Relative Color Pickup of Three Different Knits and Predictive Dyeing Recipe Formulation

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Abstract

The study investigated relative color exhaustion of cotton for three different knitted structures (single jersey, rib, and fleece) in the same dyebath. The knitted structures were produced from the yarn of same size. Reactive dyes with three fundamental colors such as red, yellow, and blue were used in the dyeing process simultaneously based on industrial practice. After dyeing all the knitted structures in the same bath, CIELAB values were obtained from all of them and statically analyzed by ANOVA. However, the purpose was to see if there was any difference in color pick-up for different fabric structures. The second part of the study comprised of rib and fleece dyeing with the adjusted recipe based on CIELAB values. In this case, single jersey was considered as the target swatch. Results revealed that adjusted recipe worked well for optimizing the process to get uniform color for all three types of knits. Developed adjustment technique can be used advantageously by the professionals from industry as well as academia.

Keywords - *Dyeing, Color Pickup, Knits, Spectrophotometer, Fiber Content*

I. INTRODUCTION

Colors make the world attractive and pollute it with pleasing venom [1]. Colors have been applied to improve the appearance of the surface since the prehistoric time. Historical records show that humans extracted color from vegetables, fruits, flowers, animals and insects to dye the objects dating back to 3500 BC [1]. Textiles industry is one of the biggest users of dyes for coloring the fabrics. However, the textile dyeing process is not as easy as it sounds and requires a lot of time and effort to create the uniform shade [2]. Uniformity in the shade is important for the textile product. Garments are made of different fabric constructions (knitted or woven and their variations) that absorb dye differentially [3]. Several garments use both knitted and woven materials together. Woven garments could have knitted cuffs or collars. Or, fleece/jersey t-shirts or sweat shirts could have cuffs and collars made from rib knit. In such cases, consumer expects uniform dyeing. Therefore, manufacturer needs processes in place that can create uniformity of dyeing between and among various constructions.

Textile dyeing consists of several stages. For reactive dyeing, they include such as scouring and bleaching, neutralizing wash, dyeing, and removing unfixed colors through neutralization wash and soaping [4]. In each stage, the water bath is discharged, and fresh water is taken. This discharged water contains various kinds of hazardous chemicals, which can be harmful to the environment. Most of the textile industries established ETP (effluent treatment plant) near to the dyeing facilities for the purification of dyeing discharge and the process is very expensive [5]. The amount of reprocessing is a vital problem for the textile dyeing industry [6]. Whenever there is a slight deviation in the shade, the manufacturer re-dyes the fabric to match with the standard swatch. Each re-dyeing process is accounted for 6 to 8 hours extra time, water, color and chemicals, and energy loss, which is not desirable for the manufacturers. The reported study provides a framework for the manufacturer that might reduce the amount of reprocessing.

The knitted fabrics influx in casual apparel worldwide demonstrated through the proceeding information compelled the researchers to focus on knitted materials. The global market of knitted products was estimated $77.7 billion in 2017, and the Asian region was the contributor for 68.8% of the global knit market [7]. Over the years, the growing knit apparel industry is replacing woven products continually [8]. On the other hand, knit production facilities do not require high investments as it is required for the woven industry. Low manpower, low energy consumption, and automation have brought revolutionary changes in the knit industry. In recent years, the reducing costs of knit products has given it a comparative advantage over woven products without losing their quality [7]

The knitted structures were made of cotton was used for the study because they are used most widely globally. Statista also revealed that the global cotton business increased from the last 30 years [9]. The apparel products made of cotton are comfortable to human skin and famous for its moisture absorption capacity. There are several dyestuffs to color cotton fabrics. Reactive dyes are the most common dyestuff used for cotton dyeing because it renders an excellent colorfastness by creating covalent bonds with color [4]. Several textile industries of Bangladesh use reactive dyes in the coloration process. The revenue generated by U.S. dye market from 2014 to 2018 is the highest in history [10].

The study of relative color exhaustion is essential from the viewpoint of the manufacturer because it provides a basic framework for shade correction which can reduce the amount of reprocessing, water and chemical consumption, and energy loss. The twofold purpose of the study was as follows. (1) The first part of the study compared relative color exhaustion of three different knitted structures of cotton (single jersey, rib, and fleece). The color exhaustion was measured on the basis CIELAB value after dyeing each specimen. (2) The second part of the study included rib and fleece dyeing with the adjusted recipes from the target swatch, and formulation of the best predictive recipe for rib and fleece by shade analysis.

II. LITERATURE REVIEW

Color theory and Munsell color system

Since prehistoric time, scientists and artists investigated the nature of colors and developed many theories [11]-[13]. The purpose of these theories was either to produce them or express them with a set of attributes. The Young-Helmholtz trichromatic color theory revealed that all the color can be produced by the combination of red, green, and blue colors [14] which is completely true for additive color theory of light mixture. All the colors can be produced digitally after combing red, green, and blue color light sources with specific portions. However, textile industry does not follow this color model, since it requires to color the product physically. Textile industries use RYB color model for dyeing and printing, where it is possible to produce all the shade physically by creating mixtures of red, yellow, and blue colors at different proportions [15].

Even though the color theory was utilized by many industries that time, it startled the manufacturers with color intensity, whiteness or darkness in the shade, and saturation level with other colors. To solve this problem, A.H. Munsell underlined "music is equipped with a system by which it defines as each sound terms of its pitch, intensity, and duration" and in the same way he pointed out "color should be supplied with an appropriate system based on the hue, value, and Chroma" [11]. According to Munsell color system, color was expressed by three variables: a) Hue; to express the saturation level of colors. b) Value; to express whiteness or darkness. c) Chroma; it expresses depth of the color [16].

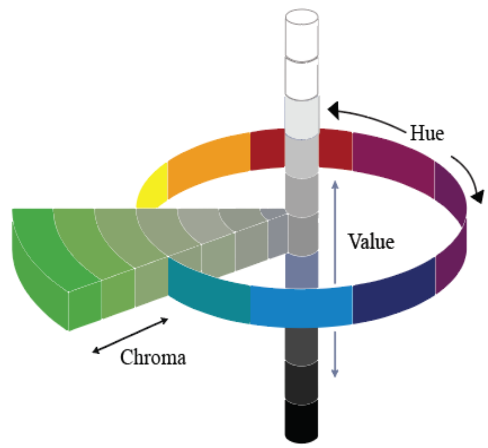

Fig 1: Munsell Color system [16].

