# Screening of Process Parameters for Color Fast Finishing Process Using Fractional Factorial Design : A Textile Case Study

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## Abstract

**Screening experiments are the most powerful of design of experiment techniques for uncovering the power factors in a manufacturing process. Often, there are many possible factors, some of which may be critical and others, which may have little or no effect on a response. It may be desirable, as a goal by itself, to reduce the number of factors to a relatively small set (2-5) so that attention can be focused on controlling those factors with appropriate specifications, conducting the main experiment and control charts, and so forth. In this screening design, with eight factors, the experiments were conducted according to the layout of $2_{IV}^{8-4}$ fractional factorial design and five response functions values were obtained with two replicates. The factors that had less effect upon the responses were eliminated from the main experiment. The linear model for estimating the responses (shade variation to the standard, color fastness to washing, center to selvedge variation, color fastness to light, and fabric residual shrinkage) was constructed using software Design Expert 8.0. After examining the surface plots and contour plot, it was revealed that the direction of optimum range for responses can be obtained by increasing the significant factors' value. The response functions, surface plots, and contour plots provided a convenient way to find a path of the steepest ascent for the main experiment.**

***Keywords :*** **fractional factorial design, screening design, ANOVA, textile industry**

**JEL Classification : C6, C8, C9**

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Color Fast Finish (CFF) is a one-step-process of textile dyeing and finishing, which enables to do impregnation, drying, and curing in a single step. In the conventional method of dyeing polyester (PES), PES/cotton blend and cotton have to be dyed separately before going to finishing (Figure 1). Now, with CFF, all this can be done in one step (Figure 2). The innovative CFF process is much faster than the conventional procedure. It saves time and energy – which allows to reduce the overall process costs: less energy, less equipment needed, and reduced staff costs. The fact that the total conventional process can be considerably shortened by the color fast finish provides not only economic benefits, but also considerable ecological benefits, like: (a) reduced

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Figure 1. Conventional Method of Textile Dyeing and Finishing Flow Diagram

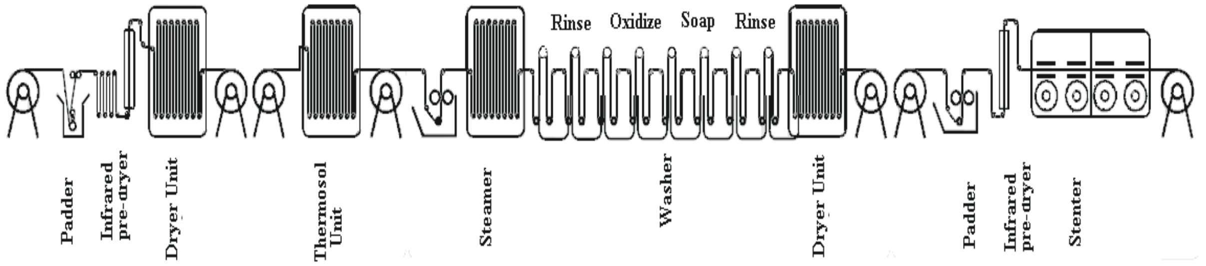
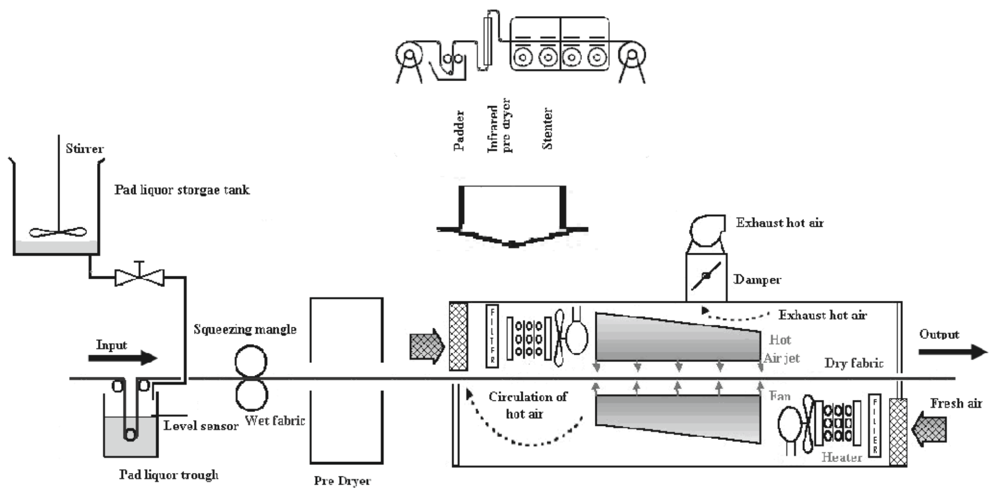


Figure 2. Color Fast Finish Process Flow Diagram and Schematic Diagram



energy consumption, (b) reduced water use and subsequent wastewater load, (c) Reduction of $CO_2$ emissions (BASF, n.d.). Color fast finish saves time and energy compared to the traditional dyeing process, but it requires a lot of attention in a parameter study, which yields robustness and an optimized process.

The present paper presents the key concepts associated with the screening for process parameters of color fast finish process for a robust process development. During the process development, both the inputs and outputs of the process are studied. The purpose of this study is to determine the significant process parameters and its interaction effects for the main experiment. The goal of this development phase is to have a good understanding of the process and the relationship of the parameters to the attributes. The main objectives of this paper are to:

- Select a significant parameter to the main experiment for the CFF process,
- Find the significant interaction between the parameters,
- Find the linear relationship between the response and factors,
- Select the direction of optimum of response point,
- Select the range of factors for the main experiment,

This paper is organized as follows: The literature review is presented next followed by an experimental setup; then the methodology used for the study with a case of a textile company is discussed. A screening experiment is proposed to select the significant process parameters with the help of fractional factorial design (with analysis). Finally, the linear relationship between the factors and the response is provided. With the help of surface plot and contour plot, the response models are studied for the direction of optimum response and direction of optimum factor range.

## Literature Review

There have been some studies in literature about improving the textile dyeing process quality characteristics. Fathi, Moghadam, Taremi, and Rahmani (2011) studied the wool dyeing parameters using five different parameters. They compared the dyeing behavior with two different optimization approaches : with and without robust parameter design using response surface methodology. Kuo and Pietras (2010) proposed a regression-based new approach to pH control in open beck dyeing to improve its process quality.

Ravikumar, Krishnan, Ramalingam, and Balu (2006) successfully employed full factorial central composite designs for experimental design and analysis of the results. The combined effect of pH, temperature, particle size, and time on the dye adsorption was investigated and optimized using response surface methodology (RSM). Kuo, Chang, Su, and Fu (2008) aimed to find the optimal conditions for dyeing polyester (PET) and Lycra®-blended fabric and predicted the quality characteristics, where PET and Lycra®-blended fabrics were taken as raw materials with dispersed dyes using a one-bath two-section dyeing method, characterizing the color strength of gray fabric.

Hench and Al - Ghanim (1995) presented a two-phase approach to the development of neural network architecture to determine the underlying function that governs the dyeing process. Koksal (1992) developed a methodology for robust design of the batch dyeing process parameter settings, which produced target color with the least color variation within and among dyed fabric pieces. The robust design problem was formulated and solved as a nonlinear programming problem. Kuo and Fang (2006) applied the Taguchi method to find the optimal dyeing processing parameters within a least number of experiments for achieving the color required on the raw fabrics.

Modeling and fuzzy control of pH in exhaust dyeing was studied by Jahmeerbacus, Kistamah, and Ramgulam (2004). The main aim of their study was to bring about improvement in the product (acrylic fiber) quality so that the desired (nominal) color strength, maximized acrylic fiber strength, and minimized dyestuff on dye bath as three quality characteristics could be achieved by improving the process conditions during the dyeing process. Ramachandran, Gobi, Rajendran, and Lakshmikantha (2009) studied the process parameters for citric acid finishing treatment on cotton fabric. An experiment was designed using Box and Behnken method with three levels and their three variables. Regression equations were obtained to analyze fabric properties of 27 combinations, and the optimum process parameters were identified.

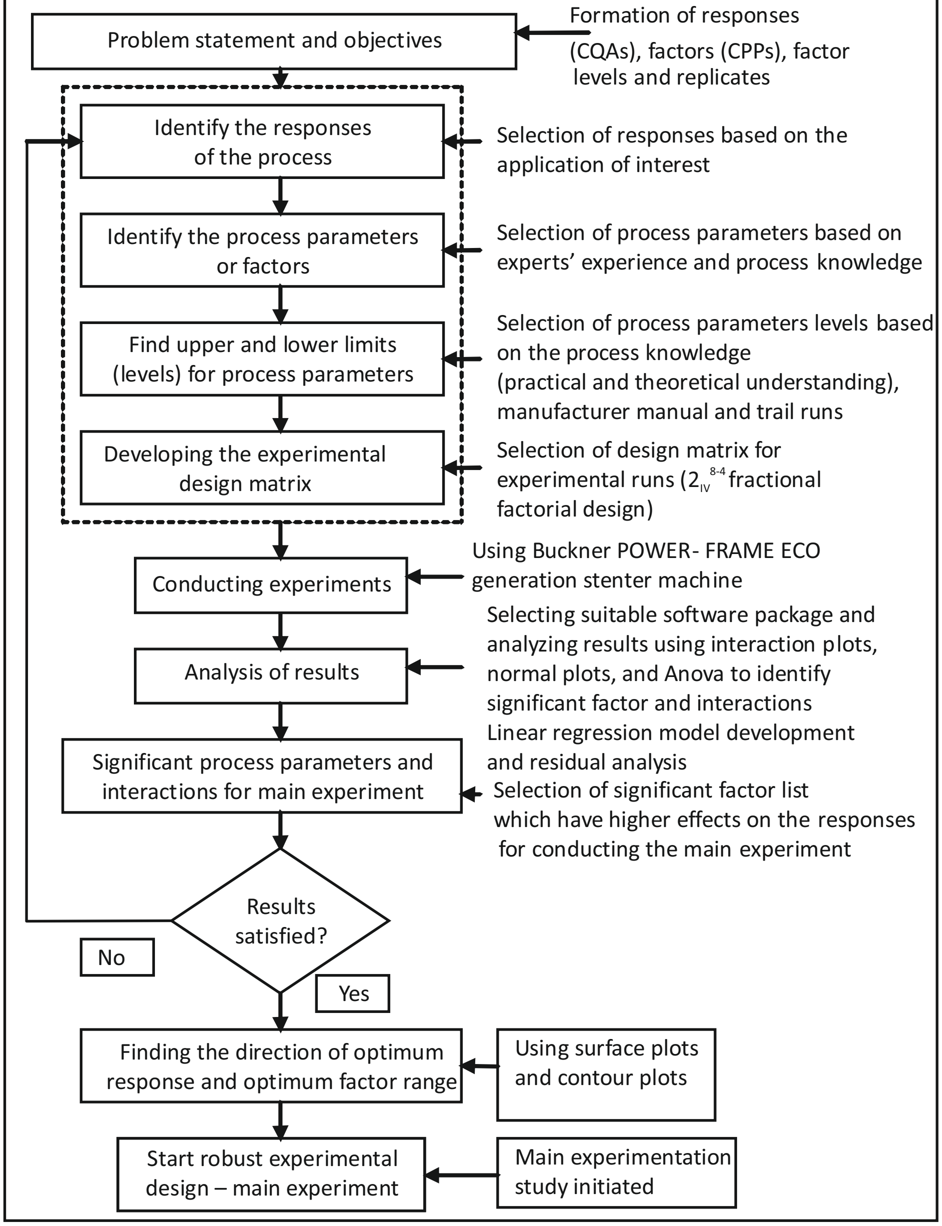
The studies showed that different experimental design techniques were applied in different textile processes (spinning, knitting, combined scouring and bleaching, tufting, garmenting, and effluent treatment). Some studies in the literature discussed about improving the textile dyeing process quality characteristics. However, none of the researchers concentrated on the basics of selection of response, factors, significant factors, significant interactions, direction of optimum response, and direction of optimum factor range to the main experiment. This study proposed a screening of process parameters to the main experiment for robust and optimized experimental design.

