MINIMIZING SHADE VARIATIONS IN KNIT DYEING THROUGH PROCESS STANDARDIZATION

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Abstract - Shade variation is a persistent quality challenge in industrial knit fabric dyeing, leading to increased costs and reprocessing. This study investigates minimizing these variations in reactive-dyed cotton knitted fabrics through systematic process standardization across pre-treatment, dyeing, finishing, and reprocessing stages. Utilizing CIELAB parameters (ΔE, ΔL*, Δa*, Δb*, ΔC*, ΔH*), the research identifies that shade inconsistency stems not only from dyeing variables but also from finishing conditions and absorbency uniformity. Key interventions included regulating steam-based compacting, optimizing Cold Pad Batch (CPB) squeezer pressure, implementing continuous scouring (CBR), and controlling reprocessed water pH (≤ 6.5). Results demonstrated a significant improvement in Right First Time (RFT) performance, increasing from approximately 82–85% to 92–95%, while reducing the reprocess rate by over 50%. Furthermore, the study achieved a chemical cost reduction of ₹3.21 per kg of fabric. This research highlights that a holistic, integrated standardization framework is essential for sustainable shade consistency.

Index Terms - Shade variation, knit dyeing, process standardization, color consistency, textile dyeing, liquor ratio, fabric GSM, spectrophotometer, Re-dyeing minimization, Delta E (ΔE), Delta L (ΔL), Delta A (ΔA), Delta B (ΔB), Delta C (ΔC), Delta H (ΔH) Metamerism, Right First Time (RFT), softener pickup, CIELAB, cost minimization.

1. Introduction

1.1 Background of Shade Variation in Knit Dyeing

In the textile wet processing industry, shade consistency is a critical quality parameter, particularly in knit dyeing where fabric structure and processing sensitivity significantly influence color reproducibility. Shade variation refers to the measurable or perceptible difference in color between a standard reference and a dyed fabric sample, or between different production batches of the same shade. Even minor deviations in shade can result in rejection, reprocessing, increased cost, and delayed deliveries.

Knitted fabrics, owing to their looped structure, higher porosity, and greater absorbency compared to woven fabrics, are highly sensitive to variations in dyeing parameters. Small fluctuations in liquor ratio, dye concentration, salt and alkali dosing, pH, temperature gradient, machine loading, and water quality can cause uneven dye uptake and inconsistent shade development. Additionally, differences between laboratory dyeing (lab dip) and bulk production further contribute to shade mismatches.

Traditionally, shade evaluation was conducted visually under standardized lighting conditions. However, visual assessment is subjective and influenced by observer perception, light source, and surrounding environment. To overcome this limitation, instrumental color measurement using spectrophotometry has become the industry standard. The CIELAB color space system is widely adopted for objective evaluation of color differences and quantification of shade variations.

1.2 CIELAB Color Space and Shade Difference Measurement

The CIELAB (Commission Internationale de l'Éclairage) color space is a three-dimensional model designed to approximate human vision and quantify color differences numerically. In this system, color is represented using three coordinates:
L* – Lightness coordinate (0 = black, 100 = white)
a* – Red (+) to Green (−) axis
b* – Yellow (+) to Blue (−) axis

The difference between a reference standard and a dyed sample is expressed as:
ΔL* (Difference in lightness)
Δa* (Difference in red–green axis)
Δb* (Difference in yellow–blue axis)
From these primary differences, additional derived parameters are calculated to better understand the nature of shade deviation.

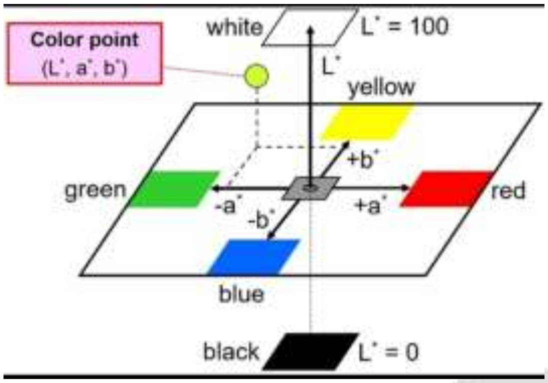


Figure 1 CIELAB color Space

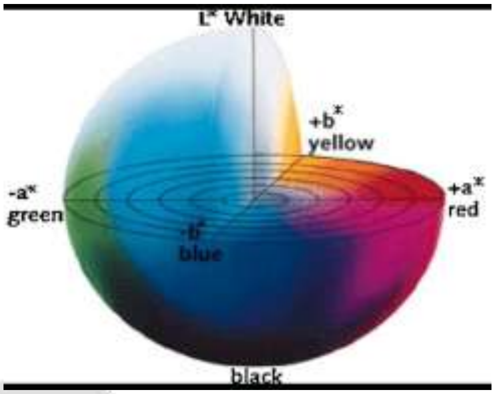


Figure 2 Three Dimensional View

1.3 Total Color Difference (ΔE)

The overall color difference between a standard and a sample is represented by ΔE. It is calculated using the following formula:

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

ΔE provides a single numerical value indicating the magnitude of total color deviation. A lower ΔE value indicates better shade matching. In industrial standards, acceptable ΔE tolerance typically ranges from 0.7 to 1.0 depending on buyer specifications and shade depth.
However, ΔE alone does not explain the direction or cause of variation. Therefore, individual component analysis is essential.