Measurement of color difference

CIELAB color space system is the most popular and widely used by most of the textile dyeing industries, where CIE stands for International Commission on Illumination. CIELAB color measurement system has three color coordinates; L* (same as "Value" in Munsell system) indicates lightness or darkness of the shade, a* indicates the color tone toward red or green, b* indicates the color tone toward yellow and blue [17]. For a colored specimen with L^*_2, a^*_2, b^*_2 values and standard swatch with L^*_1, a^*_1, b^*_1 values, the color difference Δ E is expressed by the following equation [18].

$$\Delta E = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2}$$

Where $\Delta L* = L^*_2 \sim L^*_1$, $\Delta a* = a^*_2 \sim a^*_1$, and $\Delta b* = b^*_2 \sim b^*_1$

Reactive dyeing of cotton

In early 1900s, Ratte and Stephen developed a dyeing process to dye cellulosic fibers with reactive dyes by creating covalent bond in their structures under alkaline condition [4]. See following reaction; Cell-OH represents cellulose, and Dye-Cl represents reactive dye.

$$\text{Cell-OH} + OH^- \rightarrow \text{Cell-O}^- + H_2O$$

$$\text{Cell-O}^- + \text{Dye-Cl} \rightarrow \text{Cell-O-Dye} + \text{Cl}^-$$

Ratte and Stephen started dyeing at neutral pH = 7. The salt is added in the dye bath to promote initial exhaustion of dyes into the fiber. During this step, dyes do not react with cellulose and it facilitates fiber to fiber dye migration. Then the alkali is added in the dye bath to promote the reaction between fiber and dyes [4].

Relative color pickup

Sadeghi-Kiakhani and Safapour (2015) emphasized the salt-free dyeing of cotton fabric. They used chitosan-poly (propylene imine) dendrimer hybrid (CS-PPI) instead of traditional textile dyeing salts. The study suggested that the amount of CS-PPI cationizing agent affects positively on dye exhaustion percentage [19]. Khatri et al., (2012) reported that the color exhaustion of cellulosic fiber relies on the dye diffusion into the fiber polymer system and the degree of diffusion depends on the amount of electrolyte concentration and temperature of the dye bath [20]. Zhang et al., (2015) examined that the cotton fabric dyed with Hemicyanine fluorescent dye in presence of PMA (poly-maleic acid) crosslinking agent possessed an undeniable fluorescence effect. However, they found that the amount of PMA crosslinking agent also contributed to wrinkle resistance property [21]. Fu et al., proclaimed that dyeing in a nonaqueous medium in the D5-suspension system significantly improves color pickup compared to the traditional reactive dyeing process. Additionally, this process minimizes the risk of dye-hydrolysis [22]. Tang et al., (2014) stressed that the creation of polymer layer on the knit fabric surface by applying dye attracting nanoparticles enhances color exhaustion [23]. Ali et al., (2015) informed that the application of cationic starch (Q-TAC) in the reactive dyeing process instead of salt augments the dye exhaustion [24].

Zhao, Feng, and Wang (2014) stated that the color exhaustion of cellulase enzyme treated flux fabric improves compared to untreated fabric. Dyeing bath temperature, temp and P^H increases color exhaustion to a certain extent [25]. Bhuiyan et al., (2017) investigated the dyeing properties of jute fiber with natural dye henna after carrying out the treatment by chitosan solution and assessed that chitosan treated fabric appeared darker in shade compared to untreated fabric [26]. Bouzidi et al., (2016) endeavored to dye wool fabric with a natural colorant extracted from Limoniastrum monopetalum stems. They found that color exhaustion and evenness depend on the optimization of the color extraction process from the natural source. Besides that, different types of mordants contribute to the different depth of shades [27]. Hasan, Nayem, and Azim (2014) approached to dye cotton and silk with natural curcumin in the presence of different mordanting chemicals. They suggested that exhaustion curcumin significantly relies on mordanting performance [28]. Shimo and Smriti (2015) examined the relative color strength and color coordinates based on fabric GSM and the amount of dye concentration. They asserted that color strength and color coordinates increased with the colorant concentration and GSM of the same knit structure [29]. Acharya et al., (2014) introduced trimethyl-ammonium chloride (CHPTAC) cationizer in salt-free reactive dyeing of cotton and demonstrated that there is a pivotal effect of CHPTAC concentration in the percent of color exhaustion [30]. Hasan et al., (2015) revealed that the cotton and silk fabric dyed with Lawsone extracted from henna leaves provides better color coordinates and depth in the shade depending on the used mordant [31]. Sufian et al., (2016) compared conventional Remazol reactive dye and Avitera reactive dye for better color yielding. They found the quality of dyes greatly affected color exhaustion and levelness [32]. Kamruzzaman et al., (2016) have shown that the relative color exhaustion depends on the optimum use of soda ash and sodium hydroxide in the reactive dyeing process [33].

Most of the previous studies suggested that the investigation regarding relative color exhaustion has been done based on pretreatment, dyeing auxiliaries, dyeing condition, dyes type, and process. Table I provides summary of scholarly literature on relative color exhaustion regarding pretreatment, additives, conditions, dyes and processes. However, the authors inferred that there is a gap in the study of color exhaustion and knit structures. From the findings of Shimo and Smriti (2015) regarding GSM (grams per square meter) and color strength [29] and literature review the author developed the following hypothesis.

Hypothesis 1: Color exhaustion depends on the type of knit structure in the same dye bath

TABLE I
Previous scholarly works on relative color exhaustion

Study	Covered topics	Description
Relative color exhaustion	Pretreatment	Pre-mordanting
		Scouring and bleaching
		Enzymatic treatment

		Cationization
	Dyeing auxiliaries	Salt
		Soda
		Mordants
		other auxiliaries
	Dyeing condition	pH
		Temperature
		Time
	Dyes	Organic
		Inorganic
	Innovative Process	Plasma treatment
		Supercritical fluid treatment

III. MATERIALS

The investigation compared color exhaustion of three different knit constructions (single jersey, rib, and fleece) for cotton dyeing. Reactive dye was chosen for the study as it is the most widely used dyestuff in textile dyeing, produces even shades with excellent color fastness, and the process is less complex [4].

