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Experimental Study and Mathematical Model to Follow the Colour Changes as Result of Washing Treatments

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ABSTRACT— ***In this paper, we present the results of an experimental study of the influence of washing treatments of jeans on its colour. It provides a systematic analysis of the changes in colour between two textile substrates: treated and untreated jeans dyed fabrics. The changes of the colour as a result of the washing treatments of the jean fabric were analyzed using the colour strength "K/S" and the colorimetric coordinates (L*, a*, b*) associated with these various treatments. The work also offers a useful modeling to study the influence of different types and parameters of washing treatments on colour changes and colorimetric coordinates, which is important to the textile industry.***

Keywords—Colorimetric coordinates, experimental design, changes in colour, jeans fabric, washing treatments.

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1. INTRODUCTION

The most preferred and popular clothing of today's youth stays forever the Denim fabrics, especially the washed-out jeans or the Denim jeans with old look. In industry, to obtain a distinctive aspect of the Denim, a modification of the ready-made garments by washing treatments can be investigated [1-4]. The most commonly denim washing methods are bleach wash, enzyme wash, normal wash, stone wash, etc. [5,6]. In this work, we will be mainly interested in the acidic and neutral enzymatic wash treatments which have emerged in the textile industry in the last decade. These treatments cause worn appearance and aged look for the garment, thus provoking degradation of the colour level.

Certainly, the behavior of Denim fabric under these treatments varies with the variation of bath's parameters. For example, S.V. Chikkodi et al [7] showed that physical properties of the fabric changed after treatment of cellulose and protease enzymes. Similarly, M. M. Hartzell and Hsieh [8] studied the influence of the enzymatic treatment on the surface wetting properties of raw and pre-treated cotton fabrics. Also, the influence of enzymatic treatment on different characteristics of cotton was the subject of numerous studies by selecting multiple variables [9,10].

Modification of cotton denim ready-made garments was investigated by using bleach treatment [11]. Authors [11] showed that bleaching powder had remarkable effect in washing on denim garment modification. Indeed, it was observed that the degradation of the denim garments with bleach caused a serious drop in fabric strength, stiffness and colour fading.

In the same case, the aim of this paper is to analyze the change in colour of the Denim fabrics after applying to them different finishing methods. Then a mathematical modeling of these changes was put in place.

2. MATERIALS AND METHODS

2.1. Fabrics and finishing treatments

Currently popular and basic denim was selected for this study (fig. 1). A summary of the fabric characteristics used in this investigation are shown in Table 1.

Figure 1: Unwashed leg

Table 1: Characteristics of untreated denim

Composition		100% Cotton
Weave structure		Twill 4
Density (yarns / cm)	Warp	30
	Weft	20
Linear density (Tex)	Warp	96
	Weft	100
Surface density (g/m²)		430

The selected fabric has been processed by different industrial washing treatments, which are often used for final finish of the denim garments. These treatments were acidic enzyme wash and neutral enzyme wash (Table 2).

Table 2: Description of the denim industrial treatments

Treatment	Description
Acidic enzyme wash	We are prepared different enzyme wash baths. The enzyme is introduced in acidic bath (pH=5). Two different concentrations of enzyme are used (20 g for a load of 1 kg and 40 g for a load of 1 kg of the merchandise). For each concentration, Temperature is raised up to 50°C and items are turned for 25 minutes and 50 minutes, respectively.
Neutral enzyme wash	This one is analogous to the Acidic enzyme washing, only the enzyme used is neutral (pH = 7). Equally, we used two concentrations of enzyme (20 g/kg and 40 g/kg) and two durations of treatments (25 and 50 min).

2.2. Experimental design method

A statistical analyze of the behavior of the input variables is done in order to evaluate the significance of the parameters used in the process. The statistical technique is used to investigate and model the relationship between the response variable and the independent input variables. Statistical approaches are the ideal means for optimization studies in industrial processes. The level and code of variables considered in this study are shown in table 1. The concentration of the enzyme, the pH and the duration of the treatment are selected as independent variables.