1.4 Interpretation of Individual Shade Difference Parameters

1.4.1 ΔL^* (Lightness Difference)

ΔL^* indicates whether the dyed sample is lighter or darker than the standard.
Positive ΔL^* → Sample is lighter
Negative ΔL^* → Sample is darker
In knit dyeing, variations in dye exhaustion, temperature control, and liquor ratio significantly affect ΔL^*. Improper alkali dosing can result in inconsistent dye fixation, leading to lightness deviations.

1.4.2 Δa^* (Red–Green Difference)

Δa^* represents the shift along the red–green axis.
Positive Δa^* → Shade is redder
Negative Δa^* → Shade is greener
Reactive dye combinations in knit dyeing are highly sensitive to pH and electrolyte concentration. Any imbalance in recipe components can cause selective dye absorption, shifting the shade toward red or green tones.

1.4.3 Δb^* (Yellow–Blue Difference)

Δb^* represents the shift along the yellow–blue axis.
Positive Δb^* → Shade is more yellow
Negative Δb^* → Shade is more blue
Temperature variation, dye compatibility, and water hardness influence Δb^*. In pastel and light shades, small Δb^* deviations are highly visible and can lead to rejection.

1.4.4 ΔC^* (Chroma Difference)

Chroma (C*) represents color saturation or intensity. ΔC* indicates the difference in color strength between standard and sample.
Positive ΔC* → Sample is brighter
Negative ΔC* → Sample is duller
In knit dyeing, chroma variation may occur due to improper dye fixation, uneven chemical dosing, or variation in fabric absorbency. Controlling process standardization helps maintain consistent color strength.

1.4.5 ΔH* (Hue Difference)

ΔH* represents the hue difference, indicating a shift in the actual shade tone independent of lightness and chroma. Hue variation is often caused by:
Dye incompatibility
Improper mixing sequence
pH Variance
Hue deviation is critical in brand-sensitive colors where slight tonal differences are unacceptable.

1.5 Relevance to Process Standardization

Understanding ΔE, ΔL*, Δa*, Δb*, ΔC*, and ΔH* provides a scientific foundation for identifying the root cause of shade variation in knit dyeing. Rather than relying solely on total color difference, analyzing individual components enables precise correction of process variables.

Process standardization — including controlled chemical dosing, automated temperature profiling, liquor ratio control, water quality monitoring, and SOP adherence — directly contributes to minimizing these deviations. By linking instrumental color difference parameters with process variables, shade reproducibility can be systematically improved.

2. Literature Review

Shade variation and reproducibility in textile dyeing have been widely investigated due to their significant impact on fabric quality, production efficiency, and customer satisfaction. Previous studies highlight that both process parameters and shade depth play critical roles in determining the final appearance and performance properties of dyed fabrics.

Mahbubur Rahman et al., in their study published in the International Journal of Research in Engineering and Technology, reports that shade percentage significantly influences the physical and mechanical properties of cotton knitted fabrics dyed with reactive dyes. The authors state that as shade depth increases, GSM, CPI, WPI, and shrinkage values also increase. However, they observe that higher shade percentages negatively affect color fastness properties. The study concludes that while deeper shades enhance fabric compactness, they simultaneously reduce fastness performance, particularly to washing and rubbing.

Similarly, Asif Sakib et al., in the International Journal of Clothing Science, examine the effect of shade depth ranging from 1% to 8% on cotton knitted fabrics dyed with reactive dyes. The authors explain that increasing shade depth results in higher GSM but leads to a decrease in bursting strength. Furthermore, they emphasize that color fastness to washing, rubbing, and perspiration deteriorates as shade percentage increases. The study highlights the trade-off between shade intensity and fabric durability.

Chowdhury Jony Moin and A.K.M. Mahabubuzzaman, in their research on level dyeing of 100% cotton knit fabrics, state that shade uniformity largely depends on proper control of process parameters rather than additional chemical usage. The authors emphasize the importance of controlling temperature gradients, dosing time, cycle time, and water hardness to minimize meter-to-meter shade variation. Their findings indicate that optimized machine settings can significantly improve dye leveling without increasing operational costs.

Ashaduzzaman et al., in the Journal of Textile Science & Engineering, discuss the major causes of batch-to-batch shade variation in textile dyeing. The authors identify factors such as water hardness, dye lot variation, fabric GSM differences, material-to-liquor ratio, temperature fluctuations, and improper alkali dosing as key contributors to shade inconsistency. They suggest that strict adherence to standardized recipes and process control measures is essential to maintain uniform shade across production batches.

Prasun Das, Shirshendu Roy, and Jiju Antony, in their study published in the Journal of Industrial Textiles, apply the Six Sigma DMAIC methodology to reduce lot-to-lot shade variation in linen fabrics. The authors report that statistical process control significantly improves shade matching accuracy and reduces reprocessing time. Their research demonstrates that systematic quality improvement techniques can enhance production efficiency and reduce financial losses caused by shade defects.

In addition, Gurdeep Singh, in his research on the development of a solid colour shade detection and matching machine, states that traditional manual shade inspection is prone to human error. The author explains that the use of RGB color sensors and image processing techniques can effectively detect shade variations and improve matching accuracy. The study concludes that automated shade detection systems offer better reliability compared to conventional visual assessment methods.

Collectively, these studies indicate that shade variation in textile dyeing is influenced by multiple interrelated factors, including shade depth, process control parameters, material characteristics, and measurement techniques. While higher shade percentages affect mechanical and fastness properties, improper process control contributes significantly to batch-to-batch variation. Furthermore, the integration of statistical quality tools and automated color detection systems provides promising solutions for improving shade reproducibility and overall product quality.

