Effect of UV-Curable Inkjet Printing Parameters on Physical, Low-Stress Mechanical, and Aesthetic Properties of Polypropylene Knitted Fabrics

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Abstract: As the use of textile polypropylene (PP) fibers becomes more common in commercial textiles and sportswear, the investigation of the effects of UV-curable ink on the heat-sensitive PP knitted fabrics is crucial to optimize functional clothing design. This study investigated the effects of UV-curable ink on the heat-sensitive PP knitted fabrics when the ink was cured using UV light at room temperature, to avoid degradation of the PP fabric by high temperature, and provided an alternative coloring method for PP fabric used in sportswear. The influences of printing parameters such as the printing distance, number of overprints, and color of ink on fabrics as well as aesthetic, physical, and low-stress mechanical properties in terms of tensile, bending, shearing, surface, and compression were systematically investigated. The results indicated that the physical properties and low-stress mechanical properties of PP fabrics printed with UV-curable ink were significantly affected by the number of overprints and the color of the prints, whereas the color appearance was affected mainly by the number of overprints and the printing distance. In terms of the fabric's hand value, only 2HB and 2HG5 were significantly affected by the number of overprints and the color of the prints, with the prediction rate exceeding 40% among the low-stress mechanical properties. The fabric's hand value was not significantly affected by the thin UV-cured ink film when compared with the fabric itself. Fabric printed in a color with the greatest lightness and the fewest overprints had the lowest fabric weight, thickness, and color difference (ΔE) towards the reference color, in addition to better bending recovery and resilience properties. The new knowledge from this study can provide an alternative coloring method for PP knitted fabric to increase the design variety available to textile designers who use PP fabric. The results from this study contribute to the textile and knitwear design industry.

Keywords: UV-curable inkjet printing, Heat-sensitive fabric, Color difference, Polypropylene, Kawabata Evaluation System

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Introduction

Knitted fabrics are commonly used in sportswear, functional and intimate apparel because of their soft, stretchy, and recovery properties that provide freedom of movement [1-3]. In recent years, interest has grown in the development of polypropylene (PP) knitted fabric [4,5]. PP is crucial in textile production because of its strength, abrasion resistance, and low cost [6]. In the field of medical textiles, PP is widely used in the fabrication of disposable surgical gowns, facemasks, and head covers [7]. In the apparel industry, Babu *et al.* investigated the moisture management of laminated fabric composed of PP and cotton fabric, which was ideal for the manufacture of sportswear [8]. Suganthi *et al.* developed a knitted fabric structure made of polypropylene that showed better thermal comfort properties, which was recommended as sportswear for volleyball players [5]. However, the inability of PP to be dyed and its relatively low melting point have limited its use in the apparel industry [9]. Also, the processing of heat-sensitive fabrics, such as PP, is restricted to low temperature because of the fabrics' relatively low melting point. Therefore, the conventional printing system is not suitable for processing such fabrics as the high curing temperature associated with the thermal curing process deteriorates the heat-sensitive fabric [10].

In the commercial industry, PP is colored by adding dyestuff pigments to the resin before extruding and melt spinning polymers [6]. However, additional coloring time for nonstandard colors is required for this method, and the dyed materials have limited potential for recoloration [11]. Two coloration methods are used to improve the dyeability of PP fibers, namely the synthesis of new dyes and the physical and chemical modification of fibers [12]. The first method involves the development of dyes with a greater affinity to fibers [13]. In the second method, the physical and chemical properties of fibers can be improved by grafting, electron beam irradiation, sulfonic acid incorporation, and atmospheric plasma treatment [6,12,14].

However, dyeing the modified PP fibers involves complex and additional treatment. Therefore, the inkjet printing of PP fabrics using UV-curable inks is of particular interest because the room temperature curing process can overcome traditional processing limitations.

Ultraviolet (UV)-curable inkjet printing techniques to control the appearance of fabrics in digital fabrication are rapidly being developed. UV-radiation curing technology has received considerable interest from numerous industries because of several advantages that it offers [15]. UV-curable inkjet printing can be used to print on various materials and has the advantages of high-quality printed images, excellent color fastness, low energy demand, room temperature curing, and low environmental pollution rate [15-19]. In UV-curable inkjet printing, the inkjet printing process is combined with UV-curable ink. The chemical reaction of curing is based on the photopolymerization of the binder, which is initiated by the absorption of UV radiation of a specific wavelength from the UV light source equipped on the print head of the inkjet printer. The binder comprises pigment particles and forms a thin film that is deposited on the printing substrate after exposure to UV light [15,19-21].

Printing technology with UV-curable ink is widely used in various applications, such as bioinspired self-cleaning surface printing on glass for use in liquid crystal display and electromagnetic applications [20,22-24]. Yang *et al.* observed a considerable difference between the printing quality of paper and poly vinyl chloride (PVC) plastic films when using the same UV-curable inkjet inks [16]. Takatani *et al.* proposed a method to control the translucency of the 3D-printed object as a replacement to printing a white layer before normal printing with UV-curable ink [21]. For textile printing applications, several studies have focused on various UV-curable pigment pastes and the effect of the pigment/resin ratio of the ink [18,19]. Karim *et al.* discovered that UV-cured inkjet-printed biodegradable poly (lactic acid) (PLA) fabrics exhibit a relatively high color strength without affecting the physical and mechanical properties of the fabrics compared with thermally cured inkjet-printed PLA fabrics

[10].

UV-curable ink is formulated by four basic elements, including a photo-initiator, a telechelic oligomer, a monomer, and pigment [15]. Baysal *et al.* showed that the color value of the UV-cured samples was changed significantly when the proportions of the photo-initiator were changed [25]. The pigment color in the ink also affected the curing degree of the printed films because the UV absorption/transmission intervals of each color differed [26]. Hakeim *et al.* studied UV-curable inkjet inks for textile printing application, and the printed fabrics exhibited soft handling and desirable fastness properties [18]. El-Molla investigated whether polyurethane acrylate could be used as a UV-curable binder for ink preparation to be used for inkjet printing of all types of fabric using pigment dyes [27]. Hong *et al.* screen-printed the UV-curable conductive inks on nylon woven fabric to fabricate textile-based electronics with a low curing temperature [28].

