knit construction and modal fiber composition, which provide greater elastic recovery and dimensional stability. Overall, the widthwise shrinkage values remained within acceptable limits for knitted apparel, indicating that the DTG printing process did not adversely affect the dimensional performance of the fabrics (ISO 5077:2020; Glogar et al., 2022).

3.5. Effect of DTG Digital Printing on Bursting Strength

The bursting strength results of the knitted fabrics before and after DTG digital printing are presented in Figure 7. A slight reduction in bursting strength was observed for all fabric groups following the printing process. The bursting strength decreased from 421 to 414 kPa for the 100% cotton single jersey, from 439 to 432 kPa for the 50% modal/50% cotton single jersey, and from 463 to 457 kPa for the 100% modal rib knit fabric. The reduction in bursting strength remained within approximately 1–2% for all fabric groups.

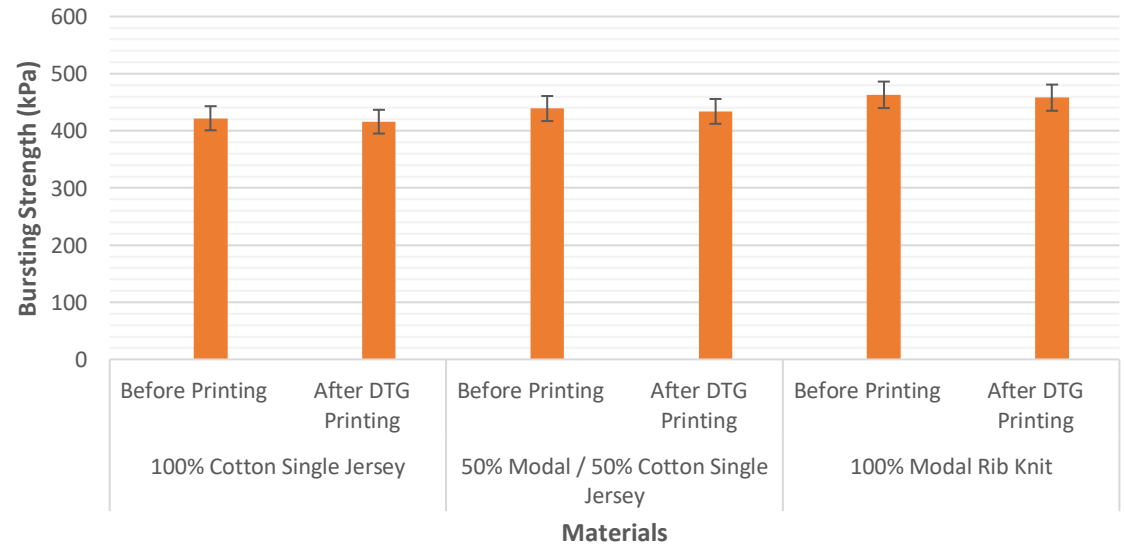

Figure 7 Effect of DTG digital printing on the bursting strength of knitted T-shirts.

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One-way ANOVA indicated that fabric type had a statistically significant effect on the post-printing bursting strength ($p < 0.05$). According to Tukey's HSD multiple comparison test, the 100% modal rib knit fabric exhibited significantly higher bursting strength than both single jersey fabrics ($p < 0.05$), whereas no statistically significant difference was observed between the 100% cotton single jersey and 50% modal/50% cotton single jersey fabrics ($p > 0.05$). The slight reduction in bursting strength is likely associated with the combined effects of the pre-treatment, pigment–binder deposition, and thermal curing applied during the DTG printing process. Nevertheless, the limited decrease indicates that DTG printing did not adversely affect the structural integrity of the knitted fabrics, confirming its suitability for apparel applications. Similar observations have been reported for pigment-based digital textile printing, where only minor changes in mechanical performance were observed after printing.

3.6. Evaluation of Color Fastness Performance

The color fastness results of the DTG-printed knitted fabrics are presented in Table X. Overall, the DTG printing system exhibited excellent color fastness performance across all knitted fabric structures. The washing, water, acidic perspiration, and alkaline perspiration fastness ratings ranged between 4 and 5, indicating effective fixation of the pigment-based ink to the fiber surface after thermal curing and satisfactory color stability under simulated end-use conditions.