3. Root Cause – Analysis

3.1 Overview

Based on the literature findings and industrial observations, shade variation in knit dyeing is not caused by a single parameter but is the result of multiple interrelated variables affecting dye uptake, fixation, and distribution. The analysis of shade deviation through instrumental parameters such as ΔE, ΔL*, Δa*, Δb*, ΔC*, and ΔH* enables identification of specific process inconsistencies.

To systematically identify the root causes, the contributing factors are classified under the following major categories:

- Raw Material Variability
- Chemical and Dye Factors
- Process Parameter Deviations
- Machine and Mechanical Factors
- Measurement and Evaluation Errors
- Environmental and Utility Factors

3.2 Raw Material Variability

3.2.1 Fabric GSM and Structural Variation

Knitted fabrics are highly sensitive to structural variations. Differences in GSM, CPI (Courses Per Inch), and WPI (Wales Per Inch) influence fabric absorbency and dye penetration.

Higher GSM → Increased dye uptake → Negative ΔL* (darker shade)
Lower GSM → Reduced dye absorption → Positive ΔL* (lighter shade)

Variations in shrinkage behavior also alter fabric compactness, directly affecting chroma (ΔC*) and lightness.

3.2.2 Fiber Quality and Pretreatment Inconsistency

Residual impurities, uneven scouring, or improper bleaching result in variable absorbency. This leads to uneven dye fixation and hue shift (ΔH*) across batches.

3.3 Chemical and Dye-Related Factors

3.3.1 Dye Lot Variation

Reactive dye strength may vary between manufacturing lots. Even slight variations in tinctorial strength cause:

Increased dye strength → Negative ΔL* (darker) and positive ΔC* (higher chroma)
Reduced dye strength → Positive ΔL* (lighter)

Failure to adjust dye concentration according to strength variation leads to batch-to-batch ΔE increase.

3.3.2 Improper Salt and Alkali Dosing

Salt controls dye exhaustion while alkali controls fixation in reactive dyeing.

Excess salt → Rapid exhaustion → Poor leveling → Higher ΔH*
Improper alkali dosing → Uneven fixation → Δa* and Δb* shifts

Sudden alkali addition may cause patchiness and localized hue deviation.

3.3.3 Water Hardness

Calcium and magnesium ions interfere with dye solubility and reactivity.

High hardness → Dye aggregation → Uneven shade → Increased ΔE
Metal ion interference → Tone shift (Δa*, Δb*)

3.4 Process Parameter Deviations

Process standardization plays a dominant role in shade reproducibility.

3.4.1 Liquor Ratio Variation

Material-to-liquor ratio affects dye concentration in bath.

Lower liquor ratio → Higher dye concentration → Darker shade (Negative ΔL*)
Higher liquor ratio → Dilution effect → Lighter shade (Positive ΔL*)

Inconsistent loading between batches causes significant ΔE variation.

3.4.2 Temperature Gradient and Holding Time

Reactive dye fixation is temperature-dependent.

Rapid heating → Uneven dye migration → Increased ΔH*
Insufficient holding time → Incomplete fixation → Lower chroma (Negative ΔC*)

Improper temperature profiling leads to hue and saturation deviations.

3.4.3 pH Control

Reactive dye fixation requires precise pH range.

Low pH → Incomplete fixation → Positive ΔL*
High pH → Hydrolysis of dye → Reduced color yield → ΔC* decrease

pH fluctuation is a critical contributor to Δa* and Δb* imbalance.

3.5 Machine and Mechanical Factors

3.5.1 Fabric Circulation and Flow Pattern

In batch dyeing & continuous range machines, uneven fabric movement causes:

- Roll to Roll shade variation
- Center to side shade variation
- Side to Side shade variation

Poor nozzle pressure or loading imbalance increases shade patchiness.

3.6 Measurement and Evaluation Errors

3.6.1 Instrument Calibration

Improper calibration of spectrophotometer results in inaccurate ΔE reporting, leading to false acceptance or rejection.

3.6.2 Visual Assessment Subjectivity

Manual shade matching under inconsistent lighting leads to human error. Automated systems improve detection sensitivity and minimize observer bias.

3.7 Environmental and Utility Factors

3.7.1 Nozzle Pressure and Temperature Stability

Fluctuations in steam pressure affect heating rate and dye fixation kinetics, leading to ΔH* and ΔC* variation.

3.7.2 Water Quality and TDS

High Total Dissolved Solids (TDS) affect dye solubility and shade brightness.

3.8 Relationship Between Root Causes and Color Difference Parameters

The nature of root causes can be interpreted through instrumental values:
ΔL* → Mainly influenced by dye concentration, liquor ratio, GSM variation
Δa* → Influenced by pH imbalance and dye compatibility
Δb* → Affected by temperature variation and water hardness
ΔC* → Controlled by fixation efficiency and dye strength
ΔH* → Indicates improper leveling, dosing sequence, or temperature rise
ΔE → Cumulative impact of all above factors

4. Methodology

4.1 Experimental Approach

This research adopts an industrial experimental methodology aimed at minimizing shade variation and reprocessing in reactive dyed cotton knitted fabrics through process route optimization and post-dyeing process standardization. Instead of focusing only on dyeing parameters, the study emphasizes downstream processing control, particularly compacting and reprocessing strategies, which are often overlooked sources of shade deviation.

The methodology involves controlled trials at production scale by modifying selected process parameters while maintaining all other conditions constant. Shade variation was evaluated instrumentally using CIELAB color difference values (ΔE, ΔL*, Δa*, Δb*, ΔC*, ΔH*).