Fabrics can affect not only the quality of the textile material but also the appeal of the product, which is a crucial performance attribute of the apparel textile [29]. Hajipour and Shams-Nateri investigated that the print quality of inkjet-printed polyester was decreased by increasing the weft-weaving density [30]. Karim *et al.* found that the bending rigidity, shear rigidity and stiffness of heat-sensitive fabric increased after thermally cured inkjet printing [10]; however, it was less significant after UV-curable inkjet printing. Seipel *et al.* found that the handle of the UV-cured photochromic textiles was stiffer than the unprinted fabric as a result of ink jetting and curing of the photochromic ink on the fabric surface [31]. Studies have shown that printing quality is affected by the material to be printed and the hand value of the printed heat-sensitive fabric was improved by UV-curing [10,16]. Although various studies focused on the formation of UV-curable ink for textile printing, the relationships among printing parameters, such as the printing distance, the number of overprints, and the color of the prints, as well as the physical, low-stress mechanical, and aesthetic properties of the printed PP knitted fabric, are not well understood. This study investigated the effects of the printing parameters on the hand value of the printed fabric and the printing quality, which was not examined in previous studies. This study is essential to provide knowledge when UV-curable inkjet print is applied for any textile and apparel design. In this study, the effect of UV-curable inkjet printing on PP knitted fabric was investigated. A single jersey knitted PP fabric was printed using UV-curable inks under various printing parameters such as the printing distance between the print head and fabric surface, number of overprints, and color of prints. The performance characteristics of UV-cured printed fabrics, such as aesthetic, physical, and low-stress mechanical properties, were evaluated and analyzed.

Experimental

To study the factors that affect the fabric's aesthetic, physical, and low-stress mechanical properties, the PP fabric was knitted and printed on an inkjet printer with UV-curable ink. The pigment films were analyzed via Fourier transform infrared (FTIR) spectroscopy to confirm the curing of the ink. To evaluate the main factor that affects the fabric's physical properties and low-stress mechanical properties, the data obtained from the experiment were analyzed using SPSS 23 (IBM Corp., Armonk, New York). The effects on the fabric's aesthetic, physical, and mechanical properties of various printing distances, numbers of overprints, and colors of prints are analyzed in the Discussion.

Inkjet Printing of Fabric with UV-Curable Inks

Inkjet printing with UV-curable inks on heat-sensitive knitted fabric was conducted using a Roland VersaUV LEF-200 benchtop UV flatbed printer, and the ink was cured using a built-in UV-LED curing lamp with an emission wavelength–range of approximately 200 to 400 nm

(Figure 1). A UV-curable ink is offered by Roland® that contains hexamethylene diacrylate, exo-1,7,7-trimethybicyclo[2,2,1]hept-2-yl acrylate, diphenyl phosphine oxide, benzyl acrylate, 2-methoxyethyl acrylate, and 1-vinylazepan-2-one. The UV-curable ink is supplied in six cartridges, including cyan, magenta, yellow, and black in CMYK color. An additional cartridge of white color adds touches of bright color-quality on dark or clear surfaces, and a clear-gloss ink offers spot gloss or matte finishes [32]. The printing parameters included the printing distance, number of overprints, and color of prints, which were controlled using Roland VersaWorks Dual RIP software. The number of overprints indicates the number of times printing should be performed in the same location. The printing speed was varied with the printing quality, which can be selected by using Dual RIP software, such as high quality (resolution: 1440 × 720 dpi; printing speed: 88 cm^2/min), standard (resolution: 720 × 720 dpi; printing speed: 112 cm^2/min), high speed (resolution: 720 × 720 dpi; printing speed: 279 cm^2/min) and draft (resolution: 360 × 360 dpi; printing speed: 838 cm^2/min). The standard printing quality was selected in this study and the resolution of print was set into 720 × 720 dpi with the CMYK color mode. In the Roland Versa UV LEF-200 benchtop UV flatbed printer, the number of overprints was set using a one-time printing process with the adjusted UV-curable ink. The printing distance between the print-head and the fabric surface was calculated by the fabric thickness, with a safety allowance of less than 1 mm deducted from the value of 100 mm. The safety allowance was used to prevent the print head and fabric surface from colliding. A printing distance of 100 mm indicates the closet position of the benchtop to the print head [33]. Three overprint levels and a printing distance interval of 2 mm were selected because the VersaUV LEF-200 printers have an intuitive distance print mode with a 2-mm height tolerance. For testing the resolution of the print, the word "resolution" in Myriad Pro font with a 30-point font size was typed in Adobe illustration CC software in black for easy observation. This illustration was printed on the PP fabric with the pale blue (PANTONE P115-

4C) background color in three printing distances (Figure 2). Fabric samples in each color were printed with various printing distances and number of overprints.

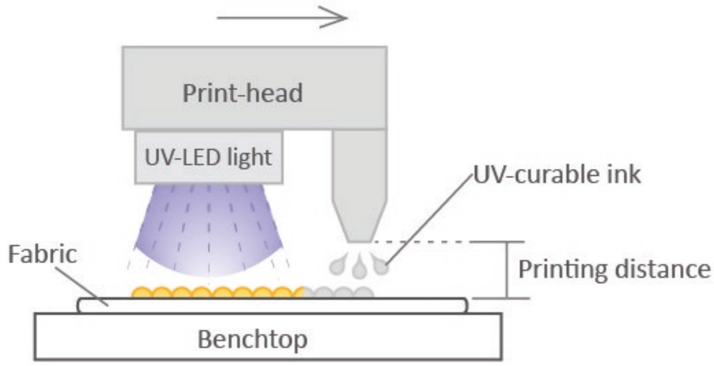


Figure 1. UV-curing process using the overhead UV-LED curing system.

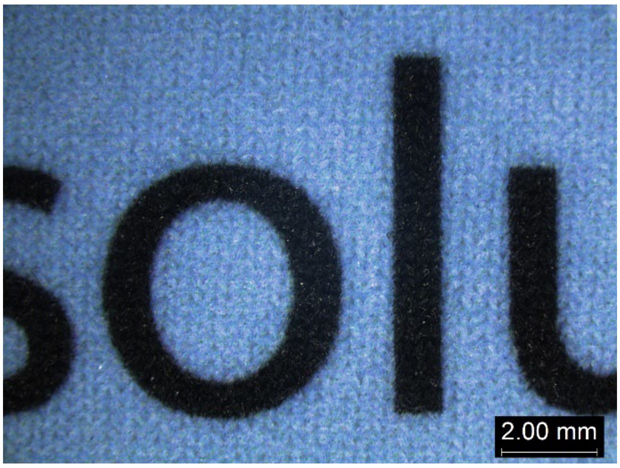


Figure 2. SEM of fabric R2 printed with words for the test of resolution.

Preparation of Material Samples

In this study, circular knitted PP fabrics were prepared for printing with UV-curable ink. One end of 75D/72F 100% PP and One end of 20/20 100% Nylon/Lycra were fabricated in a single jersey stitch. All samples were prepared under the same knitting tension and parameters.

A 28-gauge circular knitting machine (SM8-TOP2, Santoni, Italy) was used. Circular knitted fabrics were printed in three colors: pale blue (PANTONE P115-4C), basic magenta, and black in CMYK. Various degrees of lightness of the printing color were selected to investigate the effects of color on the fabric's properties. The unprinted fabric was used as the control fabric and labelled O. For testing the resolution of the print in three printing distances, the fabric was named as R2, R4, and R5. Each printing condition was repeated three times on the same fabric. Details of sample specifications are summarized in Table 1.