## Experimental Setup

Commercially available 100% cotton fabrics, sort no: 1846 (20$^s$ cotton × 20$^s$ cotton 108 × 56 3/1 Drill) and shade: Royal blue. BASF color fast finishing system (PAD N colorants and finishing recipe) was employed as suggested by the BASF manual (BASF, n.d.). Buckner POWER-FRAME ECO generation stenter machine was used for the color fast finish process. The machine is equipped with left, middle, and right adjustable squeezing rollers, chemical trough, SPLIT-FLOW hot air circulation system, and seven drying chambers with an automatic heat setting feature. Order of mixing of the bath (bath liquor) components (color fast finish chemicals) is critical and should be poured according to the sequence (BASF, n.d.).

The ingredients should not be mixed in their concentrated form; although, the PAD N colorants could be pre-mixed, diluted with water, and strained prior to addition. Fabrics to be dyed with the color fast finish system should be properly prepared; they should be dried uniformly before they are padded. Padding is carried out at room temperature on a two bowl padder with left, middle, and right adjustments. Padder pressure setting can be varied from 10-70 N / mm. In the two bowl padder, top roll of 65 shore A hardness and bottom roll of 75 shore A hardness will give best results. Padding is carried out at a cloth speed of 5-100 m / min. The bath liquor should be fed continuously from a storage tank so as to maintain a constant level of the trough. Unless the liquor is being re-circulated, it should be stirred in the storage tank with a paddle or mixture every 15-20 minutes. The fabric leaving the padder ideally should be between 40-80% wet pick-up, depending upon the type and construction of the fabric. The fabric should then enter a stenter machine for curing and for obtaining the desired width. Curing for 1.5 minutes at 175°C is ample. The schematic view of color fast finish process is shown in the Figure 2.

**Figure 3. Flow Chart of the Methodology**



## Table 1. Responses (Critical Quality Attributes) for Color Fast Finish Process

| S. No | Responses | Explanation | Standard | Unit of measurement |
|---|---|---|---|---|
| 1 | Shade variation to the standard (CVS) | Shade variation of the sample fabric to the standard reference | CIE Lab 1976 | ΔE |
| 2 | Color fastness to washing (CFW) | Shade change of the sample fabric after detergent washing | AATCC 61 | Grey scale |
| 3 | Center to selvedge variation (CSV) | Shade variation across the width of the fabric | CIE Lab 1976 | ΔE |
| 4 | Color fastness to light (CFL) | Shade change of the sample fabric after exposing the sample to sun or xenon light | ISO 105 B02 | Blue wool scale |
| 5 | Fabric residual shrinkage (SHR) | Fabric shrinkage after detergent washing | ISO 5077 / ISO 6330 | mm |

## Table 2. Factors (Critical Process Parameters) for Color Fast Finish Process

| S. No | Factors | Explanation | Unit of measurement | Range |
|---|---|---|---|---|
| 1 | Temperature of pre-dryer *($T_p$)* | Temperature of the stenter machine pre-dryer | °C | 100-800 |
| 2 | Bath liquor pickup *(B)* | Bath liquor observed by the fabric (ratio of the observed liquor weight to the fabric weight) | % | 30-80 |
| 3 | Blower circulation *(C)* | Hot flue gas circulation fan mass flow rate max : 99% - 15 $m^3$ / hr and min : 30% - 0.5 $m^3$ / hr | % | 30-99 |
| 4 | Blower exhaust *(E)* | Hot flue exhaust fan mass flow rate max : 99% - 5 $m^3$ / hr and min : 30% - 0.5 $m^3$ / hr | % | 30-99 |
| 5 | Machine speed *(V)* | Stenter machine speed or fabric production per minute | m / min | 0-100 |
| 6 | Padder pressure *(P)* | Padding roller squeezing pressure of the stenter machine | N / mm | 10-70 |
| 7 | Trough level *(L)* | Prepared bath liquor (CFF) level of the stenter machine tank | mm | 0-100 |
| 8 | Bath liquor temperature *($T_b$)* | Prepared bath liquor (CFF) temperature | °C | 20-40 |

**Figure 4. Fishbone Diagram of the CFF Process**

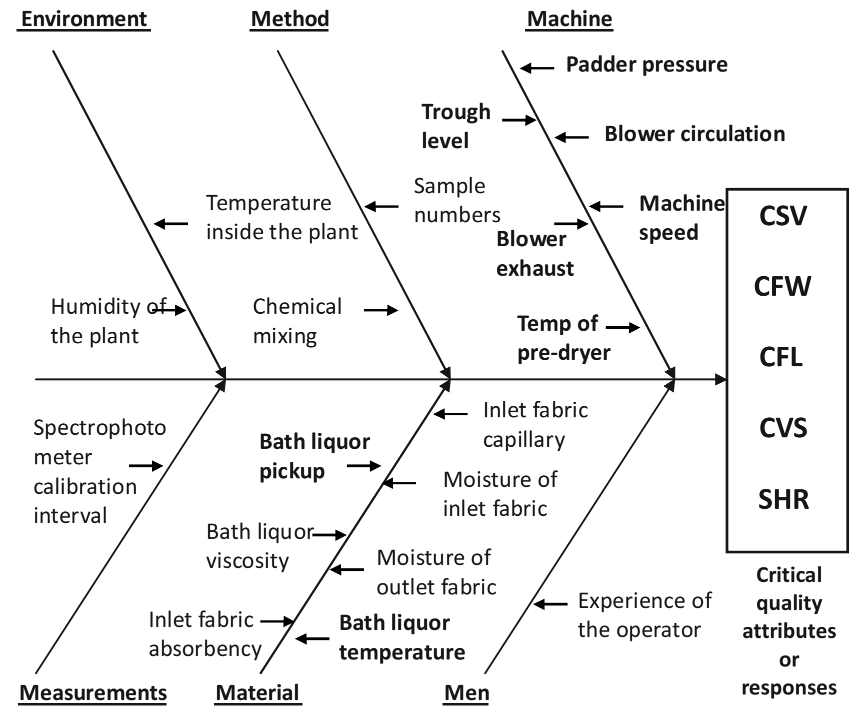


**Table 3. Details of the Factor (Critical Process Parameter) Levels**

| S. No | Factors | Low -1 (coded) | High +1 (coded) |
|---|---|---|---|
| 1 | Temperature of pre-dryer ( $T_p$) | 300 | 700 |
| 2 | Bath liquor pickup *(B)* | 40 | 80 |
| 3 | Blower circulation *(C)* | 30 | 90 |
| 4 | Blower exhaust *(E)* | 30 | 90 |
| 5 | Machine speed *(V)* | 20 | 60 |
| 6 | Padder pressure *(P)* | 20 | 60 |
| 7 | Trough level *(L)* | 20 | 80 |
| 8 | Bath liquor temperature ( $T_b$) | 15 | 35 |

## Methodology

The proposed methodology is given as a flow chart (Figure 3), which starts from the problem formulation. For the selection of significant process parameters, interactions, and direction of optimum factor range for the main experiment, the proposed systematic approach is as follows:

➩ **Identification of Responses and Factors :** The Table 1 shows the details about the selected responses and their measurement system. The selected factors are temperature of the pre-dryer, blower circulation, blower exhaust, trough level, bath liquor temperature, bath liquor pickup, machine speed, and padder pressure (Figure 4). The Table 2 shows the details of the factors and their measurement system. The selection of process parameters levels is based on the process knowledge (practical and theoretical), manufacturer manual, trail runs, book readings, and literature review. The range of the factors in the Table 2 was obtained from the manufacturer's manual of stenter machine. The maximum and minimum values of the range can be set in the Buckner POWER-FRAME ECO generation stenter machine. In this screening experiment plan, two levels of the eight factors were selected (Table 3).

➩ **Temperature of Pre-Dryer ($T_p$):** The minimum level for this factor is 300°C, any value below 300°C will not pre-dry the fabric during the CFF process. The maximum level is 700°C, this is the safe limit to avoid overheating the fabric during the CFF process in the stenter machine.

➩ **Blower Circulation *(C)*:** The minimum level for this factor is 30%, less than this limit will not provide sufficient mass transfer of circulation of hot air. The maximum level is 90%, the higher value (>90%) will provide more variation in flow rate of hot air in the stenter machine.

➩ **Blower Exhaust *(E)*:** The minimum level for this factor is 30%, less than this limit will not provide sufficient mass transfer of exhaust hot air and moisture. The maximum level is 90%, the higher value (>90%) will provide more variation in flow rate of hot air in the stenter machine.

➩ **Trough Level *(L)*:** The minimum level for this factor is 20mm, less than this value will not have any contact of CFF chemical with the fabric. The maximum level is 80mm, more than this value will provide more agitation in the chemical and spillage due to overflow.

➩ **Bath Liquor Temperature ($T_b$) :** The minimum level for this factor is 15°C, less than this value will make the chemical instability of the CFF size bath. The maximum level is 35°C, more than this value will not provide sufficient wash fatness to the fabric.

➩ **Bath Liquor Pickup *(B)* :** The minimum level for this factor is 40%. If less than this value is applied in the

**Table 4. $2_{IV}^{8-4}$ Experimental Design Matrix for Screening**

| Standard | $T_p$ | $B$ | $C$ | $E$ | $V$ | $P$ | $L$ | $T_b$ |
|---|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2 | +1 | -1 | -1 | -1 | -1 | +1 | +1 | +1 |
| 3 | -1 | +1 | -1 | -1 | +1 | -1 | +1 | +1 |
| 4 | +1 | +1 | -1 | -1 | +1 | +1 | -1 | -1 |
| 5 | -1 | -1 | +1 | -1 | +1 | +1 | +1 | -1 |
| 6 | +1 | -1 | +1 | -1 | +1 | -1 | -1 | +1 |
| 7 | -1 | +1 | +1 | -1 | -1 | +1 | -1 | +1 |
| 8 | +1 | +1 | +1 | -1 | -1 | -1 | +1 | -1 |
| 9 | -1 | -1 | -1 | +1 | +1 | +1 | -1 | +1 |
| 10 | +1 | -1 | -1 | +1 | +1 | -1 | +1 | -1 |
| 11 | -1 | +1 | -1 | +1 | -1 | +1 | +1 | -1 |
| 12 | +1 | +1 | -1 | +1 | -1 | -1 | -1 | +1 |
| 13 | -1 | -1 | +1 | +1 | -1 | -1 | +1 | +1 |
| 14 | +1 | -1 | +1 | +1 | -1 | +1 | -1 | -1 |
| 15 | -1 | +1 | +1 | +1 | +1 | -1 | -1 | -1 |
| 16 | +1 | +1 | +1 | +1 | +1 | +1 | +1 | +1 |