4.2 Selection of Critical Process Stages for Control

Based on historical reprocessing data, shade rejection analysis, and Fishbone analysis with the help of Industrial engineers, the following stages were identified as critical contributors to shade variation and reprocess:

- **Compaction using steam-based Sympact**
- **Cold Pad Batch (CPB) squeezer pressure**
- **Scouring route selection (CBR vs Soft flow)**
- **Shade correction through dye stripping**
- **Post-dye fixation and re-fixation**
- **Water quality control during reprocessing**

Each stage was studied individually and then integrated into a standardized process route.

4.3 Sympact (Steam-Based Compacting) Control Trial

4.3.1 Objective

Steam compacting significantly influences fabric surface appearance, light reflection, and optical shade perception. Inconsistent steam pressure and over-compaction can result in apparent shade darkening (negative ΔL*) or tone shift after finishing, even when dyeing shade is within tolerance.

4.3.2 Method of Trial

Fabric lots with identical dyeing parameters were passed through Sympact compacting.
Steam pressure, dwell time, and fabric speed were maintained at standardized levels.
Shade measurement was conducted:

- Before compacting
- After compacting

4.3.3 Evaluation Criteria

- Change in ΔL* after compacting
- Increase or decrease in ΔE due to finishing
- Visual uniformity and fabric handle

4.3.4 Outcome Measurement

Controlled Sympact parameters showed reduced post-finishing ΔE variation and minimized false shade rejection caused by finishing-induced optical changes.

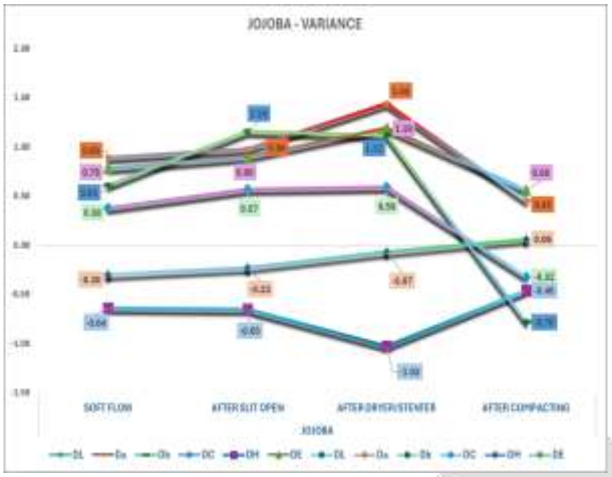


Figure 3 Jojoba - Variance

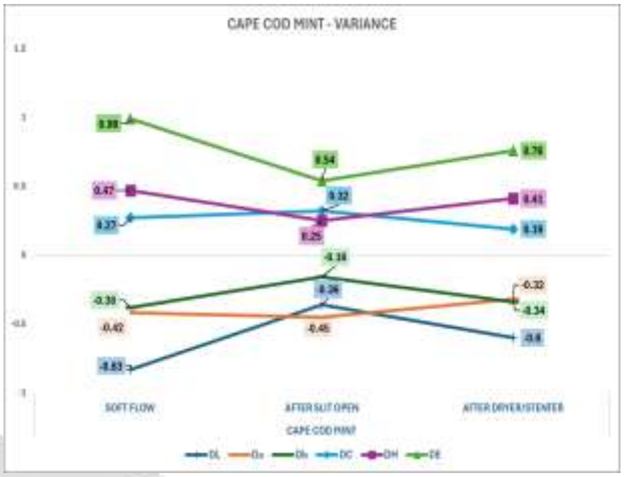


Figure 4 Cape Cod Mint - Variance

4.4 CPB Squeezer Pressure Optimization Trial

4.4.1 Rationale

In CPB, squeezer pressure directly controls liquor pick-up uniformity, which influences scouring efficiency, absorbency, and ultimately dye uptake consistency. Uneven pressure causes localized absorbency variation, leading to shade inconsistency.

4.4.2 Method of Trial

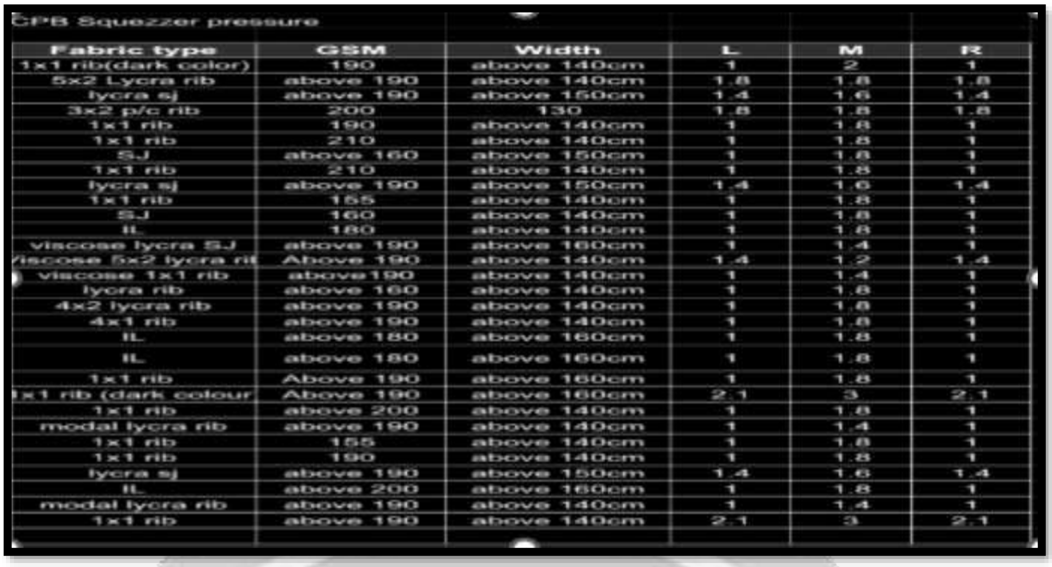
- Squeezer pressure was varied in controlled steps while keeping chemical concentration constant.
- Fabric absorbency was evaluated post-scouring.
- Uniformity across fabric width was monitored.