Table 1. Specification of the knitted specimens

Fabric Code	Print	Number of overprints	Printing distance (mm)
B1	Pantone P115-4C (P)	1	98.9
B2		2	98.9
B3		3	98.9
B4		2	96.9
B5		2	94.9
BK1	Black (K)	1	98.9
BK2		2	98.9
BK3		3	98.9
BK4		2	96.9
BK5		2	94.9
M1	Magenta (M)	1	98.9
M2		2	98.9
M3		3	98.9
M4		2	96.9
M5		2	94.9
R2	Wordings "Resolution"	2	98.9
R4		2	96.9
R5		2	94.9
O	Unprint	-	-

Fourier Transform Infrared (FTIR) Spectroscopy

The cured ink film was analyzed to confirm the occurrence of UV-curing as the decrease and disappearance of the twisting peak at 810 cm^{-1}, and a stretching peak at 1410 cm^{-1} represented the polymerization that occurred after the UV-curing process [25,26,34]. The UV-curable ink was printed and cured on 2-mm acrylic plates in pale blue PANTONE P115-4C (fabric samples B2), magenta (fabric samples M2), black (fabric samples BK2), cyan, and yellow by VersaUV LEF-200 printers under the corresponding print setting on fabric. The chemical changes in the UV-curable ink were characterised by FTIR spectroscopy (Nicolet 380 FTIR). Film samples were scraped off from the acrylic plate, and the top of the film was measured. The measurement was conducted at 500 to 4000 cm^{-1} with 10 scans. The results of FTIR of the ink film confirmed the UV-curing of the ink (Figure 3).

The chemical changes of the cured ink films were analyzed by the reflectance peaks, which represent the functional groups at certain wavenumbers according to their transmittance values. Studies of UV-cured acrylates have reported that curing occurs via the decrease and disappearance of the vibration peaks of the C=C double bonds. The absorption peaks of vibration of the C=C double bond appear at 810, 840, and 950 cm^{-1}, stretching over the range of 1410 to 1420 cm^{-1} [26,34~~35~~]. In Figure 3, the decrease and disappearance of the twisting peak at 810 cm^{-1} and the stretching peak at 1410 cm^{-1} reveal that polymerization occurred after the UV-curing process.

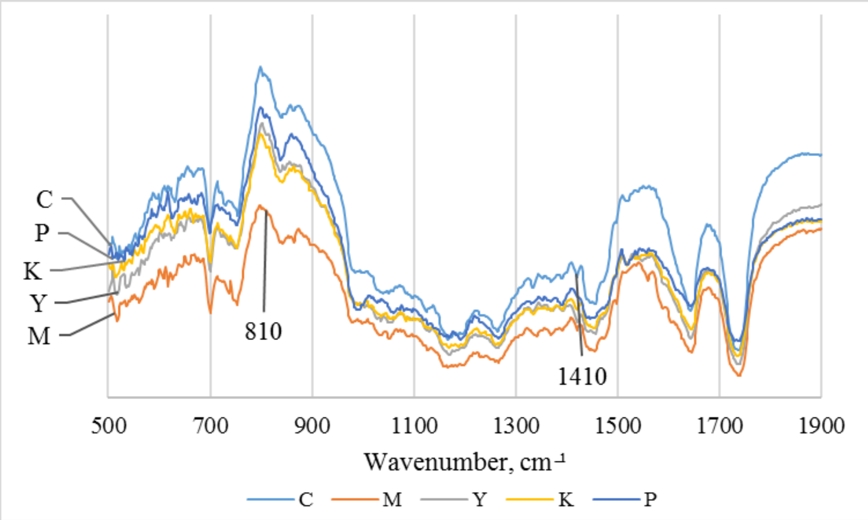


Figure 3. Fourier transform-infrared analysis of the pigmented films prepared with C, M, Y, K, and Pantone P115-4C (P) formulations.

Physical, and Mechanical Properties of the Printed Fabric

The mechanical properties of the untreated and printed PP knitted fabrics were determined using the Kawabata evaluation system for fabrics (KES-F). The system offers an objective measurement of hand properties including the analysis of bending, surface, shearing, tensile, and compression [35,36]. The samples were conditioned for 24 h at 20 ± 1 °C and 65% ± 5% relative humidity before measurement. Three specimens were printed for each printing condition, and each specimen was tested three times in both warp and weft directions. The mean value obtained from 18 tests was used. The fabric thickness was measured using Logic Basic (BC1110-1-04, AMES, USA) with pressure of 4 gf/cm^2.

Color Measurement and Resolution of Prints

Color measurement of the printed fabric was conducted using an X-Rite ColorEye 7000A spectrophotometer. The standard pale blue (Code: P115-4C) color in the PANTONE® color book was selected as the reference color, and the color difference value (ΔE) between the reference color and the printed fabric was evaluated using the spectrophotometer. Here, L^*

value represents the lightness value of the color. A greater L^* value represents a lighter color. The a^* value measures the redness ($+a^*$) or greenness ($-a^*$), and the b^* value evaluates the yellowness ($+b^*$) or blueness ($-b^*$) of the color [37,38]. Each specimen was measured once in the warp and weft directions. CIE $L^*a^*b^*$ values were measured, and the mean value was calculated from six measurements. The visual quality of prints on fabrics for various printing distances in terms of resolution was analyzed using the Leica M165C stereomicroscope and Adobe Photoshop CC software. The width and length of the letter "l" in each SEM image of the fabric printed with various printing distances were measured indirectly using Adobe Photoshop CC software, as shown in Figure 4. The tolerance of the selection tool was set to 40. The length and width are expressed in pixels, and the dimension of each picture was 2048 × 1536 pixels on a scale of 1 inch = 96 pixels. A greater number of pixels measured indicates a larger dimension of the print on the fabric, which denotes greater blurriness of the printed image.

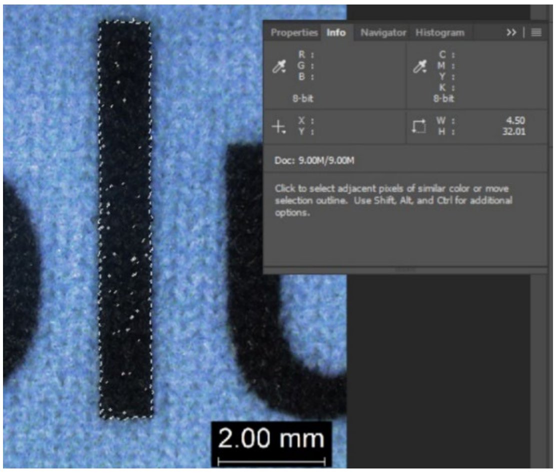


Figure 4. Length and width of the microscopic view of the printed letter "l" on fabric R2, as measured in Adobe Photoshop CC.