Fabric

Fabrics were purchased from one of the leading knit product exporters of Bangladesh. To add reliability and validity in experimentation results, the fabrics were produced by using threads of the same yarn size and fiber content. The manufacturer used ‘indirect yarn numbering system’ or ‘English cotton count’ to express the yarn size which refers to the number of hanks in one pound of cotton [34]. All knit types were made from 100% BCI cotton, where BCI stands for ‘Better Cotton Initiative’, and it also means that the cotton cultivation was carried out without any hazardous chemicals [35]-[36]. Table II below lists the details about fabrication [37], yarn size [34], composition, and fabric weight [38] represented as GSM.

TABLE II
Fabric Specification

Type	**Yarn Count**	**Composition**	**GSM**	
			Mean	*SD*
SJ	30/S	100% BCI Cotton	153.829	2.835
Rib	30/S	100% BCI Cotton	445.782	11.299
Fleece	30/S	100% BCI Cotton	293.882	3.792

Spectrophotometer

The color difference of the dyed specimens was measured by using CM-2500d spectrophotometer, which is a handheld portable instrument [39]-[42]. The researchers used CIELAB color measurement system to estimate the color difference among different shades.

Chemicals

Traditionally fabrics are collected in ‘grey form’ directly from the manufacturer, which means the fabrics have not been subjected to any kind of wet and chemical treatment previously. The outer layer of cotton contains cuticle or hydrophobic layer, so it is necessary to remove that hydrophobic layer from the fabric surface to make it dyeable. The process is called scouring. On the other hand, cotton has an inherent natural color that makes it slightly yellowish. This inherent color creates problems in light shade dyeing process since it contributes to the final appearance of the shade. Therefore, it is a good practice to remove the natural color from the surface of cotton for the standardization of dyeing process. The treatment for removal of the natural color of cotton is called bleaching and it whitens the fabric surface. The following table III contains a list of chemicals that were used for the experiments. The chemicals chosen for the study was acquired from the local market. Most of the textile industries use *Hydrogen Peroxide (50%)* as bleaching chemical for cotton [43]. However, this chemical was not available in the local market since it causes skin burn and lung cancer [44]. CLOROX was used instead of *Caustic Soda* and *Hydrogen Peroxide*, and available in the local market. CLOROX contains both *Caustic Soda* and *Sodium Hypochlorite* (instead of *Hydrogen Peroxide)* for combined scouring and bleaching purpose [45]. The dyeing process requires salt to promote initial exhaustion, color, and soda ash to facilitate reaction between dyes and fiber. Finally, vinegar was used for neutralization purpose.

Table III
List of Chemicals

Process	Commercial Name	Composition	Function
Scouring and Bleaching	CLOROX	Caustic Soda	To remove oil, and wax from the fabric.
		Sodium Hypochlorite	To remove the natural color and whiten the fabric.
Dyeing	Great Value Salt	Sodium Chloride	To create positive charges around the fabric surface and promote initial exhaustion.
	Soda Ash	Sodium Carbonate	To create covalent bonds between dyes and cotton.
	DYLON Tulip Red	Reactive Dye	To color the fabric.
	DYLON Sunflower Yellow	Reactive Dye	To color the fabric.
	DYLON Blue Jeans	Reactive Dye	To color the fabric.
Neutralizer		Acetic Acid	To neutralize the alkaline P^H

IV. METHODS

The investigation was conducted in six different steps: (1) Sampling and recipe formulation, (2) combined scouring and bleaching, (3) dyeing, (4) measurement of color difference (ΔE), (5) dyeing with the revised recipe, and (6) final assessment.

Sampling and recipe formulation (Step 1)

The combination of red, yellow, and blue colors has been employed for the dyeing recipe since these colors are widely used by the industries as primary sources of all colors. The dyeing was carried out in the same dye bath which contained three different knit structures such as single jersey, rib, and fleece specimens (Step 3). For the better understanding and minimizing forthcoming confusion, authors named this sample space as ‘sample space one’.

Step five of the methodology consisted of three activities: (1) to dye the fiber with main recipe + ΔE, (2) to dye the fiber with main recipe + 0.8ΔE, and (3) to dye the fiber with main recipe + 1.2ΔE. Furthermore, rib and fleece construction had been selected for these upper mentioned activities excluding single jersey construction, because authors regarded the shade of single jersey as target swatch. In industrial practice, the body fabric or single jersey is dyed in a huge amount with a small amount of rib and fleece, as rib and fleece are only used for collars, cuffs, and design parts of the garment products. So, it is reasonable to follow the higher quantity as the target swatch. For the better understanding and minimizing forthcoming confusion, authors named this sample space as ‘sample space two’. The study required a total of 9 specimens considering sample space one + sample space two. For the identification and allocation purpose of specimens, single jersey specimens were numbered as S1, rib specimens were numbered as R1, R2, R3, R4; and fleece specimens were numbered as F1, F2, F3, F4. Step two needs all the specimens for combined scouring and bleaching. Step three required sample space one, which included S1, R1, F1. Sample space two consisted of 6 different groups of specimens;

R2 – Rib dyeing with main recipe + ΔE
R3 – Rib dyeing with main recipe + 0.8 ΔE
R4 – Rib dyeing with main recipe + 1.2 ΔE
F2 – Fleece dyeing with main recipe + ΔE
F3 – Fleece dyeing with main recipe + 0.8 ΔE
F4 – Fleece dyeing with main recipe + 1.2 ΔE

However, each specimen was cut into 8” X 8” dimension and five different readings were taken from every specimen for CIELAB values. Though scouring and bleaching are two different processes, authors have combined both for the investigation because many industries are doing so for the reduction in water and energy consumption.

Combined Scouring and Bleaching (Step 2)

At first, all the specimen weights were measured, and recipe calculation was done in accordance with table IV. The required amount of water was added and then the fabric specimens were immersed in the solution. The temperature was raised to 60°C and CLOROX solution was added in the bath. The temperature was again raised to 98°C and maintained for 60 min. The specimens were steered continuously in the bleaching solution for better performance. After the completion of 60 min, the bleaching solution was dropped, and new hot water was poured for a hot wash. The hot wash cleaned the specimens and reduced the alkalinity of bleaching action. In the end, *acetic acid* was added in the water to neutralize the specimens.