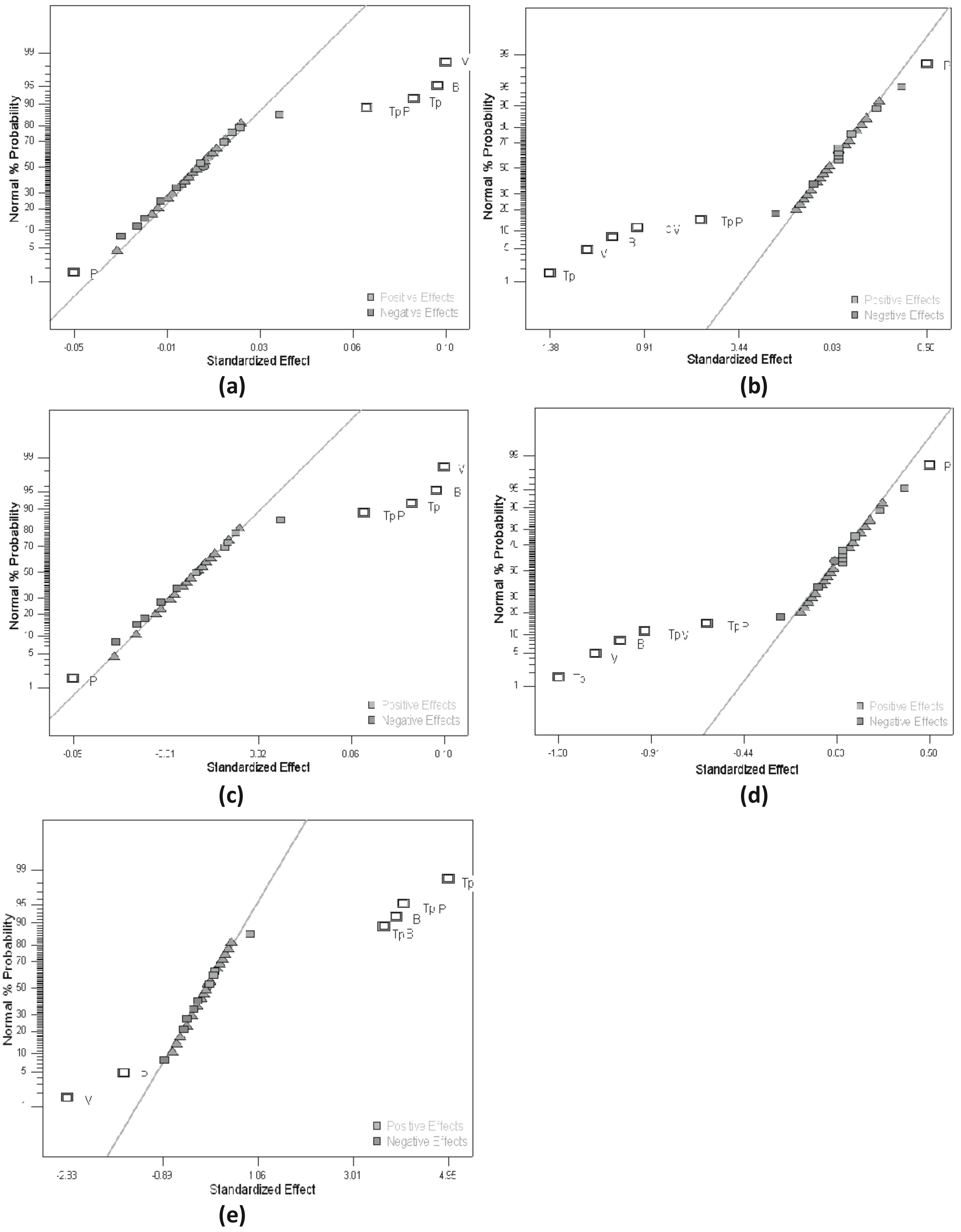
**Table 5 . $2_{IV}^{8-4}$ Experimental Design Matrix for Results**

| Run | Factors | | | | | | | | Responses (average) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_p$ | $B$ | $C$ | $E$ | $V$ | $P$ | $L$ | $T_b$ | $\overline{CVS}$ | $\overline{CFW}$ | $\overline{CSV}$ | $\overline{CFL}$ | $\overline{SHR}$ |
| 1 | 300 | 90 | 30 | 20 | 35 | 80 | 20 | 60 | 0.51 | 3.50 | 0.21 | 4.75 | 11 |
| 2 | 700 | 30 | 90 | 20 | 15 | 80 | 20 | 60 | 0.59 | 1.50 | 0.28 | 2.50 | 6 |
| 3 | 700 | 30 | 30 | 20 | 35 | 40 | 60 | 60 | 0.54 | 3.75 | 0.23 | 5.50 | 2 |
| 4 | 300 | 30 | 30 | 20 | 15 | 40 | 20 | 20 | 0.59 | 2.50 | 0.27 | 4.00 | 18 |
| 5 | 700 | 90 | 90 | 80 | 35 | 80 | 60 | 60 | 0.41 | 4.50 | 0.11 | 7.00 | 1 |
| 6 | 300 | 30 | 30 | 80 | 15 | 80 | 60 | 60 | 0.44 | 4.00 | 0.13 | 6.00 | 9 |
| 7 | 700 | 30 | 30 | 80 | 35 | 80 | 20 | 20 | 0.54 | 3.00 | 0.23 | 4.50 | 11 |
| 8 | 700 | 90 | 90 | 20 | 35 | 40 | 20 | 20 | 0.66 | 1.00 | 0.34 | 2.00 | 12 |
| 9 | 700 | 30 | 90 | 80 | 15 | 40 | 60 | 20 | 0.31 | 5.00 | 0.02 | 7.50 | 4 |
| 10 | 700 | 90 | 30 | 80 | 15 | 40 | 20 | 60 | 0.61 | 1.50 | 0.31 | 2.50 | 8 |
| 11 | 700 | 90 | 30 | 20 | 15 | 80 | 60 | 20 | 0.59 | 2.00 | 0.27 | 3.00 | 7 |
| 12 | 300 | 30 | 90 | 20 | 35 | 80 | 60 | 20 | 0.56 | 2.75 | 0.27 | 4.25 | 15 |
| 13 | 300 | 90 | 90 | 20 | 15 | 40 | 60 | 60 | 0.51 | 4.00 | 0.19 | 5.50 | 6 |
| 14 | 300 | 30 | 90 | 80 | 35 | 40 | 20 | 60 | 0.41 | 4.25 | 0.1 | 6.25 | 6 |
| 15 | 300 | 90 | 90 | 80 | 15 | 80 | 20 | 20 | 0.43 | 3.75 | 0.11 | 5.50 | 5 |
| 16 | 300 | 90 | 30 | 80 | 35 | 40 | 60 | 20 | 0.66 | 1.00 | 0.36 | 1.75 | 14 |

squeezer, it will damage the fabric surface. The maximum level is 80%, more than this value will provide dripping and uneven pickup of CFF size bath.

➥ **Machine Speed *(V)* :** The minimum level for this factor is 20 m / min, less than this value will make the fabric to overheat and the fabric can be damaged. The maximum level is 60 m / min, more than this value will provide

Figure 5. Normal Plot Effects on CVS, CFW, CSV, CFL, and SHR



improper fixation of CFF size bath.

➥ **Padder Pressure *(P)* :** The minimum level for this factor is 20 N / mm, less than this value will not squeeze the fabric. The maximum level is 60 N / mm, more than this value will damage the fabric due to higher pressure.

**Table 6. ANOVA Results for CVS** (*df* is degrees of freedom; *F* is Fisher's ratio; *p* is probability)

| Source | Sum of squares | *df* | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Model | 0.294512 | 15 | 0.019634 | 6.838549 | 0.0002 significant |
| *$T_p$ | 0.059082 | 1 | 0.059082 | 20.57823 | 0.0003 |
| *$B$ | 0.072676 | 1 | 0.072676 | 25.31293 | 0.0001 |
| $C$ | 0.007051 | 1 | 0.007051 | 2.455782 | 0.1367 |
| $E$ | 0.004395 | 1 | 0.004395 | 1.530612 | 0.2339 |
| *$V$ | 0.07752 | 1 | 0.07752 | 27 | < 0.0001 |
| *$P$ | 0.01877 | 1 | 0.01877 | 6.537415 | 0.0211 |
| $L$ | 0.003301 | 1 | 0.003301 | 1.14966 | 0.2995 |
| $T_b$ | 0.000488 | 1 | 0.000488 | 0.170068 | 0.6855 |
| $T_p \times B$ | 0.000957 | 1 | 0.000957 | 0.333333 | 0.5717 |
| $T_p \times C$ | 0.001582 | 1 | 0.001582 | 0.55102 | 0.4687 |
| $T_p \times E$ | 0.002363 | 1 | 0.002363 | 0.823129 | 0.3777 |
| $T_p \times V$ | 0.008613 | 1 | 0.008613 | 3 | 0.1025 |
| *$T_p \times P$ | 0.036113 | 1 | 0.036113 | 12.57823 | 0.0027 |
| $T_p \times L$ | 0.001582 | 1 | 0.001582 | 0.55102 | 0.4687 |
| $T_p \times T_b$ | 1.95 × 10-05 | 1 | 1.95 × 10-05 | 0.006803 | 0.9353 |
| Residual | 0.045938 | 16 | 0.002871 | | |
| Corrected total | 0.340449 | 31 | | | |
| Std. Dev. | 0.053583 | | $R^2$ | 0.865068 | |
| Mean | 0.522656 | | Adjusted $R^2$ | 0.738569 | |
| C.V. % | 10.25198 | | Predicted $R^2$ | 0.710272 | |
| PRESS | 0.18375 | | Adequacy Precision | 9.237604 | |

*Significant factor

➩ **Experimental Design :** A $2_{IV}^{8-4}$ fractional factorial design was used to explore the effect of eight factors selected on color fast finishing processes. The $2_{IV}^{8-4}$ nodal 16-run design is especially useful for screening up to eight factors. As the design resolution is *IV*, it has projectivity value of 3 (resolution -1 = 4 - 1 = 3). Increase in projectivity reduces the experimental run substantially without losing information. The $2_{IV}^{8-4}$ fractional factorial design has main effects that are alias free and two factor interactions are aliased with other two factor interactions (Box, Hunter, & Hunter, 2005). The $2_{IV}^{8-4}$ fractional factorial design with two replicates was run according to the layout as shown in the Table 4. This experimental study was conducted in the month of June 2012. The experiments were performed in random order. The results were analyzed using software Design Expert 8.0. The average response values are also tabulated in the Table 5.

➩ **Analysis of Variance (ANOVA) :** The adequacy of the developed model was tested using the analysis of variance (ANOVA) technique and the results are depicted in the Table 6. The determination coefficient ($R^2$) indicates the goodness of fit for the model. In this case, the value of the determination coefficient ($R^2$ is 0.8651) indicates that 86.51% of the total variability is explained by the model after considering the significant factors. The models are not over fitted as indicated by the comparison of $R^2$ and adjusted $R^2$ values. The value of adjusted determination coefficient (adjusted $R^2$ ) is also high, which indicates a high significance of the model. The predicted $R^2$ (0.7386) is not in good agreement with the adjusted $R^2$ and shows that the model would be expected to explain 74% of the variability in the new data. This predicted $R^2$ value could be increased to have a possible good

**Table 7. ANOVA Results for CFW** (*df* is degrees of freedom; *F* is Fisher's ratio; *p* is probability)

| Source | Sum of squares | *df* | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Model | 50 | 15 | 3.333333 | 11.85185 | < 0.0001 significant |
| *$T_p$ | 15.125 | 1 | 15.125 | 53.77778 | < 0.0001 |
| *$B$ | 9.03125 | 1 | 9.03125 | 32.11111 | < 0.0001 |
| $C$ | 1.125 | 1 | 1.125 | 4 | 0.0628 |
| $E$ | 0.03125 | 1 | 0.03125 | 0.111111 | 0.7432 |
| *$V$ | 11.28125 | 1 | 11.28125 | 40.11111 | < 0.0001 |
| *$P$ | 2 | 1 | 2 | 7.111111 | 0.0169 |
| $L$ | 0.03125 | 1 | 0.03125 | 0.111111 | 0.7432 |
| $T_b$ | 0.5 | 1 | 0.5 | 1.777778 | 0.2011 |
| $T_p \times B$ | 0.03125 | 1 | 0.03125 | 0.111111 | 0.7432 |
| $\mathrm{T_p \times C}$ | 0.125 | 1 | 0.125 | 0.444444 | 0.5145 |
| $T_p \times E$ | 0.03125 | 1 | 0.03125 | 0.111111 | 0.7432 |
| *$T_p \times V$ | 7.03125 | 1 | 7.03125 | 25 | 0.0001 |
| *$T_p \times P$ | 3.125 | 1 | 3.125 | 11.11111 | 0.0042 |
| $T_p \times L$ | 0.03125 | 1 | 0.03125 | 0.111111 | 0.7432 |
| $T_p \times T_b$ | 0.5 | 1 | 0.5 | 1.777778 | 0.2011 |
| Residual | 4.5 | 16 | 0.28125 | | |
| Corrected total | 54.5 | 31 | | | |
| Std. Dev. | 0.53033 | | $R^2$ | 0.917431 | |
| Mean | 3 | | Adjusted $R^2$ | 0.840023 | |
| C.V. % | 17.67767 | | Predicted $R^2$ | 0.769725 | |
| PRESS | 18 | | Adequacy Precision | 10.66667 | |

* Significant factor

agreement with the adjusted $R^2$. If the levels of the factors are more than 2, then the model may explain the nonlinearity behavior and the predicted $R^2$ value will be as close as possible to the adjusted $R^2$. Adequate precision was found to be 9.24, which indicates that the model will give reasonable performance in prediction. A ratio > 4 is desirable. At the same time, a relatively lower value of the coefficient of variation (C.V. % value is 10.25) indicates a high degree of precision and a good deal of reliability of the conducted experiments (experimental values).