Statistical Analysis

The data from the experiment were analysed using SPSS 23 (IBM Corp., Armonk, New York). Multiple linear regression analysis was used to examine the relationships between the dependent variables (physical properties and low-stress mechanical properties of PP knitted fabric) and the following three independent variables: the (1) printing distance, (2) number of overprints, and (3) colors of prints. Prior to linear regression, one way analysis of variance (ANOVA) and the Pearson correlation were performed to test the relationship between the independent variables and dependent variables. The significance level of the statistical analysis was set at 0.05. Histograms, Q–Q plots, and the measures of skewness and kurtosis indicated that the distributions of bending rigidity (*B*), shearing stiffness (*G*), hysteresis at 0.5 degree of shearing (2*HG*), compression energy (*WC*), and linearity of load in tensile properties (*LT*) were considerably positively skewed. Therefore, the square root transformation was applied for *B*; inverse transformation was applied for *G*, *WC*, and *LT*; and logarithm transformation was applied for 2*HG*. The evaluation of the newly transformed distributions indicated that the distributions were close to a normal curve.

Results and Discussion

The physical properties and mechanical properties in terms of tensile, bending, shearing, surface and compression were investigated, and the color difference and the resolution of print were then compared and evaluated. The results of multiple regression analysis of physical properties are listed in Table 2, and those of mechanical properties are listed in Table 3. These results are plotted in Figures 5a, 6, 7, and 8. The results of color measurement are listed in Table 4 and plotted in Figures 5b and 9, and the print resolution results are listed in Table 5.

Table 2. Results of multiple regression analysis—predictors of physical properties

Properties	Factor	*R*	R^2	*β*	*t*	*p*	*F*	*p*
Mass per unit area	Number of overprints	0.63	0.40	0.63	4.97	0.00	18.60	0.00
	Color of print	0.75	0.56	0.41	3.20	0.00	17.47	0.00
Thickness	Color of print	0.58	0.34	0.58	7.27	0.00	37.73	0.00
	Number of overprints	0.73	0.54	0.44	5.50	0.00	41.48	0.00

Note: All coefficients are rounded to two decimal places.

Table 3. Results of multiple regression analysis—predictors of low-stress mechanical properties

Properties		Factor	*R*	R^2	*β*	*t*	*p*	*F*	*p*
Tensile	*LT*[a]	Number of overprints	0.46	0.21	-0.46	-5.03	0.00	23.20	0.00
		Color of print	0.53	0.28	-0.27	-3.02	0.00	17.24	0.00
	WT	Number of overprints	0.46	0.21	-0.46	-5.17	0.00	23.45	0.00
		Color of print	0.52	0.28	-0.25	-2.85	0.01	16.46	0.00
		Printing distance	0.57	0.32	-0.22	-2.48	0.02	13.67	0.00
	RT	Number of overprints	0.47	0.22	-0.47	-5.31	0.00	25.39	0.00
		Color of print	0.56	0.31	-0.29	-3.28	0.00	19.47	0.00
Bending	*B*[b]	Number of overprints	0.41	0.17	0.41	2.40	0.02	5.76	0.02
	2*HB*	Color of print	0.52	0.27	0.52	3.92	0.00	10.31	0.00
		Number of overprints	0.73	0.53	0.51	3.84	0.00	15.08	0.00
Shearing	*G*[c]	Number of overprints	0.51	0.26	-0.51	-3.52	0.00	9.99	0.00
	2*HG*[d]	Number of overprints	0.46	0.21	0.46	2.76	0.01	7.59	0.01
	2*HG*5	Color of print	0.50	0.25	0.50	3.50	0.00	9.13	0.01
		Number of overprints	0.68	0.46	0.46	3.27	0.00	11.47	0.00
Surface	*MIU*	Color of print	0.55	0.30	-0.55	-3.50	0.00	12.26	0.00
Compression	*WC*[e]	Printing distance	0.34	0.11	0.34	2.46	0.02	5.53	0.02
		Number of	0.45	0.21	0.30	2.21	0.03	5.47	0.01

	overprints							
RC	Color of print	0.62	0.38	-0.62	-5.17	0.00	26.76	0.00

Note: All coefficients are rounded to two decimal places.

[a]Inverse of *LT;* [b]Square root of B; [c]Inverse of G; [d]Logarithm of 2HG; [e]Inverse of WC.

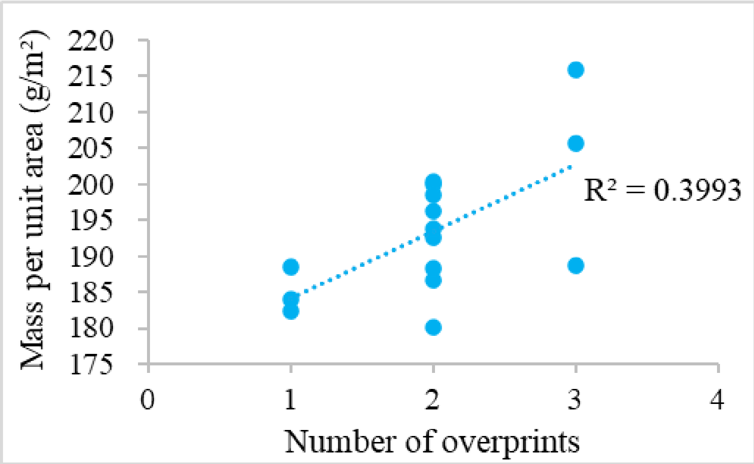
Table 4. Color parameters and differences of fabrics

Code	Number of overprints	Printing distance (mm)	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
Pantone P115-4C	–	–	83.48	-11.83	-12.01	–	–	–	–
B1	1	98.90	77.79	-8.25	-12.23	-5.45	3.41	-0.24	6.43
B2	2	98.90	69.42	-15.75	-15.40	-13.81	-4.09	-3.41	15.09
B3	3	98.90	65.83	-14.90	-21.80	-17.40	-3.24	-9.81	20.25
B4	2	96.90	69.90	-14.09	-17.25	-13.33	-2.43	-5.26	14.54
B5	2	94.90	76.33	-10.00	-12.55	-6.91	1.66	-0.56	7.17
O	Unprinted	–	85.61	-1.08	-0.79	–	–	–	–

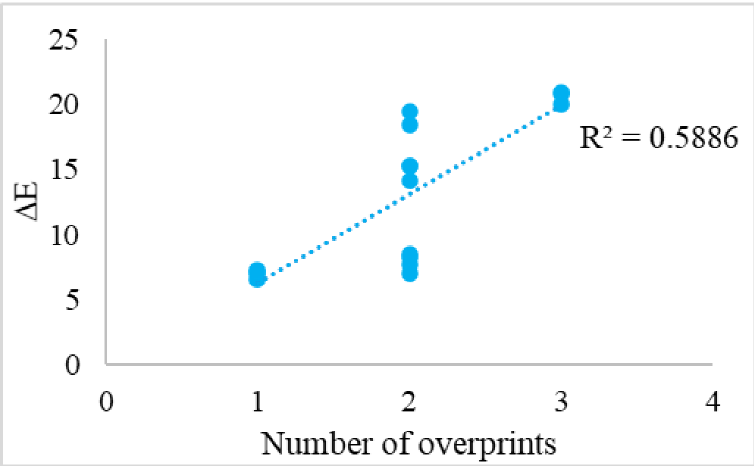
L^* - lightness coordinate.
a^* - green/red coordinate orientation; redness ($+a^*$); greenness ($-a^*$).
b^* - blue/yellow coordinate orientation; yellowness ($+b^*$); blueness ($-b^*$).
ΔE - color difference between the reference color and fabric samples.
ΔL^*- lightness difference between the reference color and fabric samples.
Δa^*- difference in green/red intensity between the reference color and fabric samples.
Δb^*- difference in blue/yellow intensity between the reference color and fabric samples.