TABLE IV
Recipe for combined scouring and bleaching

Chemicals	
CLOROX	10 g/l
Acetic acid	2 g/l
Process parameters	
Time	60 min
Temperature	98° C
M: L	1:20

Dyeing (Step 3)

The bleached specimens were then immersed in dyeing water and the required amount of salt was added. The temperature was raised to 60°C and the color solution was dosed slowly by taking time. The slow addition of color ensured uniform distribution. The temperature was again raised to 65°C and the required amount of soda ash was dosed slowly. After dosing, 65°C temperature is maintained continuously for 60 min. Then the dyeing solution was dropped, and specimens were neutralized (Table V).

Measurement of color difference (Step 4)

The color differences (ΔE) were measured by comparing CIELAB values of single jersey, rib, and fleece such as S1 vs R1, R1 vs F1, and F1 vs S1 (This was the first part of the investigation). The point to be noted, the readings of CIELAB values were taken only from the face side of samples. However, this study used CIELAB color system using RYB model, since all the colors can be produced by using these three primary colors for a textile product [46].

TABLE V
Recipe for dyeing (Step 3)

Chemicals	
Salt	100 g/l
Red	3% owf*
Yellow	3% owf*
Blue	3% owf*
Soda Ash	20 g/l
Acid	1 g/l
Process parameters	
Time	60 min
Temperature	65° C
P^H	9 to 10
M: L	1:20

*owf = on the weight of fabric.

Dyeing with the revised recipe (Step 5)

The measured ΔE for rib and fleece were then added with the main recipe for step five. Broadbent (2001) informed that the reactive dye is prone to hydrolyze by reacting with water molecules, this causes waste of dyes [4]. Considering hydrolysis effect of reactive dyes, authors decide to add two more activities for step five such as main recipe + 0.8 ΔE, and main recipe + 1.2 ΔE (Table VI). All the activities of step five were explained in step 1 (*Sampling and recipe formulation*).

TABLE VI
Dyeing with adjusted recipes (Step 5)

Chemicals	**Main Recipe + ΔE**	**Main Recipe + 0.8ΔE**	**Main Recipe + 1.2ΔE**
Salt	100 g/l	100 g/l	100 g/l
Red	3% + ΔE	3% + 0.8ΔE	3% + 1.2ΔE
Yellow	3% + ΔE	3% + 0.8ΔE	3% + 1.2ΔE
Blue	3% + ΔE	3% + 0.8ΔE	3% + 1.2ΔE
Soda Ash	20 g/l	20 g/l	20 g/l
Acid	1 g/l	1 g/l	1 g/l
Process	**Main Recipe + ΔE**	**Main Recipe + 0.8ΔE**	**Main Recipe + 1.2ΔE**
Time	60 min	60 min	60 min
Temperature	65° C	65° C	65° C
P^H	9 to 10	9 to 10	9 to 10
M: L	1:20	1:20	1:20

Final assessment (Step 6)

TABLE VII
Measurement of color difference

Specimen	ΔE
Rib	S1 vs R2
	S1 vs R3
	S1 vs R4
Fleece	S1 vs F2
	S1 vs F3
	S1 vs F4

The rib (R2, R3, R4) and fleece (F2, F3, F4) specimens which were dyed using adjusted recipes at step five are subjected to final assessment with the target single jersey swatch in this step. This decision was consistent with the industrial practice in Bangladesh. The assessment revealed the best predictive recipe for rib and fleece dyeing which will work well to get uniform color for all three types of knits. Step six includes ΔE comparison of the shades listed on the table VII.

V. RESULT AND DISCUSSION

After dyeing the fabrics (single jersey, rib, and fleece) in the same bath, five different readings of L*, a*, b* were taken from each sample by using a spectrophotometer. The mean and standard deviation were calculated (Table VIII). In later, authors used these mean values to calculate the color difference (ΔE) between shades (Table IX). The value of ΔE (0 to 1 inclusive) indicates that the shade difference is not visible to human eyes. On the other hand, if the value of ΔE is greater than 1, the shade difference is visible at a glance [47]. Nowadays, most of the textile industries consider ΔE = 1 as the highest limit of shade deviation.

Table IX compared the color difference (ΔE) among single jersey, rib, and fleece by choosing two of them each time. ΔE is calculated by the pre-mentioned equation in the literature review section [18], and six comments were developed by authors based on CIELAB color system [17] and the visibility scale [47]. Comment 1, 3, 4, and 6 implies that rib has picked up the highest amount of color in the dyeing process compared to single jersey and fleece. On the other hand, comment 2, and 5 indicates that fleece absorbed less amount of color than single jersey.

TABLE VIII
CIELAB values of knits (dyed in the same bath at step 3)

Single Jersey	L	a	b	Mean		SD	
	56.01	20.40	1.83	**L**	55.88	**L**	0.341
	56.42	20.15	1.89	**a**	20.49	**a**	0.223
	55.61	20.68	2.46	**b**	2.22	**b**	0.326
	55.77	20.55	2.44				
	55.61	20.68	2.46				
Rib	**L**	**a**	**b**	**Mean**		**SD**	
	54.72	20.90	3.98	**L**	54.01	**L**	0.553
	54.31	21.34	3.35	**a**	21.24	**a**	0.324
	53.40	20.89	3.36	**b**	3.56	**b**	0.287
	54.10	21.57	3.36				
	53.51	21.49	3.73				
Fleece	**L**	**a**	**b**	**Mean**		**SD**	
	56.83	20.85	2.84	**L**	56.55	**L**	0.480
	56.95	21.09	3.49	**a**	20.84	**a**	0.602
	56.03	21.23	2.55	**b**	2.83	**b**	0.387
	56.03	21.23	2.55				
	56.93	19.80	2.74				

Table IX
CIE LAB: Measurement of color difference (ΔE)

Comparison	ΔL	ΔL^2	Δa	Δa^2	Δb	Δb^2	ΔE
SJ vs Rib	1.88	3.52	-0.75	0.56	-1.34	1.80	2.42
SJ vs Fleece	-0.67	0.45	-0.35	0.12	-0.62	0.38	0.98
Comment 1	Single jersey is lighter than rib, and shade difference is visible at a glance.						
Comment 2	Single jersey is darker than fleece, and shade difference is not visible to human eyes.						
Rib vs SJ	-1.88	3.52	0.75	0.56	1.34	1.80	2.42
Rib vs Fleece	-2.55	6.48	0.40	0.16	0.72	0.52	2.68
Comment 3	Rib is darker than single jersey, and shade difference is visible at a glance.						
Comment 4	Rib is darker than fleece, and shade difference is visible at a glance.						
Fleece vs SJ	0.67	0.45	0.35	0.12	0.62	0.38	0.98
Fleece bs Rib	2.55	6.48	-0.40	0.16	-0.72	0.52	2.68
Comment 5	Fleece is lighter than single jersey, and shade difference is not visible to human eyes.						
Comment 6	Fleece is lighter than rib, and shade difference is visible at a glance.						