Table 3: Level and code of variables for experimental design

Treatments	Variables	Symbols	Coded levels	
			-1	1
enzyme wash	Concentration of enzyme (g enzyme/kg Textile)	[C]	20	40
	pH	pH	5	7
	Duration (minute)	D	25	50

3. COLORIMETRIC MEASUREMENTS

The Denim fabrics were conditioned at standard testing atmosphere (20±2°C of temperature and 65±4% of humidity). Then, the colour strength of treated jeans expressed as colour strength (K/S) was measured by the SpectroFlash SF600 spectrophotometer with dataMatch 2.0 software (Datacolor International, USA). Also, the colour data were analyzed and interpreted using CIE-L*a*b* colour system. L* defines the lightness; a* denotes the red-green coordinate; and b* denotes the yellow-blue coordinate; (Wyszecki and Stiles 2000). For each sample, the mean value of four measurements was taken.

Using the colour coordinate values of treated jean fabric (L_t^*, a_t^*, b_t^*) and the untreated one (L*, a*, b*), we can study and analyze the changes in colour as a result of the washing treatment and then evaluate the importance of the colour degradation. This is most easily performed using a 3-by-3 matrix colour transform after treatment. The colour coordinate values of the treated fabric can be given as following:

$$\begin{bmatrix} L_t^* \\ a_t^* \\ b_t^* \end{bmatrix} = \begin{pmatrix} t_{11} & 0 & 0 \\ 0 & t_{22} & 0 \\ 0 & 0 & t_{33} \end{pmatrix} \begin{bmatrix} L^* \\ a^* \\ b^* \end{bmatrix} \quad ...(1)$$

Where:

t_{ii}: represents the element at the i row and j column of the colour change or degradation matrix as a result of the washing treatment.

If all the elements on the main diagonal are equal to 1, the equation (1) will be rewritten as follows:

$$\begin{bmatrix} L_t^* \\ a_t^* \\ b_t^* \end{bmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} L^* \\ a^* \\ b^* \end{bmatrix} \quad \ldots(2)$$

In this case, when the matrix of the colour change or degradation of the jeans fabric due to the washing treatment is equal to the identity matrix, it is evident that there is no degradation and no change on the colour. So, to evaluate the degradation or the change of the colour as a result of the washing treatment of the jeans fabric, we must calculate and analyze the evolution of the colorimetric coordinates (L*, a*, b*) associated with these two textile substrates: treated and untreated jeans dyed fabrics. This passes through the determination of the matrix elements (t_{ii}).

The equation (1) is a matrix multiplication where the tii represent the unknowns. Conventionally, we can express the equation (1) as follows:

$$\begin{cases} L_t^* = t_{11} L^* \\ a_t^* = t_{22} a^* \\ b_t^* = t_{33} b^* \end{cases} \quad \ldots(3)$$

By solving this equations system, we can determine the matrix elements (t_{ii}) noted M_{Ch}.

4. RESULTS AND DISCUSSION

4.1. Colorimetric study

For better evaluation of the colour changes as a result of the enzyme wash treatment, the colour quality of the treated jeans fabrics was reported using the CIE L*a*b* color coordinate and the colour strength “K/S”. Table 4 shows the colour strength “K/S” and the colorimetric data (L_i*, a_i*, b_i*) of the treated and untreated jean fabrics.

Table 4: The experimental design matrix with the responses values

Processes	Variables			Responses			
	[C]	pH	D	L*	a*	b*	K/S
1 (Untreated)	0	0	0	18.98	0.85	-17.66	12.78
2	20	5	25	21.11	0.61	-15.51	11.47
3	20	7	25	20.27	0.64	-16.07	11.60
4	20	5	50	22.68	0.37	-14.02	10.99
5	20	7	50	21.94	0.42	-15.04	11.34
6	40	5	25	23.08	0.32	-13.18	10.67
7	40	7	25	22.14	0.39	-14.54	11.05
8	40	5	50	25.07	-0.02	-12.02	9.38
9	40	7	50	23.98	0.12	-12.88	10.15

According to the table 4 data, higher lightness (L*) values were obtained for the treated jeans fabrics as compared to untreated fabric. Moreover, treated jeans fabrics had lower color strength (K/S) and blueness (b*) values than untreated fabric. The degree of redness is almost constant for all jeans fabrics whatever the treatment. In general, lower color strength and blueness on the treated fabrics could be attributed to the elimination of the dye molecules and the degradation of the textile structure. Jean fabric treated by the process N°8 shows minimum value of color strength, while jean fabric treated by the process N°3 shows maximum value of color strength.