Table 5. Length and width of the printed PP knitted fabric (1 inch = 96 pixels)

Fabric Code	Printing distance (mm)	Length (pixel)	Percentage increase (%)	Width (pixel)	Percentage increase (%)
R2	98.9	32.01	-	4.50	-
R4	96.9	32.68	2.09	4.89	8.67
R5	94.9	32.78	2.41	5.56	23.56

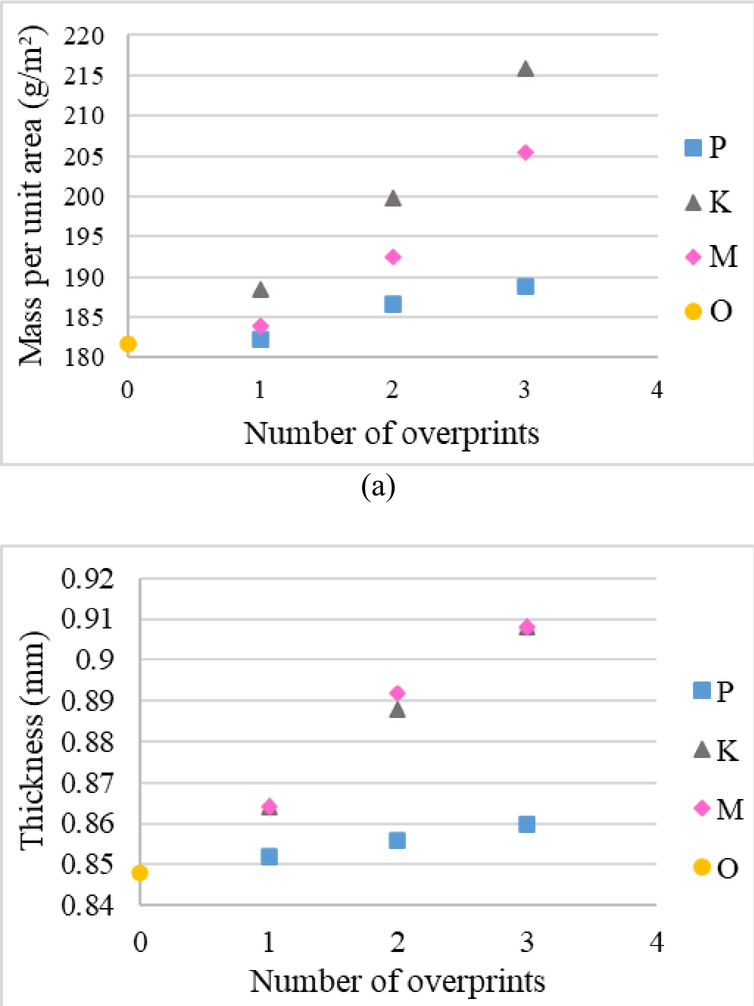


(a)



(b)

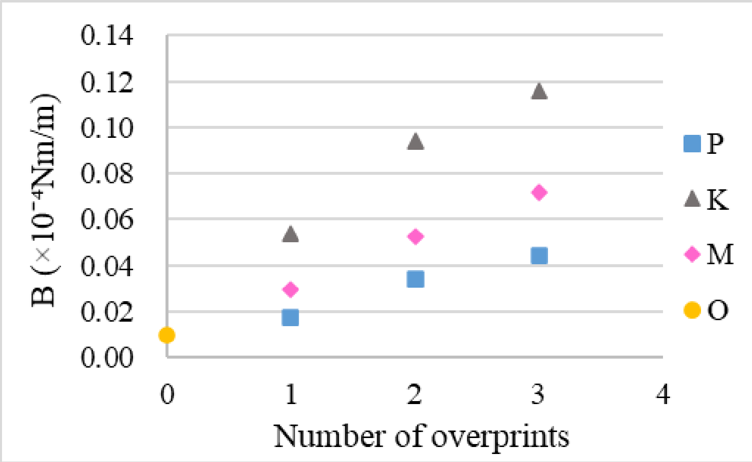
Figure 5. Bivariate scatterplots illustrating the linear relationships of (a) mass per unit area and (b) color difference (ΔE) with the number of overprints.



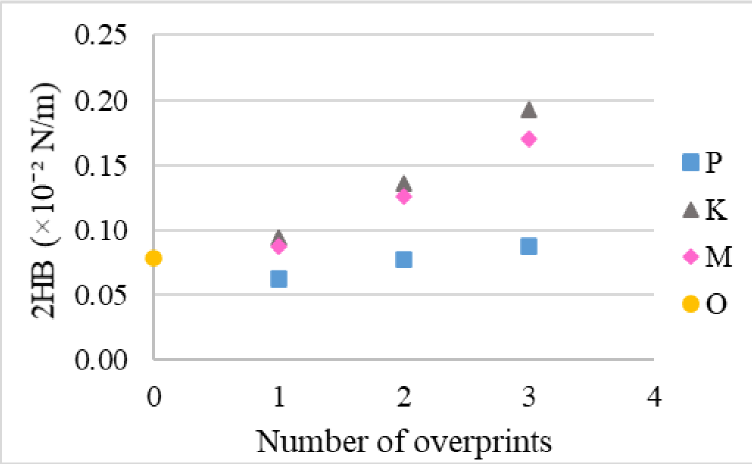
(a)

(b)

Figure 6. Changes in (a) mass per unit area and (b) fabric thickness by number of overprints.