Hypothesis Testing

Hypothesis 1: Color exhaustion depends on the type of knit structure in the same dye bath.

Table VIII shows that though single jersey, rib, and fleece are made of cotton, they have significantly different L*, a*, b* values in the dyed samples. Results from One-Way Analysis of Variance revealed that L* values of three types of knits differed significantly ($F_{2,\ 12}$ = 39.837, p<.000). Single Jersey (55.88) was lighter than rib knit (54.01) but darker than the fleece (56.55) tested for the investigation. Differences were also significant for a* values ($F_{2,\ 12}$ = 4.085, p<.044). Rib (21.24) and fleece (20.84) were more reddish than the single jersey (20.49). Results from the comparison of b* values also demonstrated significant difference by knit construction ($F_{2,\ 12}$=19.893, p<.000). Both rib (3.56) and fleece (2.83) were yellower than the single jersey knit (2.22). Significant differences in L*, a*, b* values as measured by spectrophotometer and tested by ANOVA demonstrated that the color exhaustion relies on the knit structures in the same dye bath. Hypothesis I was accepted. Previous literature did not report any information on the proposed relationship.

Next, One-Way Analysis of Variance also disclosed that GSM of the three different knits differed significantly (F2, 12 = 2130.892, p<0.000). Single jersey had the lowest mean GSM (153.829), rib had the highest mean GSM (445.782), and fleece was in the middle (293.882). Besides that, the CIELAB values were varied significantly for the knitted structures as discussed earlier. However, from t-test (at 95% confidence level) analysis, authors uncovered that the higher GSM did not always pickup more color compared to lower GSM. The statistical analysis stressed that µL (Single Jersey) > µL (Rib), µL (Fleece) > µL (Rib), and µL (Single Jersey) >/ µL (Fleece). Figure 2 showed that even though GSM was higher for fleece (293.882), it was lighter than single jersey (153.829).

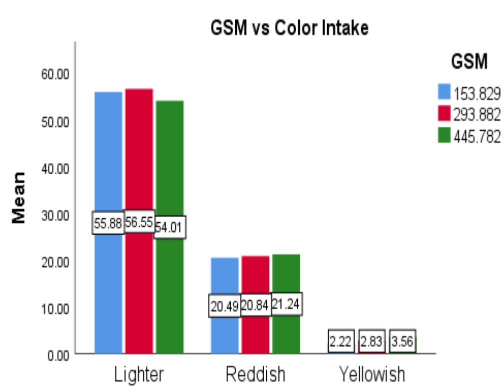

Fig 2: GSM vs the amount of dye intake.

Recipe development for step five (from Table X, and Table XI)

The second part of the study was started from step five. It included shade correction activities where CIELAB value of single jersey was considered the target shade for other two knit structures. The shade difference percentage was calculated by the following equation. Table X represents shade difference among three different knits and was obtained from spectrophotometer.

Shade difference

$$(\%) = \frac{CIE\ LAB\ Value\ of\ Rib\ or\ Fleece - CIE\ LAB\ Value\ of\ Single\ Jersey}{CIE\ LAB\ Value\ of\ Single\ Jersey}$$

TABLE X

Comments on rib and fleece shade with respect to single jersey

Fabric	**%**	**Comment on ΔL**
Rib is	3.36	Darker
Fleece is	1.20	Lighter
Fabric	**%**	**Comment on Δa**
Rib is	3.64	Reddish
Fleece is	1.70	Reddish
Fabric	**%**	**Comment on Δb**
Rib is	60.47	Yellowish
Fleece is	27.89	Yellowish

The obtained shade difference between the target and specimens were then employed in the recipe correction Table XI, and the dyeing recipe was adjusted by three pre-mentioned activities of step five; main recipe + ΔE, main recipe + 0.8 ΔE, and main recipe + 1.2 ΔE at table XII. The rib and fleece specimens were dyed with these recipes for the second part of the study.

TABLE XI

Recipe correction for rib and fleece (from table X)

Color		**Main recipe**		**ΔE (for rib)**		
Red	=	Main recipe	-	3.36 % of main recipe	-	3.64 % of main recipe
	=	3	-	0.101	-	0.109
	=	3	-	0.21		
Yellow	=	Main recipe	-	3.36 % of main recipe	-	60.47 % of main recipe
	=	3	-	0.101	-	1.814
	=	3	-	1.915		
Blue	=	Main recipe	-	3.36 % of main recipe	-	0% of main recipe
	=	3	-	0.101	-	0
	=	3		0.101		
Color		**Main recipe**		**ΔE (for fleece)**		
Red	=	Main recipe	+	1.20 % of main recipe	-	1.70 % of main recipe
	=	3	+	0.036	-	0.051
	=	3	-	0.015		
Yellow	=	Main recipe	+	1.20 % of main recipe	-	27.89 % of main recipe
	=	3	+	0.036	-	0.837
	=	3	-	0.801		
Blue	=	Main recipe	+	1.20 % of main recipe	-	0% of main recipe
	=	3	-	0.036	-	0
	=	3	+	0.036		

Table XII

Adjusted recipes for rib and fleece (from table XI)

Rib	**Main Recipe**	**ΔE**	**Main recipe + ΔE**	**Main recipe + 0.8ΔE**	**Main recipe + 1.2ΔE**
Red (%)	3.000	-0.210	2.790	2.832	2.748
Yellow (%)	3.000	-1.915	1.085	1.468	0.702
Blue (%)	3.000	-0.101	2.899	2.919	2.879
Fleece	**Main Recipe**	**ΔE**	**Main recipe + ΔE**	**Main recipe + 0.8ΔE**	**Main recipe + 1.2ΔE**
Red (%)	3.000	-0.015	2.985	2.988	2.982
Yellow (%)	3.000	-0.801	2.199	2.359	2.039
Blue (%)	3.000	0.036	3.036	3.029	3.043

Final Assessment

Table XIII presented CIELAB values of rib dyed with adjusted recipes. The Mean and standard deviation were calculated. In later, the mean values were used to compare the color difference between target (single jersey) and rib (Table XIV).