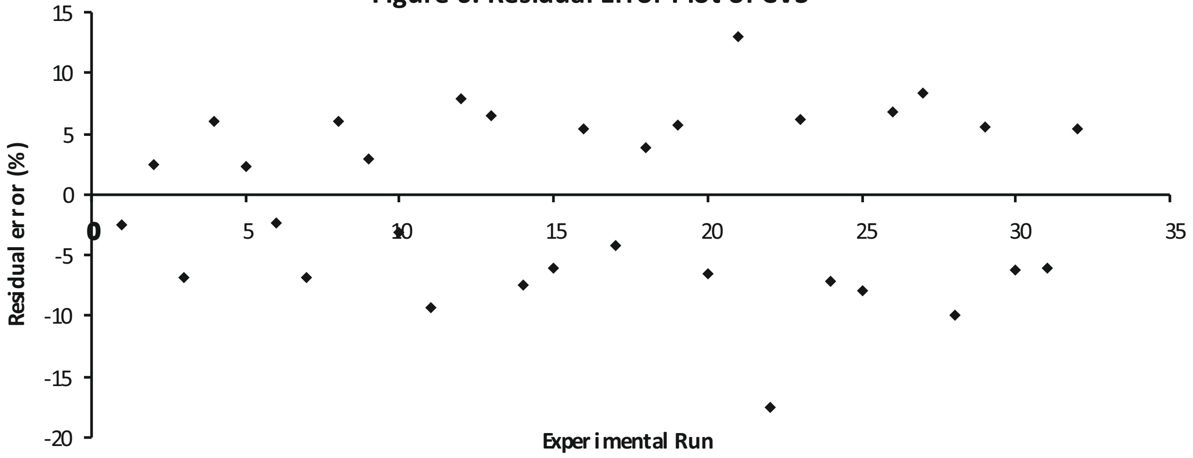
'PRESS' is a measure of how well the model of the experiment is likely to predict the responses in a new experiment. Small values of PRESS are desirable (Montgomery, 2009). The model $F$-value of 6.84 implies that the model is significant and a 'model $F$-value' this large would occur as a result of noise. A $p$-value less than 0.05 indicates the significant model terms. Value of probability > $F$ in Table 6 for the model is less than 0.05, which indicates that the model is significant. The 'factor $F$-value' for the factors; $T_p$, $B$, $V$, $P$, and $T_p \times P$ is greater than $F_{0.05, 1, 16}$. The $p$-value of the factors $T_p$, $B$, $V$, $P$, and $T_p \times P$ is less than 0.05 (upper bound $P$-value is 0.05). This ANOVA result shows that the factors $T_p$, $B$, $V$, $P$, and $T_p \times P$ are significant on the response "shade variation to the standard" (CVS). Similarly, Table 7 and Table 8 show the significant factors on the responses "color fastness to washing" (CFW) and "color fastness to light" (CFL), where the temperature of the pre-dryer *($T_p$ )*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P)*, interaction - $T_p \times V$, and interaction - $T_p \times P$ are identified as significant factors. The Table 9 shows that the temperature of the pre-dryer *($T_p$)*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P)*, and interaction - $T_p \times P$ are significant parameters on the response "centre to

**Table 8. ANOVA Results for CFL** (*df* is degrees of freedom; *F* is Fisher's ratio; *p* is probability)

| Source | Sum of squares | *df* | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Model | 95.96875 | 15 | 6.397917 | 10.23667 | < 0.0001 significant |
| *$T_p$ | 24.5 | 1 | 24.5 | 39.2 | < 0.0001 |
| *$B$ | 16.53125 | 1 | 16.53125 | 26.45 | < 0.0001 |
| $C$ | 2.53125 | 1 | 2.53125 | 4.05 | 0.0613 |
| $E$ | 0 | 1 | 0 | 0 | 1.0000 |
| *$V$ | 21.125 | 1 | 21.125 | 33.8 | < 0.0001 |
| *$P$ | 6.125 | 1 | 6.125 | 9.8 | 0.0065 |
| $L$ | 0.03125 | 1 | 0.03125 | 0.05 | 0.8259 |
| $T_b$ | 0.78125 | 1 | 0.78125 | 1.25 | 0.2801 |
| $T_p \times B$ | 0.125 | 1 | 0.125 | 0.2 | 0.6607 |
| $T_p \times C$ | 0.125 | 1 | 0.125 | 0.2 | 0.6607 |
| $T_p \times E$ | 0.03125 | 1 | 0.03125 | 0.05 | 0.8259 |
| *$T_p \times V$ | 13.78125 | 1 | 13.78125 | 22.05 | 0.0002 |
| *$T_p \times P$ | 9.03125 | 1 | 9.03125 | 14.45 | 0.0016 |
| $T_p \times L$ | 0.125 | 1 | 0.125 | 0.2 | 0.6607 |
| $T_p \times T_b$ | 1.125 | 1 | 1.125 | 1.8 | 0.1984 |
| Residual | 10 | 16 | 0.625 | | |
| Corrected total | 105.9688 | 31 | | | |
| Std. Dev. | 0.790569 | | $R^2$ | 0.905633 | |
| Mean | 4.53125 | | Adjusted $R^2$ | 0.817163 | |
| C.V. % | 17.44705 | | Predicted $R^2$ | 0.72253 | |
| PRESS | 40 | | Adequacy Precision | 10.28591 | |

* Significant factor

**Figure 6. Residual Error Plot of CVS**



selvedge variation" (CSV). The Table 10 confirms that temperature of the pre-dryer *($T_p$)*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure (P), interaction – $T_p \times B$, and interaction - $T_p \times P$ are significant parameters on the response "fabric residual shrinkage" (SHR).

➭ **Normal Probability Plot :** The Figure 5 (a) shows the normal plot of effects on the response "shade variation to the standard" (CVS). From the plot, it can be observed that the factor effect and interaction effect, temperature of the pre-dryer *($T_p$)*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P),* and interaction - $T_p \times P$ do not lie on or along the straight line. These factors are scattering at the bottom and top of the line. The normal plot validates the significance of these four factor effects and one interaction effect on the response "shade variation to the standard" (CVS). Similarly, for other responses (Figure 5 (b) to 5 (e)), the main and interaction factors can be identified by plotting their normal probability plots.

➭ **Model Development :** Representing the responses of color fast finish is a function of process parameters of the color fast finish.

$$CVS\ or\ CFW\ or\ CVS\ or\ CFL\ or\ SHR = f(T_p, B, C, E, V, P, L, T_b) \qquad (1)$$

The linear regression equation used to represent the responses $\hat{y}$ is given by (Montgomery, 2009) :

$$\hat{y} = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1,\, j=1}^{i=n,\, j=n} b_{ij} x_i x_j + e_r \qquad (2)$$

For the response function and for eight factors, the selected polynomial could be expressed as :

$$CVS\ or\ CFW\ or\ CVS\ or\ CFL\ or\ SHR = b_0 + b_1 (T_p) + b_2 (B) + b_3 (C) + b_4 (E) + b_5 (V) + b_6 (P) + b_7 (L) + b_8 (T_b) + b_{12} (T_p B) + b_{13} (T_p C) + b_{14} (T_p E) + b_{15} (T_p V) + b_{16} (T_p P) + b_{17} (T_p L) + b_{18} (T_p T_p) \qquad (3)$$

All the coefficients were obtained by applying $2_{IV}^{8-4}$ fractional factorial design using the Design Expert 8.0 statistical software package. After determining the significant coefficients (at the 95% confidence level), the final model was developed using only these coefficients. The color variation to the standard of the fabric [Article no: 1846 ($20^s$ cotton × $20^s$ cotton 108 × 56 3/1 Drill) and shade: Royal blue] is :

$$CVS = 0.52 + 0.043\, T_p + 0.048\, B - 0.015\, C - 0.012\, E + 0.049\, V - 0.024\, P - 0.010\, L - 3.91 \text{ x } 10^{-3}\, T_b + 5.47 \text{ x } 10^{-3}\, T_p \text{ x } B - 7.03 \text{ x } 10^{-3}\, T_p \text{ x } C + 8.59 \text{ x } 10^{-3}\, T_p \text{ x } E + 0.02\, T_p \text{ x } V + 0.03\, T_p \text{ x } P + 7.03 \text{ x } 10^{-3}\, T_p \text{ x } L + 7.81 \text{ x } 10^{-4}\, T_p \text{ x } T_b \quad (4)$$

where,
$T_p$ , *B, C, E, V, P, L,* and $T_b$ are coded forms of the factor levels. The relationship between the natural form (minimum value of $T_{pLow}$ is 300°C and maximum value of $T_{pHigh}$ is 700°C) and coded form of the factors (minimum value of $T_p$ is -1 and maximum value of $T_p$ is +1) is given in the Equation 5. For example, the equivalent coded form of (natural value of 500°C) :

$$T_{pNat}\ 500^{\circ}\text{C will be } T_{pNat\text{-}Coded} = \frac{500 - (300 + 700)/2}{(700 - 300)/2} = 0 \qquad (5)$$

$$T_{pNat\text{-}Coded} = \left( \frac{(T_{p\,Nat}) - ((T_{p\,Low} + T_{p\,Hight})/2}{(T_{p\,High} - T_{p\,Low})/2} \right)$$

Similarly, the other factors (*B, C, E, V, P, L,* and $T_b$) can be coded and the coded values can be obtained. The remaining responses CFW, CSV, CFL, and SHR are modeled similar to the equation 4.

All the coefficients of the Equation 4 were tested for their significance at the 95% confidence level by applying the *t* - test using Design Expert 8.0 software package. The Table 11 shows the significance of the coefficients for the response model CVS. The coefficients of the parameter temperature of the pre-dryer *($T_p$)*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P),* and interaction - *($T_p \times P$)* are significant in the *t* - test. After determining the significant coefficients and confidence interval, the final models were developed incorporating only these coefficients. Similarly, the remaining responses *CFW, CSV, CFL* and *SHR* can be tabulated.