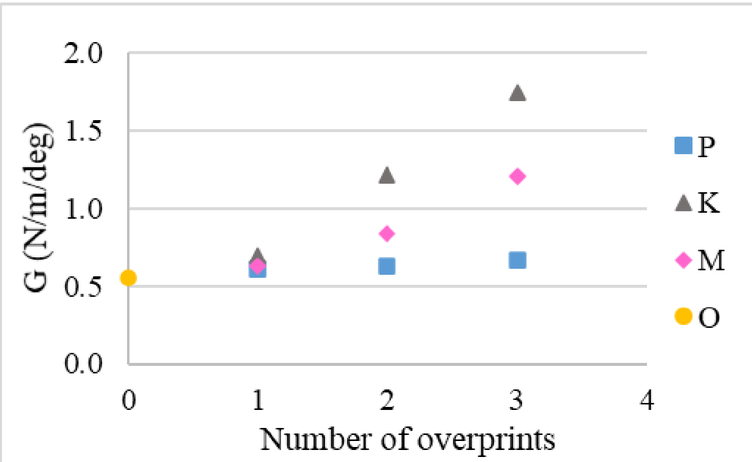


(a)

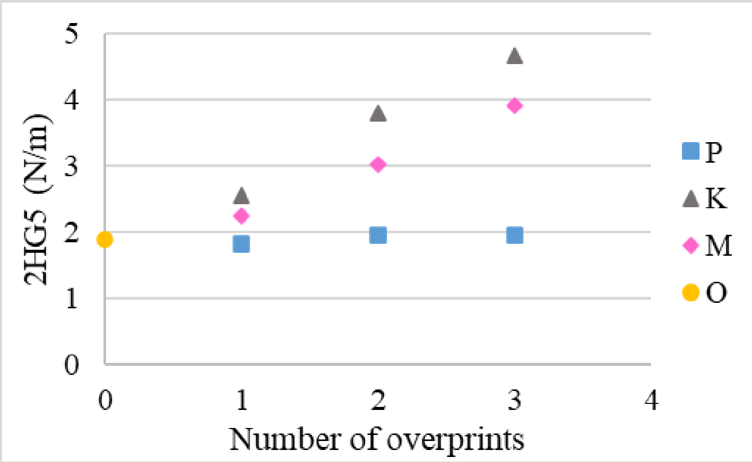


(b)

Figure 7. Changes in (a) bending rigidity (*B*) and (b) bending resilience (2*HB*) of fabrics by the number of overprints.

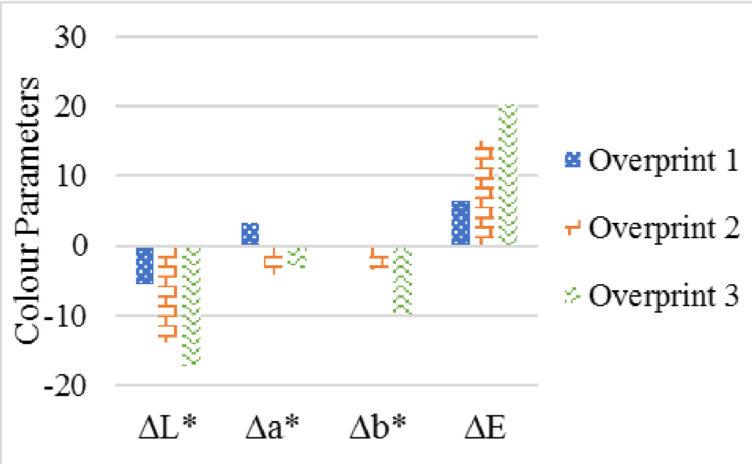


(a)

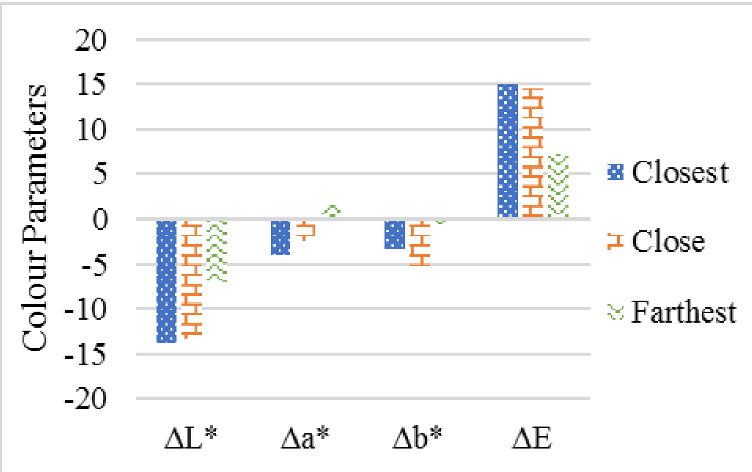


(b)

Figure 8. Changes in (a) shear stiffness (G) and (b) shear stress at 50° (2*HG*5) of fabrics by the number of overprints.



(a)



(b)

Figure 9. Color measurements of fabric samples with various (a) numbers of overprints and (b) printing distances.

Physical Properties

The result of the stepwise multiple regression analysis revealed that the mass per unit area and the thickness of the fabric increase with the increase in the number of overprints and are also affected by the color of the print (Figure 6). Generally, the mass per unit area and thickness of the fabric increased when the lightness of the printed color decreased

Mass per Unit Area

The result of a Pearson correlation analysis indicated that the mass per unit area had a significant correlation with the number of overprints ($R = 0.632$, $p < 0.05$) and color of prints ($R = 0.406$, $p < 0.05$). However, no significant correlation was determined between the mass per unit area and printing distance ($R = 0.097$, $p > 0.05$). As indicated in Table 2, the result of the stepwise multiple regression analysis revealed that only the number of overprints and color of prints emerged as significant predictors of the mass per unit area ($F = 17.47$, $p < 0.05$). With $\beta = 0.63$ ($p < 0.05$), only the number of overprints emerged as the strongest predictor of the mass per unit area, accounting for 39.9% of the variance in the mass per unit area of fabrics (Figure 5a). The second significant factor was the color of prints ($\beta = 0.41$, $p < 0.05$), accounting for an additional 16.5% of the variance in the mass per unit area. The color of the print was nominal and not included in the scale, meaning that it could be ignored. Overall, the model explained almost 56% of the variance in the mass per unit area ($R = 0.75$). The regression equation for the mass per unit area of a fabric is expressed as follows:

$$\text{The mass per unit area of a fabric} = 170.08 + (9.34 \times \text{number of overprints}) \qquad (1)$$

As depicted in Figure 6a, the mass per unit area of a fabric increased with the increase in number of overprints for all colors. The mass per unit area of the fabric printed with the black color was the greatest, followed by that of the fabric printed in magenta and pale blue colors, which indicates that the mass per unit area increases when the lightness of printed color reduced.