TABLE XIII
CIELAB values of rib (dyed with adjusted recipe)

Main Recipe + ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	57.67	18.07	2.31	**L**	58.134	**L**	0.368
	58.15	18.30	2.19	**a**	17.968	**a**	0.268
	57.93	18.07	2.12	**b**	2.226	**b**	0.126
	58.27	17.62	2.40				
	58.65	17.78	2.11				
Main Recipe + 0.8ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	57.01	20.33	2.26	**L**	56.772	**L**	0.527
	56.05	20.24	2.23	**a**	20.678	**a**	0.548
	57.02	21.60	2.49	**b**	2.294	**b**	0.117
	56.42	20.49	2.19				
	57.36	20.73	2.30				
Main Recipe + 1.2ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	59.49	17.35	1.87	**L**	58.950	**L**	0.673
	59.39	16.28	2.22	**a**	16.966	**a**	0.467
	58.28	16.72	1.87	**b**	2.048	**b**	0.197
	58.15	17.09	2.29				
	59.44	17.39	1.99				

TABLE XIV
Measurement of color difference (single jersey vs rib dyed with adjusted recipe)

Single Jersey VS Rib (Main Recipe + ΔE)	**ΔL**	**ΔL²**	**Δa**	**Δa²**	**Δb**	**Δb²**	**ΔE**
	-2.250	5.063	2.524	6.371	-0.010	0.000	3.381
Single Jersey VS Rib (Main Recipe + 0.8ΔE)	**ΔL**	**ΔL²**	**Δa**	**Δa²**	**Δb**	**Δb²**	**ΔE**
	-0.888	0.789	-0.186	0.035	-0.078	0.006	0.911
Single Jersey VS Rib (Main Recipe + 1.2ΔE)	**ΔL**	**ΔL²**	**Δa**	**Δa²**	**Δb**	**Δb²**	**ΔE**
	-3.066	9.400	3.526	12.433	0.168	0.028	4.676

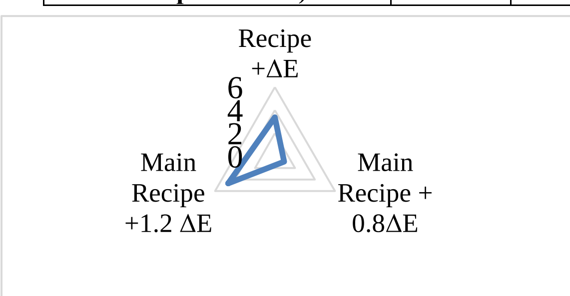

Fig 3: Color different between single jersey and rib (dyed with adjusted recipe).

One-Way Analysis of Variance revealed that L* values of rib (dyed with adjusted recipe) differed significantly ($F_{2, 12}$ = 20.9697, $p<0.001$) with each other. Rib [dyed with main recipe + ΔE] (58.134) was lighter than rib [dyed with main recipe + 0.8ΔE] (56.772) but darker than rib [dyed with main recipe + 1.2ΔE] (58.950) in the final assessment. The differences were also significant for a* value ($F_{2, 12}$ = 93.7242, $p<0.000$) where rib [dyed with main recipe + 0.8ΔE] (20.678) was more reddish than rib [dyed with main recipe + ΔE] (17.968) and rib [dyed with main recipe+ 1.2ΔE] (16.966). The b* values demonstrated no significant difference ($F_{2, 12}$= 3.5402, $p< 0.0619$ where rib [dyed with main recipe + 0.8ΔE] (2.294) was more yellowish than rib [dyed with main recipe + ΔE] (2.226) and rib [dyed with main recipe + 1.2ΔE] (2.048). Hence, the color difference is significant among these three shades. The purpose of the study was to find the closest rib shade that matches with the target (single jersey). Considering that Table XIV was created by measuring color differences between single jersey and rib (dyed with adjusted recipe). Table XIV shows that the color difference is higher for rib (dyed with main recipe + 1.2ΔE) and rib (dyed with main recipe + ΔE). On the other hand, rib (dyed with main recipe + 0.8ΔE) is the closest one with the target swatch. Figure 3 radar chart is a visual representation of shade closeness with the target.

Table XV showed CIELAB values of fleece specimens dyed with adjusted recipes. The mean and standard deviation were calculated. In later, the mean values were used to compare the color difference between target (single jersey) and fleece specimens (Table XVI).

TABLE XV
CIELAB values of fleece (dyed with adjusted recipe)

Main Recipe + ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	57.65	21.17	1.82	**L**	58.406	**L**	0.473
	58.53	20.45	1.69	**a**	21.376	**a**	0.591
	58.28	21.62	1.93	**b**	1.980	**b**	0.347
	58.73	21.97	1.88				
	58.84	21.67	2.58				
Main Recipe + 0.8ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	56.76	20.43	2.28	**L**	56.718	**L**	0.512
	56.2	20.86	2.46	**a**	20.862	**a**	0.335
	56.2	20.86	2.46	**b**	2.360	**b**	0.096
	57.3	21.37	2.34				
	57.13	20.79	2.26				
Main Recipe + 1.2ΔE	**L**	**a**	**b**	**Mean**		**SD**	
	59.66	20.97	1.95	**L**	59.648	**L**	0.654
	58.61	21.44	2.28	**a**	21.522	**a**	0.567
	59.58	21.32	1.57	**b**	1.788	**b**	0.321
	60.32	22.48	1.55				
	60.07	21.4	1.59				

TABLE XVI
Measurement of color difference (single jersey vs fleece dyed with adjusted recipe)