Study and analysis of the color changes of the treated jeans fabrics through the colorimetric coordinates are subjective. Quantification of the color change and evaluation of the degradation intensity due to the washing treatment require additional investment and the proposal of a new objective method which can offers the possibility to measure and to compare the extent of the degradation depending on the treatment process.

In this new method, we defined a new parameter based on the calculation of the determinant of the matrix colour change which given in section 3. The importance (or the degree) of the colour change of the treated fabric is evaluated using the "Ŋ" parameter defined as following.

$$Ŋ=1-\det M_{Ch}\ldots(4)$$

Where

M_{Ch} was the Matrix of the colour change

For example, after washing treatment according to the second process, the CIE L_t*, a_t*, b_t* colour coordinate of the treated fabric were "L_t*=21.11, a_t*=0.61 and b_t*= -15.51". Using eq. (3), we can calculate the Matrix of the colour change which can be written as:

$$M_{Ch}=\begin{pmatrix} 1{,}11 & 0 & 0 \\ 0 & 0{,}72 & 0 \\ 0 & 0 & 0{,}88 \end{pmatrix}\ldots(5)$$

Compared to M_{Ch} of the unwashed fabric (the identity matrix: I3), we can observe a significant change in the colour. To evaluate this change, we propose to calculate the Ŋ parameter.

Table 5 consists of values of the color change difference between unwashed & washed denim fabrics according different process.

Table 5: Influence of the washing treatment on the colour coordinates

Processes	**Variables**			**Responses**		
	[C]	pH	D	M_{Ch}	det M_{Ch}	Ŋ=1-det M_{Ch}
1 (Untreated)	0	0	0	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$	1	0
2	20	5	25	$\begin{pmatrix} 1{,}11 & 0 & 0 \\ 0 & 0{,}72 & 0 \\ 0 & 0 & 0{,}88 \end{pmatrix}$	0,70	0,30
3	20	7	25	$\begin{pmatrix} 1{,}07 & 0 & 0 \\ 0 & 0{,}75 & 0 \\ 0 & 0 & 0{,}91 \end{pmatrix}$	0,73	0,27
4	20	5	50	$\begin{pmatrix} 1{,}19 & 0 & 0 \\ 0 & 0{,}43 & 0 \\ 0 & 0 & 0{,}79 \end{pmatrix}$	0,40	0,60
5	20	7	50	$\begin{pmatrix} 1{,}16 & 0 & 0 \\ 0 & 0{,}49 & 0 \\ 0 & 0 & 0{,}85 \end{pmatrix}$	0,48	0,52
6	40	5	25	$\begin{pmatrix} 1{,}22 & 0 & 0 \\ 0 & 0{,}38 & 0 \\ 0 & 0 & 0{,}75 \end{pmatrix}$	0,35	0,65
7	40	7	25	$\begin{pmatrix} 1{,}17 & 0 & 0 \\ 0 & 0{,}46 & 0 \\ 0 & 0 & 0{,}82 \end{pmatrix}$	0,44	0,56
8	40	5	50	$\begin{pmatrix} 1{,}32 & 0 & 0 \\ 0 & 0{,}02 & 0 \\ 0 & 0 & 0{,}68 \end{pmatrix}$	0,02	0,98
9	40	7	50	$\begin{pmatrix} 1{,}28 & 0 & 0 \\ 0 & 0{,}14 & 0 \\ 0 & 0 & 0{,}73 \end{pmatrix}$	0,13	0,87

Following conclusion can be derived from Table 5:

- There is a significant change in color from the standard in all cases.
- In most of the cases the trend of change is similar. Only difference is in intensity of treatment process.

- There is a very significant change of colour when the sample is treated according the 8th process (with 40 g/Kg enzyme, pH=5 and during 50 minutes). Nevertheless, this change was negligible of the treatment according the 3rd process (with 20 g/Kg enzyme, pH=7 and during 25 minutes).