4.4.3 Evaluation Criteria

- Consistency in wet pick-up percentage
- Reduction in ΔL* variation after dyeing
- Meter-to-meter shade consistency

4.4.4 Outcome Measurement

Optimized squeezer pressure improved pre-treatment uniformity, reducing lightness deviation and lowering batch-to-batch shade variation.



CPB Squeezer pressure

Fabric type	GSM	Width	L	M	R
1x1 rib(dark color)	190	above 140cm	1	2	1
5x2 Lycra rib	above 190	above 140cm	1.8	1.8	1.8
lycra sj	above 190	above 150cm	1.4	1.6	1.4
3x2 p/c rib	200	130	1.8	1.8	1.8
1x1 rib	190	above 140cm	1	1.8	1
1x1 rib	210	above 140cm	1	1.8	1
SJ	above 160	above 150cm	1	1.8	1
1x1 rib	210	above 140cm	1	1.8	1
lycra sj	above 190	above 150cm	1.4	1.6	1.4
1x1 rib	155	above 140cm	1	1.8	1
SJ	160	above 140cm	1	1.8	1
IL	180	above 140cm	1	1.8	1
viscose lycra SJ	above 190	above 160cm	1	1.4	1
Viscose 5x2 lycra ri	Above 190	above 140cm	1.4	1.2	1.4
viscose 1x1 rib	above190	above 140cm	1	1.4	1
lycra rib	above 160	above 140cm	1	1.8	1
4x2 lycra rib	above 190	above 140cm	1	1.8	1
4x1 rib	above 190	above 140cm	1	1.8	1
IL	above 180	above 160cm	1	1.8	1
IL	above 180	above 160cm	1	1.8	1
1x1 rib	Above 190	above 160cm	1	1.8	1
1x1 rib (dark colour	Above 190	above 160cm	2.1	3	2.1
1x1 rib	above 200	above 140cm	1	1.8	1
modal lycra rib	above 190	above 140cm	1	1.4	1
1x1 rib	155	above 140cm	1	1.8	1
1x1 rib	190	above 140cm	1	1.8	1
lycra sj	above 190	above 150cm	1.4	1.6	1.4
IL	above 200	above 160cm	1	1.8	1
modal lycra rib	above 190	above 140cm	1	1.4	1
1x1 rib	above 190	above 140cm	2.1	3	2.1

Figure 5 CPB Squeezer Pressure Readings

4.5 **Process Route Optimization: CBR-Based Scouring**

4.5.1 Rationale

Soft flow scouring is time-consuming and increases water and energy usage. Additionally, frequent batch transfers introduce variability. Continuous scouring using CBR was evaluated as an alternative to reduce process time and improve consistency.

4.5.2 Method of Implementation

Majority of scouring processes were shifted from soft flow to CBR.

Key parameters controlled:

- Temperature profile
- Chemical dosing
- Fabric speed

4.5.3 Evaluation Criteria

- Absorbency uniformity
- Reduction in total processing time
- Impact on dye uptake and ΔE

4.5.4 Outcome Measurement

CBR-based scouring reduced process variation minimized handling-related inconsistencies, and improved shade reproducibility while significantly reducing lead time.

Figure 6 CBR Machine

4.6 Shade Reprocessing Using Oxalic Acid Dye Stripping

4.6.1 Rationale

For off-shade fabrics, controlled dye removal is essential to avoid fiber damage while enabling effective re-dyeing. Oxalic acid was selected due to its effectiveness in partial dye stripping with minimal cellulose degradation.

4.6.2 Method of Application

- Oxalic acid was applied at controlled concentration and temperature.
- Stripping duration was optimized to remove excess dye without over-stripping.
- Fabric was thoroughly neutralized and rinsed before re-dyeing.

4.6.3 Evaluation Criteria

- Degree of shade removal
- Fiber damage assessment
- Re-dyeing shade acceptance

4.6.4 Outcome Measurement

Oxalic acid treatment enabled controlled shade correction, reducing total reprocess cycles and improving re-dye success rate.

4.7 Use of zetesal Fixing and Eco Fixing Agents

4.7.1 Rationale

Post-dye fixing improves dye fixation stability and reduces shade bleeding during reprocessing. zetesal and eco-friendly fixing agents were evaluated for their ability to stabilize shade without affecting color tone.

4.7.2 Method of Application

- Fixing agents were applied after dyeing and after re-dyeing.
- Concentration and treatment time were standardized.
- pH conditions were maintained as per supplier recommendation.

4.7.3 Evaluation Criteria

- Improvement in ΔC* (color strength retention)
- Reduction in shade loss during washing
- Improvement in wash fastness

4.7.4 Outcome Measurement

Fixing treatment reduced chroma loss and enhanced shade durability, contributing to lower reprocessing rejection rates.

4.8 Control of Reprocessed Water pH

4.8.1 Rationale

Reprocessing water often contains residual alkali, dye, and salts, leading to unpredictable dye behavior. Maintaining a controlled pH is essential for repeatability.