**Table 9. ANOVA Results for CSV** (*df* is degrees of freedom; *F* is Fisher's ratio; *p* is probability)

| Source | Sum of squares | *df* | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Model | 0.288357 | 15 | 0.019224 | 6.142224 | 0.0004 significant |
| ***$T_p$** | 0.060426 | 1 | 0.060426 | 19.30695 | 0.0005 |
| ***$B$** | 0.066765 | 1 | 0.066765 | 21.3321 | 0.0003 |
| $C$ | 0.010899 | 1 | 0.010899 | 3.482239 | 0.0805 |
| $E$ | 0.003145 | 1 | 0.003145 | 1.004764 | 0.3311 |
| *** $V$** | 0.073952 | 1 | 0.073952 | 23.6286 | 0.0002 |
| *** $P$** | 0.015827 | 1 | 0.015827 | 5.056969 | 0.0390 |
| $L$ | 0.003211 | 1 | 0.003211 | 1.025991 | 0.3262 |
| $T_b$ | 3.48 × 10-06 | 1 | 3.48 × 10-06 | 0.001112 | 0.9738 |
| $T_p \times B$ | 0.001536 | 1 | 0.001536 | 0.490612 | 0.4937 |
| $T_p \times C$ | 0.000729 | 1 | 0.000729 | 0.233054 | 0.6358 |
| $T_p \times E$ | 0.006004 | 1 | 0.006004 | 1.91843 | 0.1850 |
| $T_p \times V$ | 0.010533 | 1 | 0.010533 | 3.365306 | 0.0852 |
| ***$T_p \times P$** | 0.03449 | 1 | 0.03449 | 11.01983 | 0.0043 |
| $T_p \times L$ | 0.000463 | 1 | 0.000463 | 0.147802 | 0.7057 |
| $T_p \times T_b$ | 0.000374 | 1 | 0.000374 | 0.119598 | 0.7340 |
| Residual | 0.050076 | 16 | 0.00313 | | |
| Corrected total | 0.338433 | 31 | | | |
| Std. Dev. | 0.055944 | | $R^2$ | 0.852035 | |
| Mean | 0.214427 | | Adjusted $R^2$ | 0.713317 | |
| C.V. % | 26.09017 | | Predicted $R^2$ | 0.708138 | |
| PRESS | 0.200306 | | Adequacy Precision | 8.721227 | |

*Significant factor

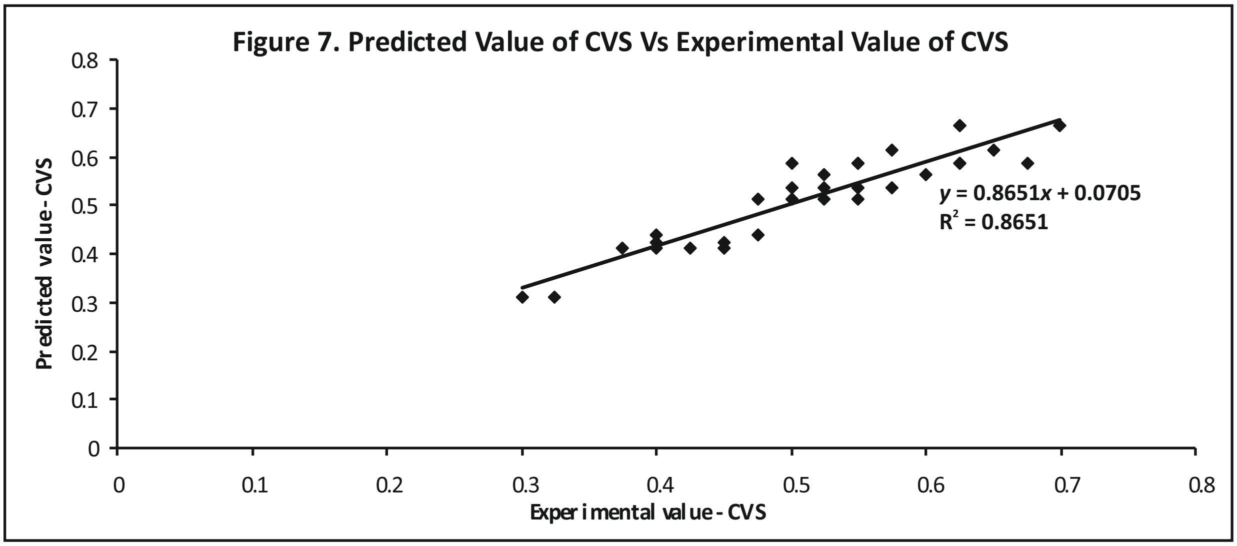


**Figure 7. Predicted Value of CVS Vs Experimental Value of CVS**

**Table 10. ANOVA Results for SHR** (*df* is degrees of freedom; *F* is Fisher's ratio; *p* is probability)

| Source | Sum of squares | *df* | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Model | 656.3464 | 15 | 43.75643 | 17.2467 | < 0.0001 significant |
| *$T_p$ | 196.3914 | 1 | 196.3914 | 77.40815 | < 0.0001 |
| *$B$ | 120.6099 | 1 | 120.6099 | 47.53866 | < 0.0001 |
| $C$ | 5.674238 | 1 | 5.674238 | 2.236515 | 0.1542 |
| $E$ | 1.60877 | 1 | 1.60877 | 0.6341 | 0.4375 |
| * $V$ | 64.19861 | 1 | 64.19861 | 25.30404 | 0.0001 |
| * $P$ | 22.40314 | 1 | 22.40314 | 8.830253 | 0.0090 |
| $L$ | 0.215332 | 1 | 0.215332 | 0.084874 | 0.7745 |
| $T_b$ | 0.50627 | 1 | 0.50627 | 0.199547 | 0.6611 |
| *$T_p \times B$ | 106.1242 | 1 | 106.1242 | 41.82912 | < 0.0001 |
| $T_p \times C$ | 1.172363 | 1 | 1.172363 | 0.46209 | 0.5064 |
| $T_p \times E$ | 0.276582 | 1 | 0.276582 | 0.109015 | 0.7456 |
| $T_p \times V$ | 6.592988 | 1 | 6.592988 | 2.598642 | 0.1265 |
| *$T_p \times P$ | 130.3103 | 1 | 130.3103 | 51.36213 | < 0.0001 |
| $T_p \times L$ | 0.046895 | 1 | 0.046895 | 0.018484 | 0.8936 |
| $T_p \times T_b$ | 0.215332 | 1 | 0.215332 | 0.084874 | 0.7745 |
| Residual | 40.59344 | 16 | 2.53709 | | |
| Corrected total | 696.9398 | 31 | | | |
| Std. Dev. | 1.592824 | | $R^2$ | 0.941755 | |
| Mean | 8.400656 | | Adjusted $R^2$ | 0.88715 | |
| C.V. % | 18.96071 | | Predicted $R^2$ | 0.767019 | |
| PRESS | 162.3738 | | Adequacy Precision | 14.45001 | |

* Significant factor

The ANOVA analysis (Table 6) and the normal plot (Figure 5 (a)) suggest that the four parameters - temperature of the pre-dryer *($T_p$ )*, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P),* and interaction - *($T_p \times P$)* had substantial effects on shade variation to the standard. The remaining four parameters have not produced an effect distinguishable from noise. All the subsequent tests were run without it. It was ,therefore, decided to explore further possibility of minimizing the color variation to the standard by changing the factors $T_p$ , *B, V,* and *P* along the path of the steepest ascent. The reduced linear model for estimating the color variation to the standard was then :

$$CVS = 0.52 + 0.043\, T_p + 0.048\, B - 0.049\, V - 0.024\, P + 0.03\, T_p \,\mathrm{x}\, P \qquad (6)$$

Similarly, the other reduced linear model for the responses CFW, CSV, CFL, and SHR is given in the Equations 7 to 10.

$$CFW = 3.00 - 0.69\, T_p - 0.53\, B - 0.59\, V + 0.25\, P - 0.47\, T_p \,\mathrm{x}\, V - 0.31\, T_p \,\mathrm{x}\, P \qquad (7)$$

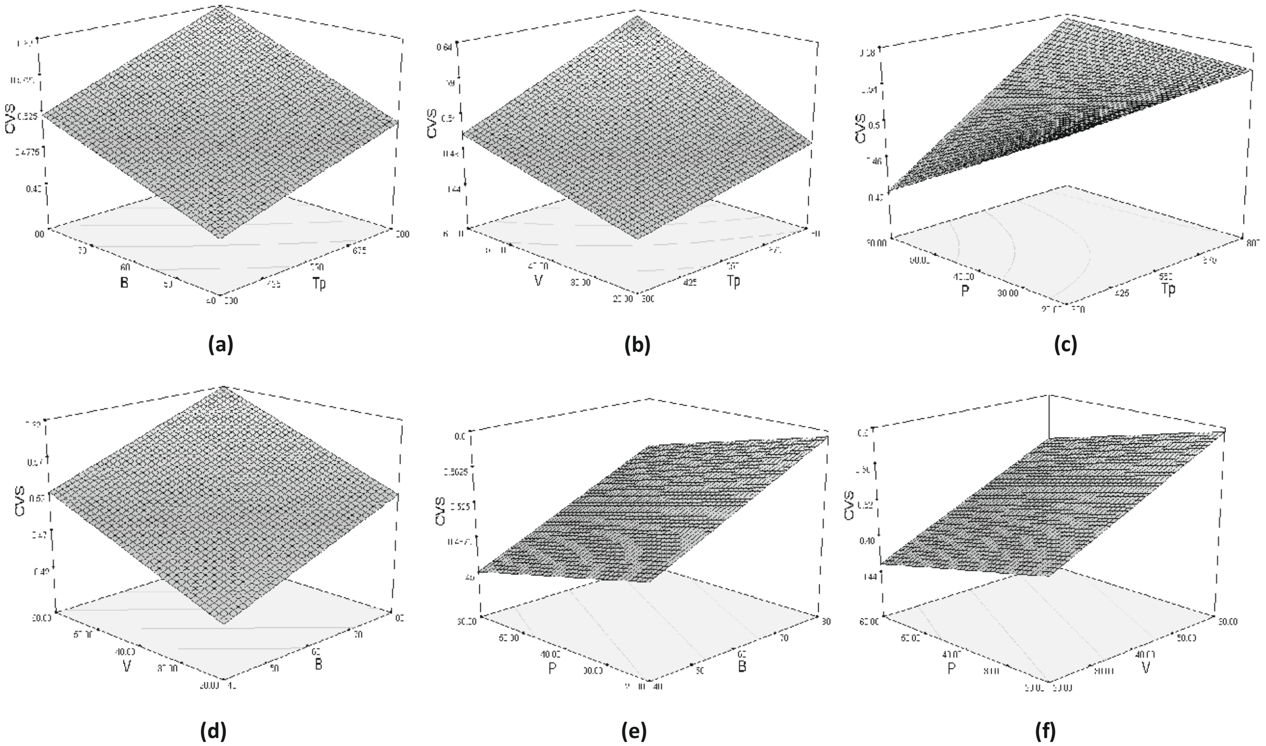
$$CSV = 0.22 + 0.042\, T_p + 0.047\, B + 0.049\, V - 0.024\, P + 0.033\, T_p \,\mathrm{x}\, P \qquad (8)$$

$$CFL = 4.53 - 0.88\, T_p - 0.72\, B - 0.81\, V + 0.44\, P - 0.66\, T_p \,\mathrm{x}\, V - 0.53\, T_p \,\mathrm{x}\, P \qquad (9)$$

$$SHR = 2.40 + 0.71\, T_p + 0.55\, B - 0.40\, V - 0.24\, P + 0.52\, T_p \,\mathrm{x}\, B + 0.58\, T_p \,\mathrm{x}\, P \qquad (10)$$

➪ **Residual Analysis :** The Table 12 shows the residual analysis of the linear regression model of the response