Factors that influence the color strength after enzyme wash treatment were evaluated by using factorial plots; main effects and interactions. Main effects of each parameter (Enzyme concentration, pH and treatment duration) on color strength after wash treatment are displayed in figure 2.

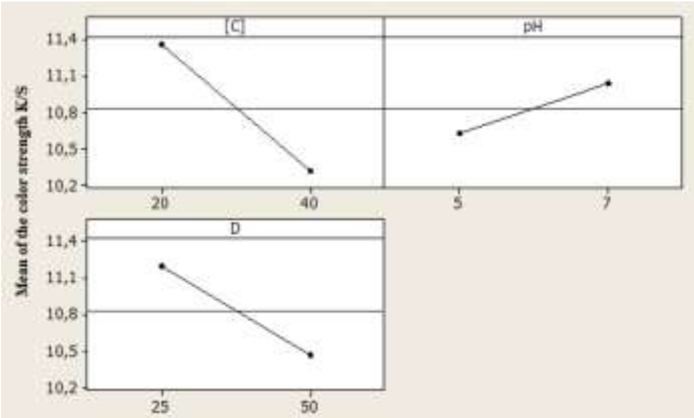


Figure 2: Maineffects diagram for colour strength (K/S) at enzyme washing treatment

From figure 2, the effect of enzyme concentration, pH and treatment duration on the color strength are clearly identified. The enzyme concentration parameter shows a more significant influence as compared to duration of treatment process and the pH parameter, respectively.

Figure 3 shows the plots of interaction. The interaction plot (figure 3) is a plot of means of color strength for each level of one factor with the level of the second factor held constant. Interactions plots are useful for judging the presence of interactions, which means that the difference in the response at two levels of one factor depends upon the level of another factor. Parallel lines in an interactions plot indicate no interaction.

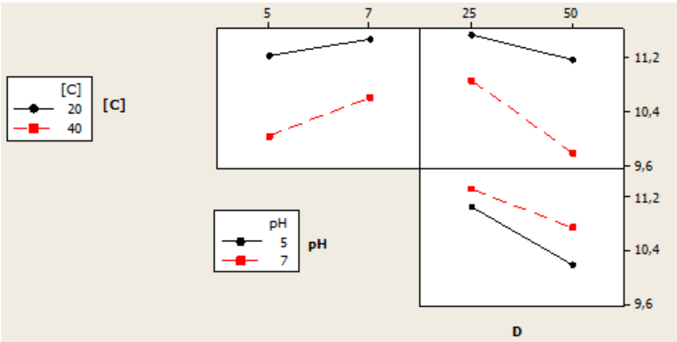


Figure 3: Interaction diagram for colour strength (K/S) at enzyme washing treatment

As it is clear from figure 3, interaction diagram shows a negligible interaction between different factors because the lines have the same tendency.

To evaluate the significance of each variable, the analysis of variance was done using the Minitab software. Indeed, the p-values lower than 0.05 [12] indicate that the terms and the model are statistically significant. Table 6 consists of ANOVA study for the colour strength loss after wash treatment.

Table 6: Analysis of variance for the colour strength response

ANOVA FOR COLOR STRENGTH LOSS AFTER WASH TREATMENT						
Source	DF	Seq SS	Adj SS	Adj MS	f	p
Regression	6	3.92347	3.923475	0.653912	181.01	0.050
Linear	3	3.55804	3.55804	1.18601	328.31	0.041
Interaction	3	0.36544	0.365438	0.121813	33.72	0.126
Residual Error	1	0.00361	0.003612	0.003612	-	-
Total	7	3.92709	-	-	-	-

R^2=99.9%

Using Minitab software, the general behavior of the colour change can be simulated by a mathematical equation. There are many types of equations that can give a good correlation between input factors, but the choice of which model should be used is dependent of the R^2-value of each one and the p-value. In our case, there are two types of equations that can be used in order to model the response of our study.