4.8.2 Method of Control

- Reprocessed water pH was monitored continuously.
- pH was maintained at or below 6.5 before reuse.
- Neutralization was carried out where required.

4.8.3 Evaluation Criteria

- Stability of Δa* and Δb* during re-dyeing
- Reduction in hue shift
- Improved reproducibility in reprocessed batches

4.8.4 Outcome Measurement

Maintaining reprocessed water pH ≤ 6.5 significantly reduced hue deviation and improved re-dye shade accuracy.

4.9 Validation and Data Analysis

All trial results were compared against baseline production data using:

- Mean ΔE comparison
- Reduction in standard deviation of ΔE
- Reprocess percentage reduction
- First-pass shade acceptance rate

The effectiveness of process standardization was validated by consistent reduction in shade variation and reprocessing frequency.

4.10 Methodology Summary

This methodology demonstrates that minimizing shade variation is achievable not only through dyeing control but also through strategic standardization of finishing, pre-treatment, and reprocessing stages. The integrated control of Sympact compacting, CPB squeezer pressure, optimized scouring routes, controlled dye stripping, fixing treatments, and water pH management provides a robust framework for sustainable shade consistency in knit dyeing.

5. Results and Discussion

5.1 Effect of Process Standardization on Shade Variation (ΔE Analysis)

To evaluate the effectiveness of process standardization, shade deviation values before and after implementation were compared using CIELAB parameters.

5.1.1 Baseline Performance (Before Implementation)

Before implementing standardized controls:

- Average ΔE: **0.75-0.80**
- Standard deviation of ΔE: High variability observed
- RFT (Right First Time): **~82–85%**
- Reprocess rate: **12-15%**

Directional deviations indicated:

- Negative ΔL* after compacting (fabric appearing darker post-finishing)
- ΔH* shifts in reprocessed lots
- ΔC* reduction after washing in some deep shades.

These variations were primarily associated with inconsistent sympact compacting, variable CPB squeezer pressure, soft flow scouring time variation, uncontrolled reprocessed water pH, and inefficient fixation in re-dyed lots.

5.2 Effect of Sympact (Steam Compacting) Control

After standardizing steam pressure, dwell time, and fabric speed:

- Post-compacting ΔL* deviation reduced significantly
- Apparent shade darkening minimized
- ΔE variation between dyed and finished fabric decreased

Discussion:

Controlled compacting minimized optical shade distortion caused by excessive compaction. Stabilizing finishing conditions reduced false shade rejection where dyeing was within tolerance.

5.3 Effect of CPB Squeezer Pressure Optimization

Optimizing squeezer pressure improved liquor pick-up uniformity during pre-treatment.
Observed improvements:

- Reduced meter-to-meter shade variation
- Improved absorbency uniformity
- Lower ΔL* fluctuation in subsequent dyeing

Discussion:

Uniform wet pick-up ensured consistent dye penetration and exhaustion, directly improving lightness reproducibility across batches.

5.4 Effect of CBR-Based Scouring Route

Shifting scouring predominantly to CBR resulted in:

- Reduced overall process time
- Reduced handling variation between batches
- Improved absorbency consistency

Observed results:

- Reduction in batch-to-batch ΔE variation
- Improved reproducibility in medium and dark shades
- Improved production efficiency

Discussion:

Continuous scouring minimized variability associated with batch-wise soft flow scouring and enhanced process stability.

5.5. Effect of Oxalic Acid Stripping in Reprocessing

Controlled dye stripping using oxalic acid enabled effective shade correction with minimal fiber damage.
Observed results:

- Higher success rate in re-dye acceptance
- Reduced need for multiple stripping cycles
- Improved ΔH* stabilization in corrected shades

Discussion:

Standardized stripping protocol reduced uncontrolled dye removal and prevented over-lightening, thereby improving reprocess reliability.

5.6 Effect of zetesal and Eco Fixing

Application of fixing agents after dyeing and re-dyeing showed:

- Improved chroma retention (ΔC* stability)
- Reduced shade loss during washing
- Improved wash fastness ratings

Discussion:

Fixing agents enhanced dye-fiber bonding stability, minimizing chroma reduction and preventing post-wash shade variation.

5.7. Effect of Reprocessed Water pH Control (≤ 6.5)

Maintaining reprocessed water pH at or below 6.5 resulted in:

- Reduced Δa* and Δb* fluctuation during re-dyeing
- Improved hue consistency
- Lower batch-to-batch ΔE variation

Discussion:

Neutral pH conditions stabilized dye reactivity and prevented uncontrolled fixation or hydrolysis during reprocessing.

5.8 Overall Improvement in RFT (Right First Time)

After integrating all process standardization measures:

- Average ΔE reduced to: **0.70 – 0.90**
- Standard deviation significantly reduced
- RFT improved to: **92–95%**
- Reprocess rate reduced to: **5–8%**

Overall improvements:

- Absolute RFT improvement: ~10–12%
- Reprocess reduction: ~50–60%
- Improved shade stability across depth ranges

6. Dyeing Time

6.1. Rationale

To analyze and compare the standard processing times of soft flow, CDR, and CPB dyeing methods. It aims to evaluate the additional time incurred during shade correction scenarios and identify their impact on overall production efficiency. It further focuses on highlighting the significance of achieving first-attempt shade accuracy in reducing reprocessing requirements, minimizing delays, and improving operational productivity in textile wet processing.