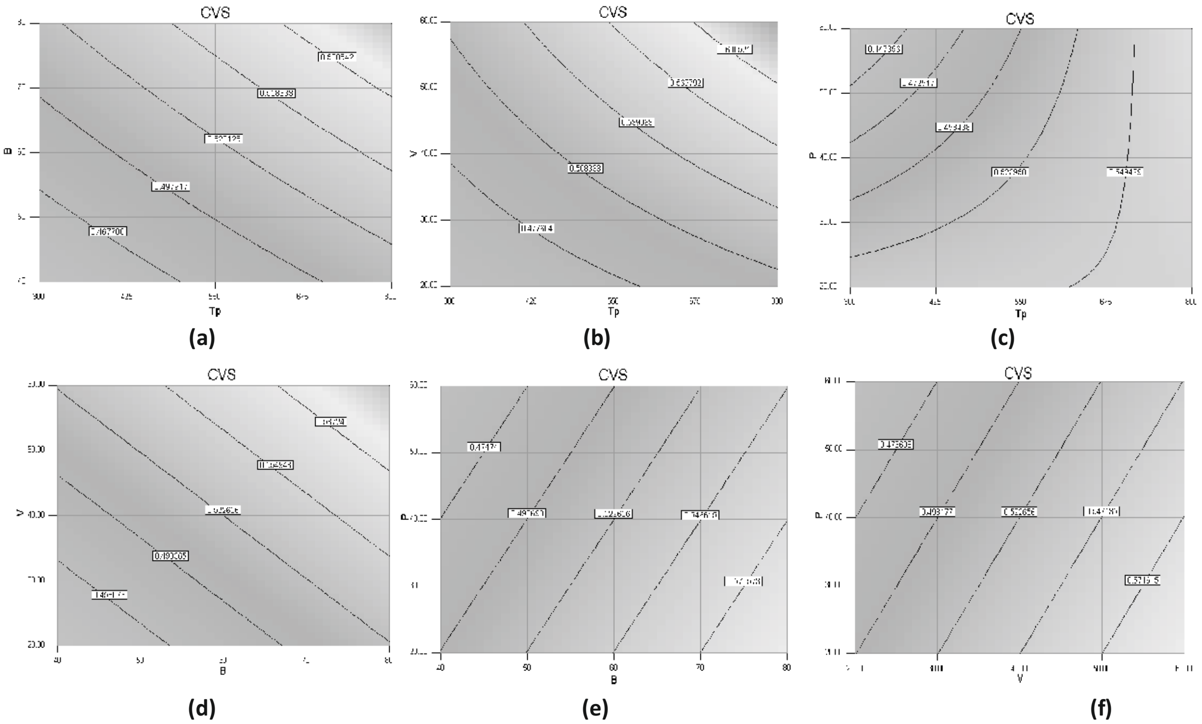
**Figure 8. Surface Plots of Response CVS Against the Significant Factor $T_p \times B$, $T_p \times V$, $T_p \times P$, $B \times V$, $B \times P$ and $V \times P$**



(a) (b) (c)

(d) (e) (f)

**Figure 9. Contour Plots of Response CVS Against the Significant Factor $T_p \times B$, $T_p \times V$, $T_p \times P$, $B \times V$, $B \times P$ and $V \times P$**



(a) (b) (c)

(d) (e) (f)

Figure 10. Relationship Between the Responses CVS and CSV

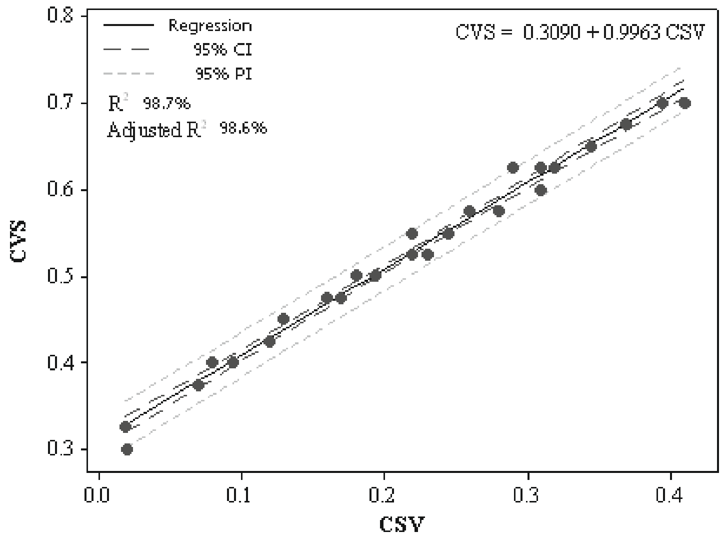
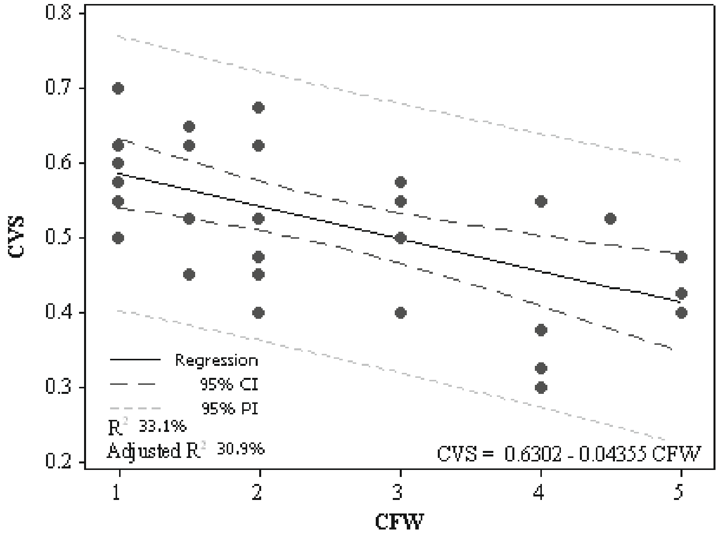


Figure 11. Relationship Between the Responses CVS and CFW



CVS. The model's predicted values are calculated with eight factors coded form of inputs. Then, the predicted values are compared with the experimental values. Finally, the residual percentage is calculated ([Experimental value – Predicted value] / Experimental value × 100).

In the Figure 6, the residual (%) values are plotted as a graph. The prediction intervals of the response CVS are also given in the Table 12. The Figure 7 shows the least square analysis to find out the correlation coefficient. The correlation coefficient was used to measure the relationship between the experimental and predicted values. The $R^2$ value of '1' means a close relationship and '0' means a random relationship. It is observed that a regression coefficient of $R^2 = 0.8651$ was obtained for "color variation to the standard" (CVS). Hence, accurate prediction of CVS was possible using the models. A studentized residual is the quotient resulting from the division of a residual by an estimate of its standard deviation. Typically, the standard deviations of residuals in a sample vary greatly from one data point to another, even when the errors all have the same standard deviation. Thus, it does not make sense to compare only the residuals at different data points without studentizing it. Sometimes, it is desirable to exclude the $i^{th}$ observation (since it an outlier) from the process of estimating the variance for calculating the

Figure 12. Interaction Between the Factors *($T_p$ × P)* on Response CVS

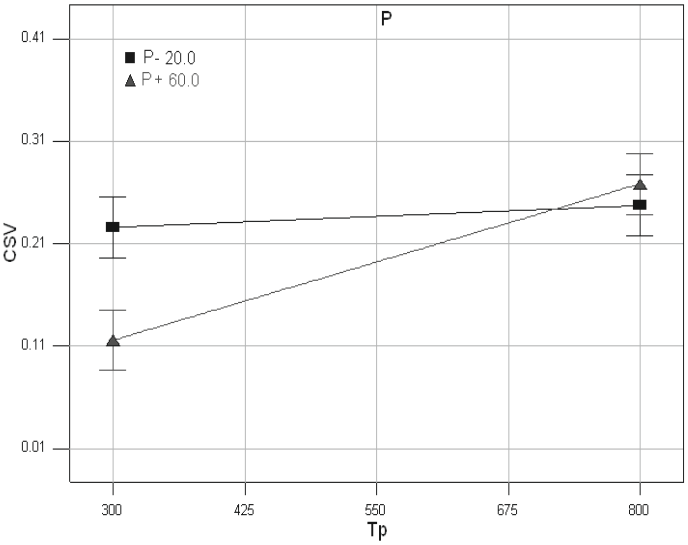
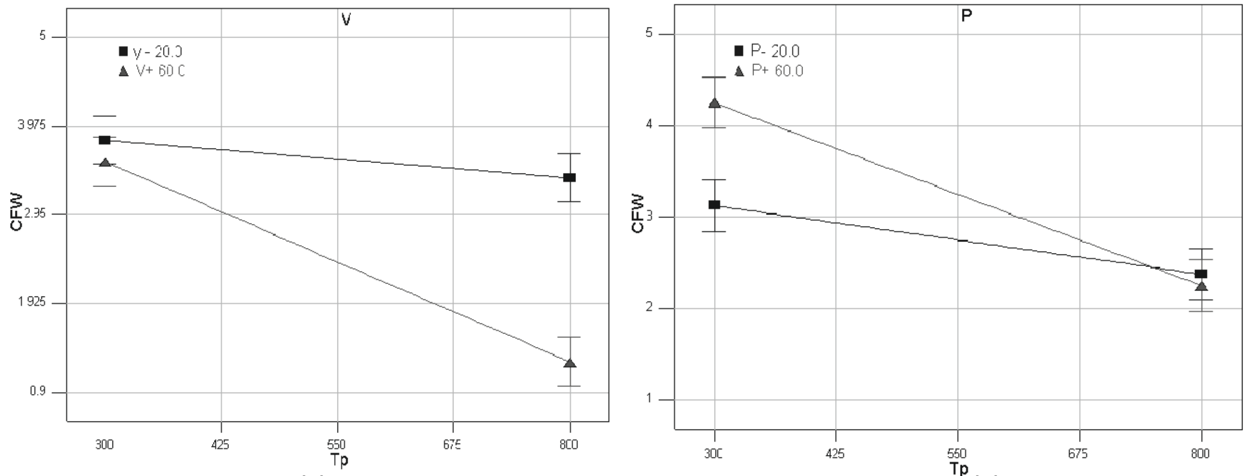


Figure 13. Interaction Between the Factors *($T_p$ × V)* and *($T_p$ × P)* on Response CFW



(a) (b)

studentized residual, then the residual is said to be externally studentized. When one is considering whether the $i^{th}$ case may be an outlier for calculating the studentized residual, then it is called as internally studentized. The Table 12 shows the externally studentized and internally studentized residuals of response CVS. The scaled form of the residuals provide better variations as compared to the least square residuals. The externally studentized and internally studentized residuals only show the least difference, since there is no significant outlier in the regression model.

Leverage is an influence diagnostic of regression analysis and, in particular, is aimed to identify those observations that are far away from the corresponding average of predicted values. A significant leverage has an unusual *x*-space value in the plot of "predicted value vs experimental value" (Figure 7), and provides high leverage value as compared to other observations. This leverage does not affect the estimates of the regression coefficients, but it certainly makes dramatic effect on the model summary statistics such as $R^2$ and the standard errors of the regression coefficients.

The Table 12 shows the equal leverage value (0.5) of the experimental runs for the response CVS. The experimental run's leverage values are less than 2 $p$ / $n$ value (2 x 9/16) = 1.125 ; where, $p$ is the rank of the