Thickness

Similarly, the result of the stepwise multiple regression analysis revealed that only the color of the print and number of overprints emerged as significant predictors of the thickness of the fabric (F = 41.48, $p < 0.05$). With $\beta = -0.02$ ($p < 0.05$), the color of prints emerged as the strongest predictor of the thickness of the fabric, accounting for 34.1% of the variance in the thickness. The second strongest factor was the number of overprints ($\beta = 0.44$, $p < 0.05$), accounting for an additional 19.4% of the variance in the thickness of the fabric. Greater thickness corresponded to a larger number of overprints of the fabric, and the thickness was also affected by the color of the print, as depicted in Figure 6b. Fabrics printed with black and magenta colors had greater thickness than those printed with the pale blue color. Overall, the model explained approximately 54% of the variance in thickness of the fabric (R = 0.73). The regression equation for the thickness of the fabric is expressed as follows:

$$\text{Thickness of the fabric} = 0.829 + (0.016 \times \text{number of overprints}) \qquad (2)$$

The result for the thickness of the fabric concurred with that for the mass per unit area of the fabric. When the number of overprints was increased, more ink drops were deposited on the same area of the fabric's surface to produce a printing effect similar to the printing appearance under the corresponding number of overprints; therefore, the fabric's weight and thickness increased. Inkjet printers work by applying tiny droplets of ink to the material to be printed [39]. To create the illusion of different colors, different amounts and proportions of ink dots are deposited on the material, which the human eye integrates to produce an impression of the required color [40]. This implies that additional ink dots were deposited on the fabric surface to produce an impression of a darker color. More ink dots appeared when printing in black and magenta color than in pale blue (P115-4C); therefore, the fabric's weight and thickness were also affected by the color. The mass per unit area and fabric thickness did not show a significant correlation with the printing distance, which implies that the reduction in ink drops deposited on the fabric due to the larger printing distance did not significantly affect the fabric's weight and thickness when compared with the fabric itself.

Kawabata Evaluation of Printed PP Fabrics

The relationships between printing parameters and low-stress mechanical properties were analyzed to determine the effect on fabric hand value evaluation. KES-F was used to measure low-stress mechanical properties in terms of bending, shearing, tensile, surface, and compression. The results indicated that only 2*HB* and 2*HG*5 were significantly affected by the number of overprints and color of prints, with a prediction rate above 40% (Table 3). The results showed that the handle of the fabric was not significantly influenced by the UV-cured ink layer in the KES measurements, as noted in previous studies [10,31]. This implies that the thin UV-cured ink film on the fabric may not significantly affect the fabric's hand value when compared with the fabric itself. The results obtained in this study were similar to those of previous studies in that the stiffness (*B* value) of the fabric increased after printing with UV-curable ink [10,31]. This can be explained by the application of ink film after curing with a UV light on the fabric surface and increased the stiffness of the fabric after printing. As in previous studies [10], the *G* value of the fabric printed with UV-curable ink was generally higher than that of the untreated fabric (Figure 8a).

Bending Properties

The bending properties of printed PP fabric were measured using *B* and 2*HB*. A higher *B* value indicated greater resistance to a bending motion and greater stiffness. The recovery ability of fabric after bending is represented by the value of 2*HB*. A smaller 2*HB* corresponds to better bending recovery [41]. Table 3 presents the results of the linear regression analysis, which revealed that only the number of overprints emerged as significant predictors of *B* (F = 5.76, $p < 0.05$). When the number of overprints increased, the *B* value increased, which indicated that the stiffness of fabric increased in all colors (Figure 7a). However, the model only explained approximately 17% of the variance in *B* ($R = 0.41$), which indicated that the *B* value may not have been considerably affected by the printing parameters.

For the value of 2*HB*, only the number of overprints and the color of print emerged as significant predictors of 2*HB* ($F = 15.08$, $p < 0.05$). With a beta of .52 ($p < 0.05$), the color of print emerged as the strongest predictor of 2*HB*, accounting for 26.9% of 2*HB* variance. The second strongest factor was the number of overprints ($\beta = 0.51$, $p < 0.05$), accounting for an additional 25.9% of the variance in 2*HB*. This indicated that these two factors had almost the same importance to 2*HB*; higher 2*HB* corresponded to a higher number of overprints and also affected by the color of the print. Overall, the model explained approximately 53% of the variance in 2*HB* ($R = 0.73$). A similar graphical trend was obtained in 2*HB*; a smaller number of overprints corresponded to better bending recovery for the fabric, as shown in Figure 7b. Generally, the fabric printed with the pale blue color had the best bending recovery, followed by the fabric printed with magenta and black colors. The result can be attributed mainly to the deposition of additional ink dots on the fabric printed with magenta and black colors, which limited recovery after bending.

Shearing Properties

The shear stiffness (*G*) value represents the ability of the fabric to resist shear stress to slide against one another. Low *G* values indicate the superior fabric draping properties and high mobility in garment during physical activity [36]. The lower 2*HG* and 2*HG*5 represents better resiliency and feel of the fabric [35]. With a beta of −0.51 ($p < 0.05$), the number of overprints emerged as the only predictor of G, accounting for 26.3% of the variance in G. A higher G value is a function of larger number of overprints.

Similarly, only the number of overprints emerged as a significant predictor of $2HG$ ($F = 7.59$, $p < 0.05$), which accounted for 21% of the variance in $2HG$ ($R = 0.46$). A higher $2HG$ corresponded to a higher number of overprints. As depicted in Table 3, the color of prints emerged as the strongest predictor of $2HG5$, accounting for 24.6% of the variance in $2HG5$. The second strongest factor was the number of overprints ($\beta = 0.46$, $p < 0.05$), accounting for an additional 21.3% of the variance in $2HG5$. These two factors equally affected the prediction of $2HG5$; a higher $2HG5$ corresponded to a higher number of overprints, and $2HG5$ was also affected by the color of prints. The regression model explained approximately 46% of the variance in $2HG5$ ($R = 0.68$). The G and $2HG5$ values increased with the increase in number of overprints, which indicated that the fabric demonstrated greater mobility in the garment during physical activity and superior resilience with a low number of overprints, as shown in Figure 8. The fabric printed with the pale blue color had the best draping properties and resilience, followed by the magenta and black colors. It can be seen that additional ink dots were deposited on the fabric when printing in magenta and black color, during which a larger area of fabric surface was covered by the cured ink film, which lowered the draping performance and resilience.

Tensile Properties

LT indicates the linearity of the load–elongation curve and influences the fabric extensibility at the initial strain range. A lower LT value reflects greater fabric extensibility but lower fabric dimensional stability [42]. A higher RT value reflects a more resilient fabric. The tensile energy, WT, indicates the stretchability of fabric; a larger WT corresponds to higher fabric stretchability [35,43]. The LT, WT, and RT values in tensile properties were affected by both the number of overprints and the color of the print, whereas *WT* was also affected by the printing distance (Table 3). The regression model explained approximately 28%, 31%, and 32%, of the variance in *LT*, *RT*, and *WT*, respectively. The regression model with percentage lower than 40% could be because the fabric's hand value was not significantly affected by the thin ink film when compared with the fabric itself. The regression model indicates that a higher *LT* value corresponds to a higher number of overprints. Higher *RT* and *WT* values correspond to a smaller number of overprints; Higher *WT* is also correlated with a shorter printing distance.