6.2 Soft Flow Dyeing Time:

The standard soft flow dyeing cycle requires approximately **8 hours** under normal operating conditions. when shade correction is required, additional sequential processes contribute to the overall time consumption.

The shade correction scenario includes lab-based shade analysis and approval**,** which typically requires **8 hours**, followed by bulk dyeing correction**,** which may take **5–6 hours** depending on the shade depth (approximately **6 hours for dark shades** and **5 hours for light shades**). Additional handling, preparation, and machine-related operations further contribute to the total processing duration.

Therefore, the cumulative time required in a shade correction case is approximately **15–20 hours per batch**, excluding the initial dyeing cycle. This indicates that correction processes significantly increase the overall processing time compared to first-attempt dyeing, emphasizing the importance of accurate shade matching to optimize production efficiency.

6.3 CDR Dyeing Time:

Under standard operating conditions, the CDR dyeing process requires approximately **15–20 minutes**. When shade correction is necessary, the total processing time increases significantly due to additional sequential operations.

The shade correction process begins with **l**aboratory analysis and correction development**,** which typically requires around **8 hours** for recipe formulation and approval. This is followed by bulk dyeing reprocessing**,** which adds another **15–20 minutes** to the cycle.

In practice, the overall time impact of shade correction also includes waiting periods, machine scheduling, and handling delays associated with lab-to-bulk transitions. When these factors are considered, the total processing time extends to approximately **20–24 hours per batch**. This highlights the substantial time implications of shade correction compared to first-attempt dyeing in CDR processes.

6.4. CPB Dyeing Time:

Under standard conditions, the CPB dyeing process requires approximately **20 minutes**. when shade correction is required, the total processing time increases significantly due to multiple sequential stages and associated delays.

The shade correction process begins with laboratory recipe development and approval**,** which typically takes around **16 hours**. This is followed by the dyeing process**,** requiring approximately **20 minutes**. In addition, fabric rotation or batch fixation is necessary to accommodate machine scheduling and material handling, which may take another **16 hours**.

When combining lab work, dyeing, and rotation along with handling and waiting times between stages, the total delay is estimated to extend to approximately **2–3 days per batch**. This demonstrates that correction cycles in CPB dyeing substantially increase overall processing time compared to first-attempt dyeing, highlighting the importance of accurate shade matching for improved production efficiency.

6.5. Outcome Analysis

- All three dyeing methods—soft flow, CDR, and CPB—have significantly lower processing times under standard conditions compared to shade correction scenarios.
- Shade correction introduces additional stages such as lab analysis, recipe development, re-dyeing, and machine-related delays, which substantially increase total processing time.
- Among the methods analyzed, CPB dyeing experiences the highest delay during correction (approximately 2–3 days), followed by CDR (20–24 hours), and soft flow dyeing (15–20 hours per batch).
- The variation in time impact is primarily due to differences in process complexity, batching requirements, and machine utilization constraints.
- Achieving accurate shade in the first attempt is critical for minimizing reprocessing, reducing delays, and improving overall productivity and operational efficiency in textile wet processing.

7. Economic Impact and Cost-Benefit Analysis of Process Standardization

The main objective of this section is to evaluate both the financial and operational benefits achieved through process standardization in the reactive dyeing of cotton knitted fabrics. In textile wet processing, shade variation and reprocessing are major factors that increase production costs.

By improving the *Right First Time (RFT)* percentage and reducing shade variation, the consumption of dyes, chemical auxiliaries, and stripping agents can be significantly minimized. This study considers a standard batch size of 1,000 kg and uses average industrial chemical prices to compare the costs before and after process standardization.

A key factor in cost reduction is the proper control of the chemical environment, especially electrolytes and alkali used for dye exhaustion and fixation. In the initial (baseline) process, variations in fabric GSM and moisture content resulted in excessive use of Sodium Chloride (NaCl) and Sodium Carbonate. This overuse not only increased material costs but also raised Total Dissolved Solids (TDS) in wastewater, leading to higher treatment expenses.

The standardization of the pre-treatment to dyeing stage reduced the need for corrective chemicals. In the earlier process, residual peroxide from bleaching required high usage of peroxide killers. Similarly, inconsistent pH levels demanded additional acetic acid to maintain the required dye bath conditions. By ensuring a uniform fabric pH of 6.5 before dyeing and stabilizing water quality, the use of sequestering agents and pH regulators was reduced by approximately 12%.

Before standardization, the reprocessing rate was about 15%, mainly due to inconsistent finishing and poor pH control. This resulted in higher consumption of dyes (23 kg per 1,000 kg batch) and salt (575 kg), along with frequent use of oxalic acid for stripping. The total chemical cost under these conditions was ₹29,105 per batch.

After implementing standardized practices such as controlled steam compacting, optimized CPB squeezer pressure, and regulated reprocessed water pH, the reprocessing rate decreased to 6%. This improvement enhanced shade consistency and reduced material usage. Dye consumption decreased to 21 kg, salt usage to 525 kg, and oxalic acid usage reduced by more than 60% to only 3 kg per batch. As a result, the total chemical cost dropped to ₹25,895 per batch.

The comparative analysis shows a total cost saving of ₹3,210 per 1,000 kg of fabric, which is approximately ₹3.21 per kg. The major savings came from reduced dye costs (₹1,600) and optimized use of auxiliaries (₹1,160). In addition to direct cost savings, the reduction in reprocessing also led to indirect benefits such as lower water and energy consumption, reduced machine usage, and improved production efficiency. Overall, process standardization significantly improved both economic performance and operational reliability in reactive dyeing.