**Figure 14. Interaction Between the Factors *( $T_p$ × P)* on Response CSV**

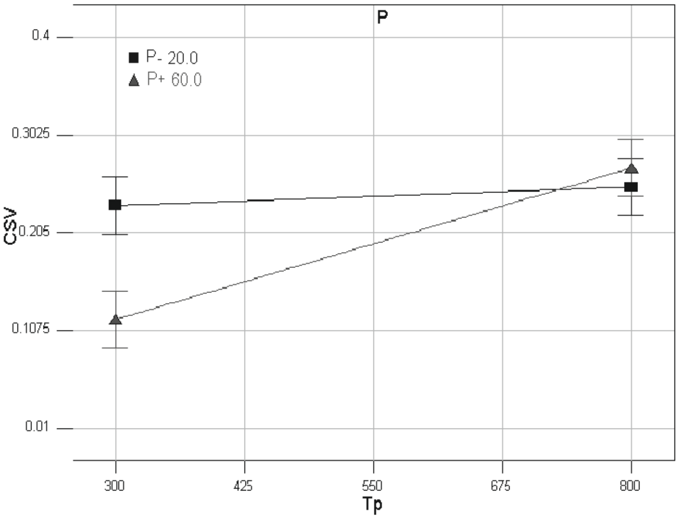
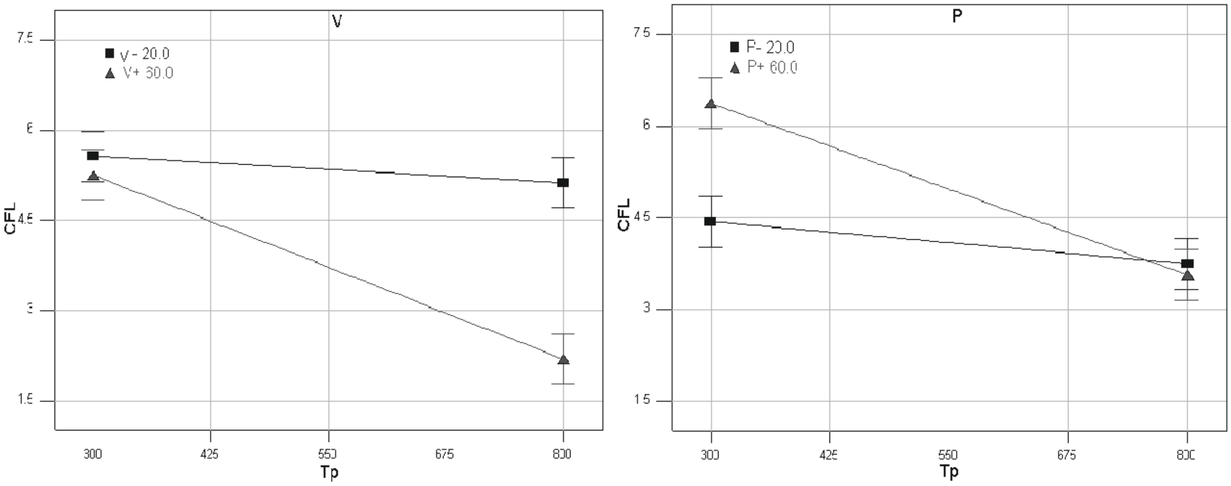
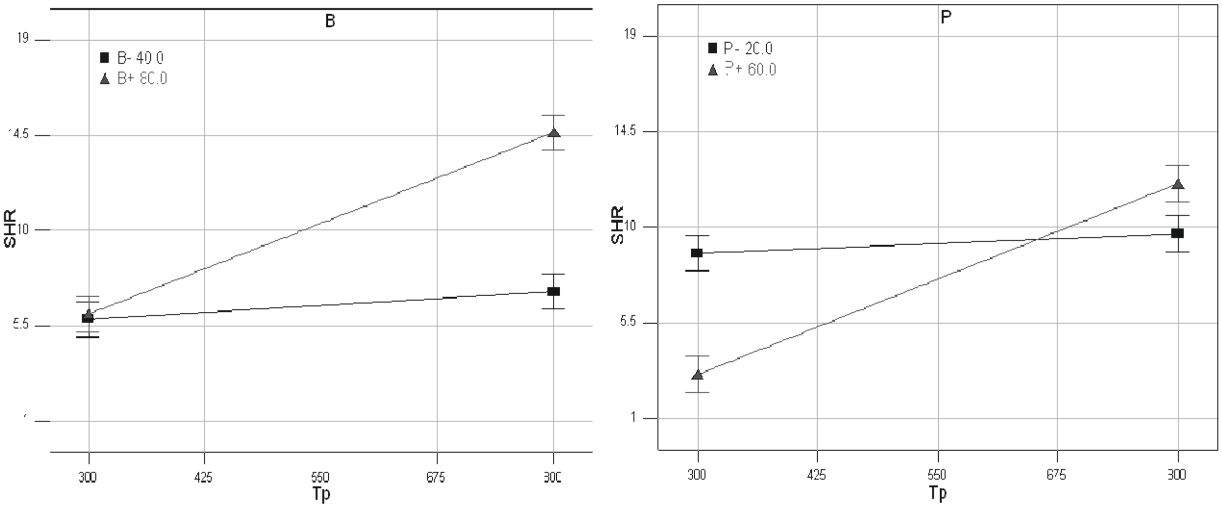


**Figure 15. Interaction Between the Factors *($T_p$ × V)* and *($T_p$ × P)* on Response CFL**



**(a)** **(b)**

**Figure 16. Interaction Between the Factors *($T_p$ × B)* and *($T_p$ × P)* on Response SHR**



**(a)** **(b)**

**Table 11. Significance of Coefficients for the Response Model CVS**

| Factor | Coefficients | Coefficient estimate | Lower bound 95% CI | Upper bound 95% CI | *df* | Standard error | *t* - value | *p* > \|*t*\| |
|---|---|---|---|---|---|---|---|---|
| Intercept | $b_o$ | 0.5227 | 0.503 | 0.543 | 1 | 0.0095 | 55.1782 | < 0.0001 |
| **$*T_p$** | $b_1$ | 0.0430 | 0.023 | 0.063 | 1 | 0.0095 | 4.5363 | 0.0003 |
| **$*B$** | $b_2$ | 0.0477 | 0.028 | 0.068 | 1 | 0.0095 | 5.0312 | 0.0001 |
| $C$ | $b_3$ | -0.0148 | -0.035 | 0.005 | 1 | 0.0095 | -1.5671 | 0.1367 |
| $E$ | $b_4$ | -0.0117 | -0.032 | 0.008 | 1 | 0.0095 | -1.2372 | 0.2339 |
| **$*V$** | $b_5$ | 0.0492 | 0.029 | 0.069 | 1 | 0.0095 | 5.1962 | 0.0001 |
| **$*P$** | $b_6$ | -0.0242 | -0.044 | -0.004 | 1 | 0.0095 | -2.5568 | 0.0211 |
| $L$ | $b_7$ | -0.0102 | -0.030 | 0.010 | 1 | 0.0095 | -1.0722 | 0.2995 |
| $T_b$ | $b_8$ | -0.0039 | -0.024 | 0.016 | 1 | 0.0095 | -0.4124 | 0.6855 |
| $T_p \times B$ | $b_{12}$ | 0.0055 | -0.015 | 0.026 | 1 | 0.0095 | 0.5774 | 0.5717 |
| $T_p \times C$ | $b_{13}$ | -0.0070 | -0.027 | 0.013 | 1 | 0.0095 | -0.7423 | 0.4687 |
| $T_p \times E$ | $b_{14}$ | 0.0086 | -0.011 | 0.029 | 1 | 0.0095 | 0.9073 | 0.3777 |
| $T_p \times V$ | $b_{15}$ | 0.0164 | -0.004 | 0.036 | 1 | 0.0095 | 1.7321 | 0.1025 |
| **$*T_p \times P$** | $b_{16}$ | 0.0336 | 0.014 | 0.054 | 1 | 0.0095 | 3.5466 | 0.0027 |
| $T_p \times L$ | $b_{17}$ | 0.0070 | -0.013 | 0.027 | 1 | 0.0095 | 0.7423 | 0.4687 |
| $T_p \times T_b$ | $b_{18}$ | 0.0008 | -0.019 | 0.021 | 1 | 0.0095 | 0.0825 | 0.9353 |

* Significant factor coefficients

dependent factors matrix and *n* is the total numbers of experiments (Montgomery, 2009). No significant leverage is observed in the model. This shows that all the experimental runs data are equally influenced to build the regression model. Leverage will identify the points that are potentially influential due to their location in *x*-space. It is desirable to consider both, the location *(x, y)* of a point and measuring the response variable influence. Cook has suggested a distance measure by incorporating both ; the location of a point called Cook's distance. Cook's distance is a deletion diagnostics; if the value of Cook's distance is more than 1.0, then it is significant for removal (Montgomery, 2009). The Table 12 shows Cook's distance of the experimental runs of the response CVS. There is no distance value that is found to be more than 1.0. Therefore, no experimental run data can be removed from building of the regression model. Similarly, other responses' (CFW, CSV, CFL, and SHR) residual analysis are examined and interpreted.

➩ **Surface Plots :** Surface plots were developed for the model, taking two parameters in the middle level and two parameters on the *X* and *Y* axis and response on the *Z* axis. The surfaces clearly reveal the direction of the optimal response point. The surface plot also reveals the direction of optimal set of process parameters that produce a maximum or minimum value of the response (Hou, Su, & Liu, 2007). Since it is the screening experiment, here, surface plots are helpful to set the parameter range for the main experiment. In the present investigation, the significant process parameters corresponding to the minimum CVS are considered. The Figure 8 presents the three-dimensional surface plots for the response CVS obtained from the regression model. The direction of optimum CVS is exhibited by the corners of the surface plots. Contour plots play a very important role in the study of the surface plot analysis, and the same was generated using software. The direction of the optimum is identified with reasonable accuracy by characterizing the shape of the surface. If a contour patterning of circular-shaped contours (or straight lines) occurs, it tends to suggest independence of factor effects ; whereas, elliptical contours (or curved lines) may indicate factor interactions (Montgomery, 2009). The Figure 12 (c) exhibits an almost curved lines contour, which suggests dependence of factor. Whereas, Figures 9 (a), 9 (b), 9 (d) to 9 (f) show

**Table 12. Residual Analysis of Regression Models of Response CVS**

| Standard order | Experimental value | Predicted value | Lower bound 95% PI | Upper bound 95% PI | Residual (%) | Leverage | Internally studentized residual | Externally studentized residual | Cook's distance |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.50 | 0.51 | 0.295 | 0.600 | -2.50 | 0.50 | -0.33 | -0.32 | 0.01 |
| 2 | 0.53 | 0.51 | 0.295 | 0.600 | 2.38 | 0.50 | 0.33 | 0.32 | 0.01 |
| 3 | 0.55 | 0.59 | 0.452 | 0.756 | -6.82 | 0.50 | -0.99 | -0.99 | 0.06 |
| 4 | 0.63 | 0.59 | 0.452 | 0.756 | 6.00 | 0.50 | 0.99 | 0.99 | 0.06 |
| 5 | 0.55 | 0.54 | 0.433 | 0.737 | 2.27 | 0.50 | 0.33 | 0.32 | 0.01 |
| 6 | 0.53 | 0.54 | 0.433 | 0.737 | -2.38 | 0.50 | -0.33 | -0.32 | 0.01 |
| 7 | 0.55 | 0.59 | 0.408 | 0.712 | -6.82 | 0.50 | -0.99 | -0.99 | 0.06 |
| 8 | 0.63 | 0.59 | 0.408 | 0.712 | 6.00 | 0.50 | 0.99 | 0.99 | 0.06 |
| 9 | 0.43 | 0.41 | 0.295 | 0.600 | 2.94 | 0.50 | 0.33 | 0.32 | 0.01 |
| 10 | 0.40 | 0.41 | 0.295 | 0.600 | -3.13 | 0.50 | -0.33 | -0.32 | 0.01 |
| 11 | 0.40 | 0.44 | 0.295 | 0.600 | -9.38 | 0.50 | -0.99 | -0.99 | 0.06 |
| 12 | 0.48 | 0.44 | 0.295 | 0.600 | 7.89 | 0.50 | 0.99 | 0.99 | 0.06 |
| 13 | 0.58 | 0.54 | 0.333 | 0.637 | 6.52 | 0.50 | 0.99 | 0.99 | 0.06 |
| 14 | 0.50 | 0.54 | 0.333 | 0.637 | -7.50 | 0.50 | -0.99 | -0.99 | 0.06 |
| 15 | 0.63 | 0.66 | 0.545 | 0.850 | -6.00 | 0.50 | -0.99 | -0.99 | 0.06 |
| 16 | 0.70 | 0.66 | 0.545 | 0.850 | 5.36 | 0.50 | 0.99 | 0.99 | 0.06 |
| 17 | 0.30 | 0.31 | 0.195 | 0.500 | -4.17 | 0.50 | -0.33 | -0.32 | 0.01 |
| 18 | 0.33 | 0.31 | 0.195 | 0.500 | 3.85 | 0.50 | 0.33 | 0.32 | 0.01 |
| 19 | 0.65 | 0.61 | 0.408 | 0.712 | 5.77 | 0.50 | 0.99 | 0.99 | 0.06 |
| 20 | 0.58 | 0.61 | 0.408 | 0.712 | -6.52 | 0.50 | -0.99 | -0.99 | 0.06 |
| 21 | 0.68 | 0.59 | 0.445 | 0.750 | 12.96 | 0.50 | 2.31 | 2.74 | 0.33 |
| 22 | 0.50 | 0.59 | 0.445 | 0.750 | -17.50 | 0.50 | -2.31 | -2.74 | 0.33 |
| 23 | 0.60 | 0.56 | 0.445 | 0.750 | 6.25 | 0.50 | 0.99 | 0.99 | 0.06 |
| 24 | 0.53 | 0.56 | 0.445 | 0.750 | -7.14 | 0.50 | -0.99 | -0.99 | 0.06 |
| 25 | 0.48 | 0.51 | 0.333 | 0.637 | -7.89 | 0.50 | -0.99 | -0.99 | 0.06 |
| 26 | 0.55 | 0.51 | 0.333 | 0.637 | 6.82 | 0.50 | 0.99 | 0.99 | 0.06 |
| 27 | 0.45 | 0.41 | 0.308 | 0.612 | 8.33 | 0.50 | 0.99 | 0.99 | 0.06 |
| 28 | 0.38 | 0.41 | 0.308 | 0.612 | -10.00 | 0.50 | -0.99 | -0.99 | 0.06 |
| 29 | 0.45 | 0.43 | 0.289 | 0.594 | 5.56 | 0.50 | 0.66 | 0.65 | 0.03 |
| 30 | 0.40 | 0.43 | 0.289 | 0.594 | -6.25 | 0.50 | -0.66 | -0.65 | 0.03 |
| 31 | 0.63 | 0.66 | 0.445 | 0.750 | -6.00 | 0.50 | -0.99 | -0.99 | 0.06 |
| 32 | 0.70 | 0.66 | 0.445 | 0.750 | 5.36 | 0.50 | 0.99 | 0.99 | 0.06 |

almost straight lines contour, which suggests independence of factors.