The dry rubbing fastness was also rated between 4 and 5, demonstrating good resistance of the printed surface to mechanical abrasion. In contrast, the wet rubbing fastness values ranged from 3–4 to 4, which is consistent with the characteristics of pigment-based DTG printing, where the pigment–binder system primarily forms a thin polymer layer on the fabric surface rather than penetrating into the fiber structure. Nevertheless, all fastness ratings satisfied the performance requirements generally accepted for apparel textiles. Similar color fastness behaviour has been reported for pigment-based digital textile printing in previous studies (Hassabo et.al (2023).

Table 1. Color fastness and pilling resistance properties of DTG-printed knitted fabrics

Property	**100% Cotton Single Jersey**	**50% Modal / 50% Cotton Single Jersey**	**100% Modal Rib Knit**
Washing Fastness – Color Change	4–5	4–5	4–5
Washing Fastness – Staining	4–5	4–5	4–5
Dry Rubbing Fastness	4	4–5	4–5
Wet Rubbing Fastness	3–4	4	4
Water Fastness	4–5	4–5	4–5
Acidic Perspiration Fastness	4–5	4–5	4–5
Alkaline Perspiration Fastness	4–5	4–5	4–5
Light Fastness	4	4–5	4–5
Pilling Resistance	4	4–5	4–5

3.7. Evaluation of Color Fastness Performance

The color fastness results of the DTG-printed knitted fabrics are presented in Table 1. Overall, the DTG printing system demonstrated excellent color fastness performance for all knitted fabric structures. Washing fastness (color change and staining), water fastness, and acidic and alkaline perspiration fastness were consistently rated between 4 and 5, indicating effective fixation of the pigment–binder system after thermal curing and excellent

resistance under end-use conditions. Similar findings have been reported for pigment-based digital textile printing (Ding, Y et al., 2019).

Dry rubbing fastness was rated between 4 and 5, confirming adequate resistance of the printed surface to mechanical abrasion. In contrast, wet rubbing fastness ranged from 3–4 to 4, which is consistent with the surface deposition mechanism of pigment-based DTG inks, where the pigment–binder layer remains primarily on the fabric surface rather than chemically diffusing into the fibers (Thakker & Sun, 2024). Light fastness and pilling resistance were also rated between 4 and 5, demonstrating that the printing and curing processes did not adversely affect the durability or surface characteristics of the knitted fabrics.

Among the investigated materials, the 100% modal rib knit and 50% modal/50% cotton single jersey fabrics exhibited slightly superior rubbing, light fastness, and pilling resistance compared with the 100% cotton single jersey fabric. This behaviour is likely associated with the combined influence of fiber composition and knitted structure, which provides a more stable substrate for pigment fixation. Overall, the results demonstrate that DTG digital printing provides high color durability on different knitted fabric structures while preserving the visual quality of traditional Anatolian motifs.

CONCLUSIONS

Traditional Anatolian motifs were successfully transferred onto knitted T-shirts using Direct-to-Garment (DTG) digital printing technology without compromising the physical performance of the fabrics. Although slight increases were observed in fabric mass and thickness and a minor reduction (approximately 1–2%) occurred in bursting strength, these changes remained within acceptable limits for apparel applications. Likewise, dimensional stability values showed only negligible changes after printing.

The color fastness results demonstrated that DTG printing provided excellent resistance to washing, water, perspiration, light exposure, and rubbing, confirming the suitability of pigment-based DTG printing for contemporary knitted apparel. Among the investigated materials, the 100% modal rib knit fabric exhibited the most stable overall physical and color fastness performance, indicating its suitability as the preferred substrate for high-quality DTG printing.

Unlike previous studies that primarily focused on print quality and color performance, the present study simultaneously evaluated physical performance, color fastness, and cultural heritage integration. Furthermore, the incorporation of a QR code-based digital information system enabled users to access the historical and symbolic meanings of traditional Anatolian motifs, transforming conventional apparel into an interactive medium for cultural heritage dissemination.

The proposed product model demonstrates that digital textile printing can serve not only as an advanced manufacturing technology but also as an effective tool for preserving and promoting intangible cultural heritage through contemporary textile products.

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