- The first type of equation: "A linear equation" :
  $K/S = Cte + a_1 [C] + a_2 pH + a_3 D$
- The second type of equation: "A linear equation with interactions" :
  $K/S = Cte + a_1 [C] + a_2 pH + a_3 D + a_{12} [C] pH + a_{13} [C] D + a_{23} pH D$

According to results showed in Table 6, the variance analysis (ANOVA) proves that, for the colour strength response parameter, only the regression linear terms in the model were highly significant (p=0.041). However, the interaction terms in the regression model were no significant (p=0.126>0.05). From the ANOVA results, we are choosing to use the first type of equation model as given by Minitab software:

$$K/S = 12.3 - 0.0519 [C] + 0.204 pH - 0.0293 D$$

Table 6 shows the analysis of variance for the colour strength parameter as modeled by the regression linear model after elimination of the interaction terms. The ANOVA study (Table 6) proves clearly that the regression linear model obtained by Minitab software is highly significant (p=0.016) and it has a very good predictability (R^2=90.6). Moreover, as shows in Table 8, all factors are statistically significant (p-value of the constant was equal to 0.000, p-value of the [C] factor was equal to 0.008<<0.05, p-value of the pH factor was equal to 0.031<0.05 and p-value of the D factor was equal to 0.027<0.05).

Table 7: ANOVA for the colour strength – the regression linear model

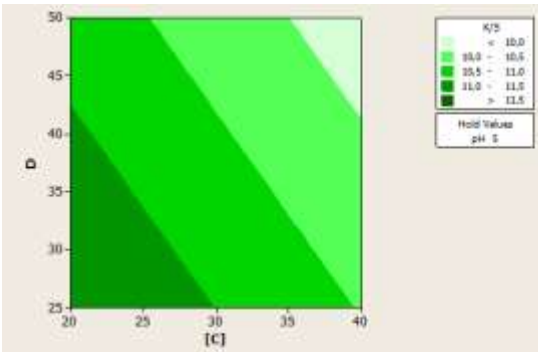
ANOVA FOR COLOR STRENGTH LOSS AFTER WASH TREATMENT					
Source	DF	Seq SS	MS	f	P
Regression	3	3.5580	1.1860	12.85	0.016
Residual Error	4	0.3690	0.0923	-	-
Total	7	3.9271	-	-	-

R^2=90.6%

Table 7: p-values of each factor

Predictor	Coef	p
Constant	12.2638	0.000
[C]	-0.05188	0.008
pH	0.2037	0.031
D	-0.029300	0.027

After determining the regression linear model for the colour strength parameter response, we are interested to application and development of the response surface method design for finding regions where there is an improvement in response instead of finding the optimum response desired by the industrial. Figure 4 illustrate the contour plots which show contour lines of [C] and D factors at pH=5 and pH=7, respectively. The contour plots were helpful to see the shape of the response surface and to understand how the response changes in a given direction by adjusting the design variables and, so, to find the optimum response.



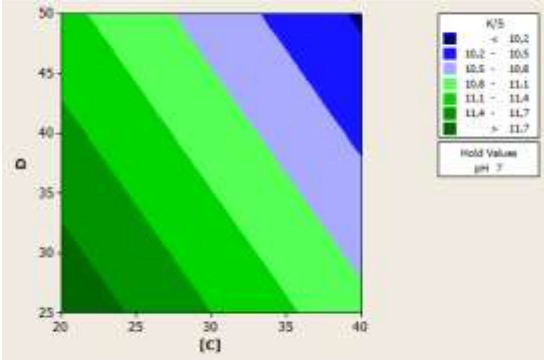


Figure 4: Contour plots of K/S versus D and [C] at pH values of 5 and 7, respectively

5. CONCLUSION

The present investigation clearly demonstrated the influence of washing treatments of fabric jeans on its colour. Experiments were carried out covering a wide range of operating conditions. The influence of pH, enzyme concentration and duration of treatment was examined. It was observed, using the colour strength "K/S" and the colorimetric coordinates (L*, a*, b*), that colour change is significantly influenced operating conditions as pH, duration and enzyme concentration. The importance of the colour change of the treated fabric is evaluated using a new method. This method is based on the calculation of the "Ŋ" parameter.

The experimental data were analyzed using the experimental design methodology. Regression equation were developed for the colour strength of the treated fabrics using experimental data and solved using the statistical software Minitab 14. It was observed that the linear model predictions are good agreement with experimental observations.

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