It is relatively easy to see, by examining the contour plots in Figures 9 (a) to 9 (f), that by an increase or decrease in the significant parameters, minimization of response CVS can be obtained for the color fast finish process. Consider the Figure 9 (a), if the value of the factors $T_p$ and $B$ decrease from 800°C to 300°C and 80% to 40%, respectively, the response value would minimize from 0.59 ΔE to 0.47 ΔE. It is understood that in the main experiment, fixing lower ranges to parameters temperature of the pre-dryer ($T_p$ < 550°C) and bath liquor pickup ($B$ < 60%) will provide minimum color variation to the standard. The Figure 9 (b) shows that low level of the factor

**Table 13. ANOVA Test Results for the Linear Regression Model (Equation (11))**

| Source | *df* | Sum of squares | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Regression | 1 | 0.336 | 0.336 | 2244 | <0.0001 |
| Error | 30 | 0.0045 | 0.00015 | | |
| Total | 31 | 0.3405 | | | |
| $R^2$ | 98.7% | | | | |
| Adjusted $R^2$ | 98.6% | | | | |

**Table 14. ANOVA Test Results for the Linear Regression Model (Equation (12))**

| Source | *df* | Sum of squares | Mean square | *F* value | *p*-value (Probability > *F* ) |
|---|---|---|---|---|---|
| Regression | 1 | 0.113 | 0.113 | 14.86 | 0.001 |
| Error | 30 | 0.228 | 0.0076 | | |
| Total | 31 | 0.3405 | | | |
| $R^2$ | 33.1% | | | | |
| Adjusted $R^2$ | 30.9% | | | | |

$T_p$ and lower level of the factor $V$ minimize the response value. The main experiment can be set with the parameters : temperature of the pre-dryer ($T_p < 550^{\circ}$C) and machine speed ($V < 40$ m / min). The Figure 9(c) confirms that a low value of the factor $T_p$ and a high value of the factor $P$ yields the minimum color variation to the standard. The main experiment parameters can be set with : temperature of the pre-dryer ($T_p < 550^{\circ}$C) and padder pressure ($P > 40$ N / mm). Considering the Figure 9 (d), the lower level of factor $B$ and the lower level of factor $V$ provide the minimum color variation to the standard. For the main experiment, lower bath liquor pickup ($B <$ 60%) and lower machine speed ($V < 40$ m / min) can be set. Consider the Figures 9 (e) and 9 (f) simultaneously, the parameters $B$ and $V$ at lower level and parameter $P$ at higher level will minimize the response. So, the main experiment parameters are bath liquor pickup ($B <$ 60%), machine speed ($V < 40$ m / min), and padder pressure ($P > 40$ N / mm).The surface plots (Figures 8 (a) to 8 (f)) and contour plots (Figures 9 (a) to 9 (f)) provide a convenient way to find a path of steepest ascent for shade variation to the standard on main experiment. Similarly, other responses (CFW, CSV, CFL, and SHR) are studied for finding a path of steepest ascent by using surface and contour plots.

↳ **Relationship Between the Responses :** The shade variation to the standard and center to selvedge variation obtained from the experimental results are related, as shown in the Figure 10. The experimental data points are fitted by a straight line. The straight line is governed by the following regression equation:

$$CVS = 0.309 + 0.9963\,CSV \qquad (11)$$

The slope of the estimated regression equation (+ 0.9963) is positive, implying that as shade variation to the standard decreases, the center to selvedge variation decreases. The coefficient of determination is $R^2 = 98.7\%$, which can be interpreted as the percentage of the total sum of squares that can be explained by using the estimated regression equation. In other words, 98.8% of the variability in shade variation to the standard can be explained by the linear relationship between the shade variation to the standard and center to selvedge variation and it is presented in the Table 13. The coefficient of determination $R^2$ is a measure of the goodness of fit of the estimated regression equation (Montgomery, 2009). The fitted regression line may be used for two purposes: (a) estimating the mean value of center to selvedge variation for the given value of shade variation to the standard; and (b) predicting an individual value of shade variation to the standard for a given value of center to selvedge variation. The relationship between the shade variation to the standard and the color fastness to washing is shown is Figure 11. The experimental data points are fitted by a straight line and it is governed by the following regression equation:

$$CVS = 0.630 - 0.0436\,CFW \qquad (12)$$

The Figure 11 shows that there is no correlation between the responses : shade variation to the standard and color fastness to washing. The coefficient of determination is $R^2 = 33.1\%$. Only 33.1% of the variability in shade variation to the standard can be explained by the linear relationship between the shade variation to the standard and color fastness to washing. This is presented in the Table 14. Similarly, the other combinations of the responses can be studied and interpreted.

## Discussion

Temperature of the pre-dryer $(T_p)$, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P)*, and interaction - $T_p \times P$ had substantial effects on the minimization of responses shade variation to the standard and center to selvedge variation. The responses to be maximized are color fastness to washing and color fastness to light are significantly affected by factors - temperature of the pre-dryer $(T_p)$, bath liquor pickup *(B)*, machine speed (V), padder pressure *(P)*, interaction - $T_p \times V$, and interaction - $T_p \times P$. In case of minimization of fabric residual shrinkage, temperature of the pre-dryer $(T_p)$, bath liquor pickup *(B)*, machine speed *(V)*, padder pressure *(P)*, interaction - $T_p \times B$, and interaction - $T_p \times P$ had significant effects. The remaining four factors and their interactions had less effect on the responses of color fast finish. The factor significance was understood from the normal probability plots, ANOVA, and interaction plots.

In the CFF process, padder pressure decides the penetration level of color fast finish size into the core of the fabric to be finished. More padder pressure is given to the stenter machine mangle; more penetration takes place and vice versa. More core penetration color fast finish size will bring a better color build-up to the fabric being dyed. If the penetration is less than the core of the yarn, the fabric will not be dyed completely. Temperature of the pre-dryer is a significant parameter to the color fast finish process that will preheat the fabric to avoid the migration of the PAD N colorants, but it will cause pre setting of color fast finish size and affect the required shade build-up. Lower padder pressure and higher temperature of the pre-dryer combine to cause the migration effect, overdryness, and presetting of the fabric. This combination results in poor shade build-up and causes more color variation as compared to the standard. On the other hand, higher padder pressure and lower temperature of the pre-dryer combine to cause no migration effect, better core penetration, moisture fabric inlet to stenter chamber, and complete setting of the fabric. This condition results in better shade build-up and causes minimized color variation as compared to the standard, and this evident from the Figure 12. Similar reasons can be explained for the Figure 14 - higher padder pressure and lower temperature of the pre-dryer combine to cause a minimized center to selvedge variation.

Machine speed is another important parameter of the CFF process; this leads to ensure the required setting time of the color fast finish process. Higher machine speed of the stenter machine, lesser setting time, and vice versa. If the setting time is less than the required level, then color fixation will be poor and results in poor fastness. If the setting time is higher, then it will create fabric strength issues, especially in tear strength. The higher machine speed and higher temperature of the pre-dryer combine to cause improper setting of PAD N colorants. This combination results in improper setting and causes less color fastness to washing. On the other hand, lower machine speed and lower temperature of the pre-dryer combine to cause complete setting of the fabric. This condition results in complete setting of colorants and causes maximum color fastness to washing, and this is clearly evident in the Figure 13 (a). The same reasons could be well explained for Figure 15 (a). Higher padder pressure and lower temperature of the pre-dryer combine to cause no migration effect, better core penetration, moisture fabric inlet to stenter chamber, and complete setting of the fabric. This condition results in better shade build-up, complete setting of PAD N colorants, and causes maximum color fastness to washing and this is evident from the Figure 13 (b). The same reasons could be applicable for the Figure 15 (b).

In CFF, bath liquor pickup decides the application required for color fast finish size (inclusive of PAD N colorants and resins). More bath liquor pickup will yield to application of more color fast finish size and vice versa. Color fast finish size contains a resin component. Resins are an anti shrinking agent. This will bring the fabric residual shrinkage under control. The lower bath liquor pickup and higher temperature of the pre-dryer combine to cause poor cross linking between the fibers of the fabric. This combination results in higher fabric residual shrinkage value. On the other hand, lower bath liquor pickup and lower temperature of the pre-dryer combine to cause a higher degree of linkage between the fibers of the fabric. This condition results in shrinkage control and causes minimized fabric residual shrinkage, which can be inferred from the Figure 16 (a). Higher padder pressure and lower temperature of the pre-dryer combine to cause more core penetration of size and minimized fabric residual shrinkage, which can be inferred from the Figure 16 (b).

## Conclusion, Implications, Limitations of the Study, and the Way Forward

Screening experiments are an efficient way, with a minimal number of runs, of determining the important factors. They may also be used as a first step when the ultimate goal is to model a response with a response surface. In this screening design, four factors were screened from eight factors. The experiments were conducted according to the layout of $2_{IV}^{8-4}$ fractional factorial design, and five response function values were obtained, and then averaged. From the estimates of normal plots and ANOVA, the insignificant factors were eliminated. Temperature of the pre-dryer, bath liquor pickup, machine speed, padder pressure, interaction - $T_p \times V$, interaction - $T_p \times P$, and interaction - $T_p \times B$ had substantial effects on the color fast finish process. The factors - blower circulation, blower exhaust, trough level, bath liquor temperature - had less effect on the responses and were eliminated for the main experiment. The factor ranges for the main experiment were selected from the inference of surface plots and contour plots. It was decided to further explore the possibility of increasing the responses : shade variation to the standard, color fastness to washing, center to selvedge variation, color fastness to light, and fabric residual shrinkage by changing the factors' temperature of the pre-dryer, bath liquor pickup, machine speed, padder pressure, interaction - $T_p \times V$, interaction - $T_p \times P$, and interaction - $T_p \times B$ along the path of steepest ascent.

Since the process of color fast finish is very new to the textile dyeing process, it requires a lot of screening in selection of quality attributes and parameters. Thus, the rule of thumb and random selection of quality attributes and parameters for process study are eliminated completely. But we cannot conclude an optimized process behavior with this screening study alone, the inference from the screening study should be further explored with the main experimental study. The system of robustness begins at the design phase of the formulation and manufacturing process; emphasis on building the quality into the product at this stage is the most effective strategy, and the same is applied to the color fast finish process. Since this study is a more generic approach, it could be deployed to other value chains of the textile process. The value chain elements: ginning, spinning, sizing, weaving, knitting, and garmenting are suitable to implement an experimental study in various requirements. But care should be taken while selecting the performance attributes and parameter selection should be done according to the field of interest.

If the textile producing companies accept this systematic experimental investigation focus trend, it will help to make the textile industry a pillar of sustainable development. The current study will help the top managements, research & development managers of textile companies, dyers, and industrial engineers to capture the quality attributes and parameters of any process related to textile processing.

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