Surface Properties

Coefficient of friction (*MIU*) is the coefficient of friction of the fabric surface, and a higher *MIU* value represents a fabric with higher friction or drag resistance [29]. The value of deviation of *MIU* (*MMD*) is large for a rough fabric surface [35]. Geometric roughness (*SMD*) is the variation in the geometrical roughness of the fabric, and an uneven surface has a high *SMD* value [41,43]. However, only the color of print accounted for variance (30%) in *MIU* in the regression model; *MMD* and *SMD* exhibited no significant difference between different groups of various printing parameters. The *MIU* value was higher in the fabric printed with the pale blue color, with rougher surface than that printed in magenta and black colors, regardless of the number of overprints or printing distance. By comparing the results of mass per unit area (lowest in pale blue color and highest in black color) and *MIU* value, it can be seen that more ink drops were evenly distributed on the fabric surface when printed with magenta and black color than with pale blue. More inks were evenly distributed on the surface of the fabric that was covered by the UV-cured ink film, and thus imparted a smoother handle to the fabric.

Compression Properties

Compressional linearity (*LC*) is the linearity of the compression thickness curve. A higher *LC* value indicates a fabric with higher compressibility [29]. The compressional energy (*WC*) is the amount of energy required to compress a fabric [44]. Compressional resilience (*RC*) indicates the recoverability of the fabric after the compression force is removed [41]. A lower value of *RC* implies that the fabric has better comfort and compression properties [35]. As depicted in Table 3, a higher *WC* value corresponded to a lower number of overprints and shorter printing distance. However, the model only explained approximately 21% of the variance in *WC* ($R = 0.45$). The color of prints emerged as the only predictor of *RC* ($F = 26.76$, $p < 0.05$), accounting for 38% of the variance in *RC*. The fabric printed with the magenta color had the lowest *RC*, followed by that printed with black and pale blue colors, which shows that the particular thickness of the magenta cured ink film increased the fabric's recoverability after removing the compression force. The analysis indicates that the thinner cured ink film in pale blue color reduced the compression recoverability of the fabric, which made the fabric printed in pale blue color less springy. However, no significant difference was observed between different groups for various printing parameters with respect to *LC*.

Aesthetic Properties according to Color Measurement and Print Resolution

The results of the Pearson correlation analysis indicated that only the number of overprints had a significant correlation with the ΔE, ΔL^*, Δa^*, and Δb^* values but not with printing distance when the p value greater than 0.05. Here, ΔE exhibited a significant positive correlation with the number of overprints ($R = 0.767$, $p < 0.05$), which implied that the color difference between the print and standard color chips of PANTONE increased with the increase in number of overprints (Figure 5b). However, ΔL^* ($R = -.773$, $p < .05$), $\Delta \mathrm{a}^*$ ($R = -0.646$, $p < 0.05$), and Δb^* ($R = -0.810$, $p < 0.05$) exhibited significant negative correlations with the number of overprints. The lower values of ΔL^*, Δa^*, and Δb^* were related to the increase in the number of overprints, which implied that the prints appeared dull with a high number of overprints.

As depicted in Figure 9, the ΔE values and ΔL^* values shared a similar graphical trend with the opposite direction. The PP fabric with one-time overprint (B1) exhibited the least color difference (ΔE) from the reference color among all the tested samples, which implies that its color was the most similar to the reference color (Table 4). The ΔE values increased and the value of ΔL^* became more negative with increased number of overprints (Figure 9a). Thus, duller print colors and a greater color difference from the reference color occurred with a greater number of overprints. Enhancement of the sample tonality was observed by increasing the number of overprints. A relatively larger number of ink drops was deposited on the same area of fabric surface when the number of overprints was increased, and more pigments appeared on the same area that covered the white fabric surface and resulted in a duller color. The print of the fabric with one-time overprint had a greater redness intensity than the reference color, and the fabric with three overprints exhibited greater blueness intensity than the reference color.

When comparing fabrics with different printing distances, as shown in Figure 9b, the color difference (ΔE) decreased when the printing distance increased, and the color difference between the reference color and printed fabric was the smallest when printed with the longest printing distance. The lightness difference (ΔL^*) become less negative with higher printing distances, which indicated that the fabric with the greatest printing distance had the most similar lightness to that of the reference color. The color of the print on the PP fabric with closest printing distance (B2) was greener than that of the reference color. The print of the fabric changed from a higher blueness intensity (B4) than the reference color to a redder appearance (B5) when the printing distance increase, as indicated in Table 4. The results showed that the printing machine obtained the best printing result under the closet printing distance and when the number of overprints was set to one. In this study, the number of overprints was set to two when evaluating the effects of a fabric's properties by the printing distance. The larger amount of ink was released, but not all the ink droplets could be deposited on the fabric surface and cured successfully when the printing distance increased. Therefore, the color that appeared on the fabric was lighter than that with the closet printing distance, and had the most similar lightness to and less color difference from the reference color. Moreover, the loss of ink droplets had a noticeable effect on the color appearance but did not have a significant effect on the physical and mechanical properties of the printed fabric.

When comparing the resolution of prints on PP fabrics with different printing distances, as shown in Table 5, both the length and width of letter “l” increased with a higher printing distance. This implied that the resolution of the letters printed on the fabric decreased when the printing distance was increased. Moreover, the percentage of changes in width was higher than that of changes in length. This can be explained by the air current created when the print head moved horizontally in the printer, which allowed the ink droplet to spread in the air and transport a great distance in the horizontal direction before landing on the fabric surface.

Conclusion

This study developed UV-curable inkjet-printed PP fabrics for sportswear applications. The results of FTIR of the cured thin film confirmed the curing of the ink after the UV-curing process. The effects of differences in the printing distance, the number of overprints and the color of the prints on the fabric weight, thickness and hand attributes, including stiffness, smoothness and softness, were explored. This study provided evidence that the physical properties, low-stress mechanical properties, and color appearance of PP fabrics printed with UV-curable ink were significantly affected by the number of overprints, the color of the prints and the printing distance. The relationships discussed in this paper have not been reported previously, and a research gap was filled. The results indicated that the fabric’s mass per unit area, thickness, $2HB$ and $2HG5$ increased when the number of overprints was increased and the lightness of the printed color was decreased. With the greater printing distance, the loss of ink droplets had a noticeable effect on the color appearance but did not have a significant effect on the physical and low-stress mechanical properties of the printed fabric. The color of the fabric was more sensitive to changes in the amount of pigment, but the effects on the fabric's weight, thickness and mechanical properties were not significantly affected. The blurriness of the print significantly increases in horizontal direction because of the air current created by the horizontal movement of the print head. Our proposed UV-curable inkjet printing on PP knitted fabric is an important step towards the manufacture of commercial PP textiles in the apparel industry, and textile designers will benefit from this study when using PP fabrics. A future study should investigate the chemistry of UV-curable ink and test the color fastness of the printed PP fabric with UV-curable inks, including wash and crock fastness, to investigate the fade resistance of UV-cured ink film for apparel application.

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