Single Jersey VS Fleece (Main Recipe + ΔE)	**ΔL**	**$ΔL^2$**	**Δa**	**$Δa^2$**	**Δb**	**$Δb^2$**	**ΔE**
	-2.522	6.360	-0.884	0.781	0.236	0.056	2.683
Single Jersey VS Fleece (Main Recipe + 0.8ΔE)	**ΔL**	**$ΔL^2$**	**Δa**	**$Δa^2$**	**Δb**	**$Δb^2$**	**ΔE**
	-0.834	0.696	-0.370	0.137	-0.144	0.021	0.924
Single Jersey VS Fleece (Main Recipe + 1.2ΔE)	**ΔL**	**$ΔL^2$**	**Δa**	**$Δa^2$**	**Δb**	**$Δb^2$**	**ΔE**
	-3.764	14.168	-1.030	1.061	0.428	0.183	3.926

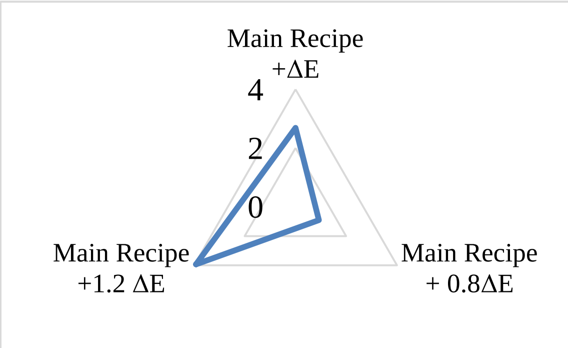

Fig 4: Color different between single jersey and fleece (dyed with adjusted recipe).

One-Way Analysis of Variance showed that L* values of fleece (dyed with adjusted recipe) varied significantly ($F_{2,\ 12}$ = 35.5105, p<0.000). Fleece [dyed with main recipe + ΔE] (58.406) was lighter than rib [dyed with main recipe + 0.8ΔE] (56.718) but darker than rib [dyed with main recipe + 1.2ΔE] (59.648) in the final assessment. The variations were not noteworthy for a* value ($F_{2,\ 12}$ = 2.5806, p< 0.1169) where fleece [dyed with main recipe + 0.8ΔE] (20.678) was less reddish than fleece [dyed with main recipe + ΔE] (21.376) and fleece [dyed with main recipe+ 1.2ΔE] (21.522). The b* values demonstrated significant difference ($F_{2,\ 12}$= 5.4633, p< 0.0206 where fleece [dyed with main recipe + 0.8ΔE] (2.360) was more yellowish than fleece [dyed with main recipe + ΔE] (1.980) and fleece [dyed with main recipe + 1.2ΔE] (1.788). Hence, the color difference is significant among these three shades.

Table XVI was built based on the color difference between single jersey and fleece (dyed with adjusted recipe). It shows that the color difference is higher for fleece (dyed with main recipe + 1.2ΔE) and fleece (dyed with main recipe + ΔE). On the other hand, fleece (dyed with main recipe + 0.8ΔE) is the closest one with the target shade. Figure 4 radar chart is a visual representation of shade closeness with the target.

Predictive dyeing recipe formulation framework

Predictive dyeing recipe formulation is an essential job for dyeing masters before any kind of bulk dyeing process as they want to ensure uniformity and quality of the shade. Figure 5 represents the workflow to develop predictive dyeing recipes for a dye-house master in a laboratory setting. At the end of the final assessment, the recipe of matched shade can be used in bulk dyeing process.

Besides that, the authors would like to propose mathematical equations for the adjusted recipe formulation that can be used for shade matching regardless of fabric structure, yarn count, twist, and fiber content. They also suggested further investigation on the proposed equations before generalizing it. The equation demands to find CIELAB values of target and the dyed specimen and red, yellow, and blue are considered as the primary color coordinates. If CIELAB values are greater than 0 in all cases for target and dyed specimen and $0.8 \leq m \leq 1.2$, then the equations for red, yellow and blue color coordinates are as follows.

Red = $R_0\,[1 + m\,(L/L_0 - a/a_0)]$ %
Yellow = $Y_0\,[1 + m\,(L/L_0 - b/b_0)]$ %
Blue = $B_0\,[1 + m\,(L - L_0)/L_0]$ %
R_0 = Initial dyeing recipe for red color.
Y_0 = Initial dyeing recipe for yellow color.
B_0 = Initial dyeing recipe for blue color.
L_0, a_0, b_0 = CIELAB value of target.
L, a, b = CIELAB value of the dyed specimen.
m = Recipe adjustment factor

However, sometimes fabrics are dyed in a single color or combination of two colors instead of all these three colors. In this case, it is reasonable to use only the equation of that color or colors to formulate the adjusted recipe. Finally, at the end of assessment one can easily find out what value *m* produces the closest shade to the target.

VI. LIMITATION

The objective of the study was to compare color exhaustion based on different knit structures and to develop a framework of recipe formulation that would facilitate the creation of more accurate shade. Even though the study conveyed by mimicking industrial dyeing process, there were some limitations. Most of the textile dyeing industries in Bangladesh uses *Sodium hydroxide* (crystal) and *Hydrogen peroxide* (50%) for combined scouring and bleaching action. Unfortunately, these chemicals are not allowed to sell in traditional market as they are harmful to human health and environment. The reported study used CLOROX to bleach the cotton knits that consists of *Sodium hypochlorite* and *Sodium hydroxide* [45]. Vinegar was used instead of acetic acid to neutralize the bleached and dyed fabric.

IR [48] and Rota [49] dyers are widely used for laboratory dyeing purpose, as it circulates the dyeing liquor within dye-pot for color levelness in the final shade. Consequently, the automatic control system of these laboratory dyers maintains uniform rotational speed, temperature, pressure and dyeing time. However, the dyeing process is carried out in a small dyeing bowl for this study where specimens were continuously steered by the investigators during the coloration process and the temperature was controlled by using digital burner and thermometer.

The dyestuffs selected for the study was purchased from the local market and all of them were reactive dyes with three fundamental colors (red, yellow, and blue). Sufian et al., (2016) showed that the brand of dye has a significant effect on the final shade. This shade variability depends on the brand to brand and origin of raw materials [32]

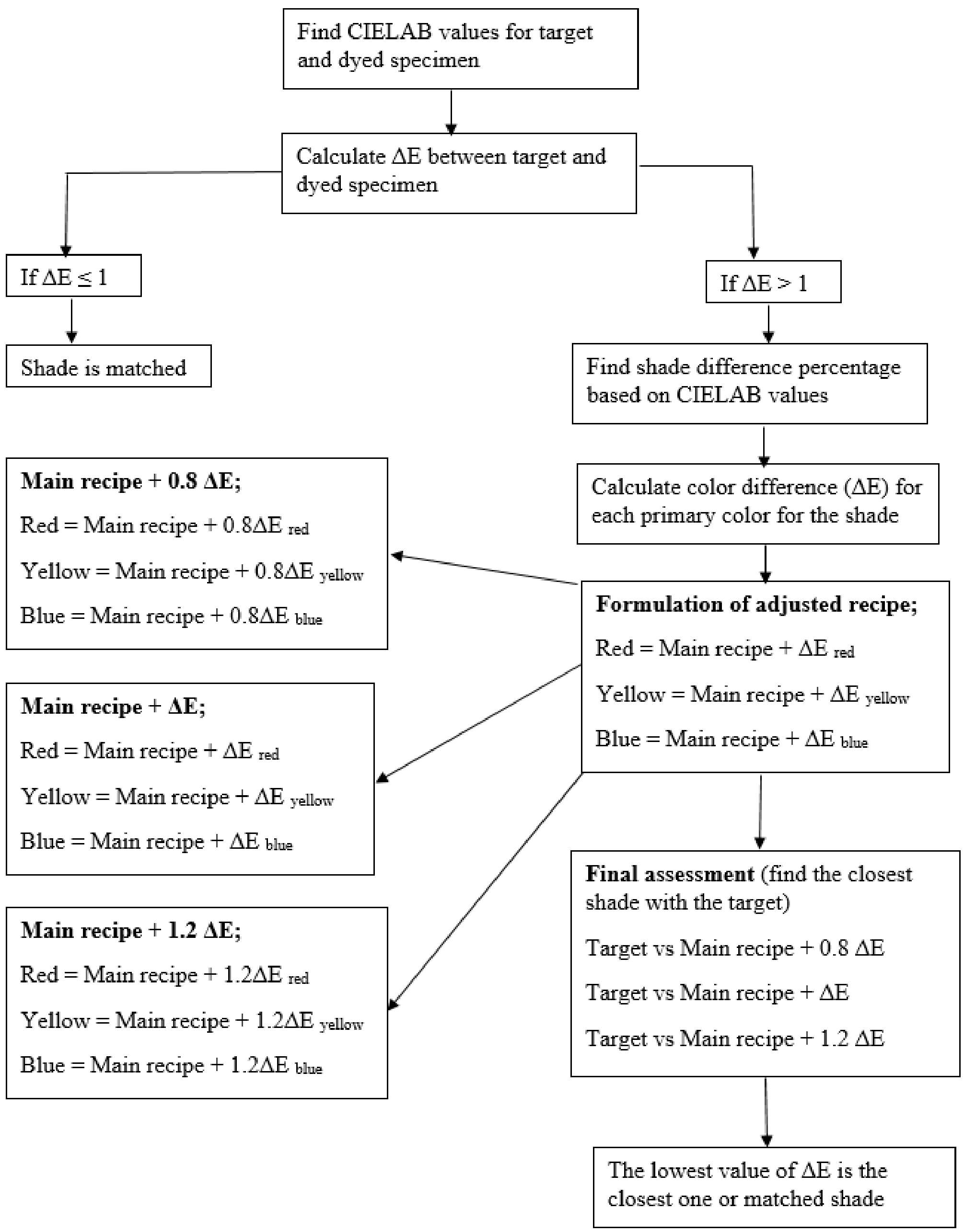

Fig 5. Predictive recipe formulation framework

VII. CONCLUSION

The study compared three different weft knitted structures (single jersey, rib, and fleece) based on color exhaustion. The "grey" fabric was gathered from one of the Bangladeshi textile industries since they produced the knit structures by controlling all parameters uniformly. The selected fabric had the same yarn count, lot, and origin. Red (3%), yellow (3%), and blue (3%) reactive dyes were combined to form the initial dyeing recipe. In industrial practice, all the colors are created by either combining these three fundamental colors or by using them separately (pure white shade does not need any color). The three knit structures were dyed in the same dye bath, and CIELAB values were measured for each construction to analyze the relative color exhaustion. One-Way Analysis of Variance revealed that CIELAB values differed significantly on the basis knit structure, which indicates each construction absorbed different amount of colors from red, yellow, and blue dyes in the same dye bath. The analysis also found that higher GSM did not always picked up more color in the dyeing process. Fleece (mean GSM = 293.882) was lighter than single jersey (mean GSM = 153.829). The second part of the study aimed to formulate a framework for shade correction activities. Single jersey was considered as target shade. The color difference percentage between single jersey vs rib and single jersey vs fleece were calculated from CIELAB values, and new adjusted dyeing recipes were formulated (adjusted recipe = main recipe + ΔE). The adjusted recipe was then modified to make three different recipes (main recipe + ΔE, main recipe + $0.8\Delta E$, and main recipe + $1.2\Delta E$) considering dye hydrolysis effect. After dyeing rib and fleece specimens with these adjusted recipes, CIELAB values were assessed again. The resulted CIELAB values were varied significantly because of the different color concentration. However, the ultimate purpose of the study was to find the closest shade of rib and fleece (dyed with adjusted recipes) with the target. The final assessment suggested that rib and fleece dyed with main recipe + $0.8\Delta E$ were the closest shade with the target. In a long run, the provided framework of adjusted recipe formulation might be helpful in the bulk dyeing process.

The result can be varied with the type of dyestuff and raw material being used for the experiment. Additionally, the authors suggest further investigation on relative color exhaustion with different type of fabric constructions as there is not enough available study on this topic.

The study should be replicated for varying GSMs, fiber contents and appropriate dye types, yarn sizes, twist/crimp, fabric count, yarn type and yarn thickness. Likewise, dyes from various manufacturers can also be compared to allow generalizing of findings. This study focused on three knit types only. However, extending it to other types of knit constructions and woven fabrics with varied weaves and structural attributes. Such extension of this work could be helpful for both industry and academia. Using spectrophotometer for improving dyeing process and outcome has not been used before. It will be a unique contribution of this study. This research study is also a good example of integrating knowledge from academia and industry to synergize the effort that will both groups. The reported study is an exploratory attempt to synthesize the existing techniques of alleviating existing issue of inducing techniques on color-pick-up for creating congruence between and among different knit construction that can bring higher opportunities in the realm of designing also. It will bring textile and apparel research closer to each other than ever before.

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