Parameter	**Baseline Condition (Before)**	**Optimized Process (After)**	**Net Savings (Reduction)**
Total Chemical Cost	₹29,105	₹25,895	**₹3,210 (11%) ↓**
Reactive Dye Cost	₹18,400	₹16,800	₹1,600 ↓
Auxiliaries & Salt	₹9,985	₹8,825	₹1,160 ↓
Reprocessing Chemicals	₹720	₹270	₹450 ↓
Reprocess Rate	**15%**	**6%**	**9% Absolute ↓**

Table 1: Comparative Analysis of Chemical Costs Before and After Standardization (Per 1,000 kg)

The results demonstrate that the systematic control of downstream finishing and pretreatment variables is not only a technical necessity for quality but a critical lever for cost minimization in knit dyeing. By shifting the focus from isolated parameter adjustments to a holistic standardization framework, manufacturers can achieve a sustainable reduction in chemical overheads while simultaneously boosting the first-pass acceptance rate.

7.8 Key Observations

7.8.1 Dye Cost Reduction

- Reduction in re-dyeing cycles lowered dye consumption
- Controlled ΔE reduced shade correction requirement

Savings: 8–10% in dye cost

7.8.2. Fixing Agent (zetesal) Optimization

- Proper fixation reduced reprocessing need
- Lower re-dye cycles → lower fixing agent usage

Savings: 15–20%

7.8.3 Setamol (Soaping Agent) Reduction

- Improved dye fixation reduced washing losses
- Less repeated soaping required

7.8.4 Oxalic Acid (Stripping) Reduction

- Major saving contributor
- Controlled reprocessing reduced chemical-intensive stripping

Savings: 60% in stripping chemical

7.8.5 Salt and Alkali Optimization

- Controlled dosing reduced excess usage
- Improved process control avoided wastage

7.9. Overall cost impact

Total chemical cost reduction:	₹3,000 – ₹3,500 per 1000 kg fabric
Cost saving per kg:	₹3 – ₹3.5/kg fabric

7.10. Technical Interpretation

The reduction in chemical cost is primarily attributed to:

- Decrease in reprocess rate (*15% → 5–8%*)
- Improved Right First Time (RFT) performance
- Controlled dye fixation and reduced hydrolysis
- Standardized auxiliary dosing
- Optimized post-dyeing processes

7.11 **Outcome Analysis**

Process standardization resulted in a chemical cost reduction of approximately ₹3–3.5 per kg of fabric, achieved through minimized reprocessing, optimized dye utilization, and controlled auxiliary consumption.

8. Inference

The results confirm that shade variation in knit dyeing is influenced not only by dyeing parameters but also significantly by finishing, pre-treatment uniformity, and reprocessing control.
Key inferences include:

1. Steam-based compacting has a measurable impact on ΔL* and perceived shade depth.
2. Uniform CPB squeezer pressure enhances dye uptake reproducibility.
3. Continuous CBR scouring reduces batch variation and process instability.
4. Controlled oxalic acid stripping improves reprocess success rate.
5. Fixing agents improve chroma stability and shade durability.
6. Maintaining reprocessed water pH ≤ 6.5 stabilizes hue parameters (ΔH*).

The integrated process standardization approach led to measurable reduction in ΔE and substantial enhancement in RFT performance, demonstrating that shade consistency requires holistic control across pre-treatment, dyeing, finishing, and reprocessing stages.

9. Conclusion

This study investigated the minimization of shade variation in reactive dyed cotton knitted fabrics through systematic process standardization across pre-treatment, dyeing, finishing, and reprocessing stages. Shade inconsistency, quantified using CIELAB parameters (ΔE, ΔL*, Δa*, Δb*, ΔC*, and ΔH*), was identified as a multidimensional issue influenced not only by dyeing variables but also by finishing conditions, absorbency uniformity, and reprocessing controls.

Root cause analysis revealed that variations in compacting conditions, CPB squeezer pressure, scouring route selection, reprocess water quality, and dye stripping practices significantly contributed to batch-to-batch and within-batch shade deviations. While conventional approaches focus primarily on dyeing parameter control, this research demonstrates that downstream process stages play an equally critical role in shade reproducibility.

The implementation of standardized control measures—including regulated Synpact steam compacting, optimized CPB squeezer pressure, predominant use of CBR-based scouring, controlled oxalic acid stripping for re-dyeing, application of zetesal and eco fixing agents, and maintenance of reprocessed water pH at ≤ 6.5—resulted in measurable improvements in shade stability.

Key outcomes of the study include:

- Significant reduction in average ΔE values
- Decreased variability in ΔL* and ΔH* components
- Improved chroma retention (ΔC* stability)
- Reduction in reprocessing percentage
- Substantial improvement in Right First Time (RFT) performance

The findings confirm that shade variation cannot be effectively minimized through isolated parameter adjustments. Instead, an integrated process standardization framework across the entire wet processing chain is essential for achieving consistent shade reproducibility.

From an industrial perspective, the improvement in RFT and reduction in reprocess cycles contribute directly to:

- Lower production cost
- Reduced water and energy consumption

- Improved delivery reliability
- Enhanced buyer confidence
- Increased overall process efficiency

This research establishes that systematic control of finishing and reprocessing variables, in conjunction with dyeing optimization, provides a sustainable and scalable solution for shade consistency in knit dyeing operations.

Future Scope

Future research may focus on:

- Application of Design of Experiments (DOE) for multi-variable optimization
- Real-time monitoring using IoT-based sensors for pH and temperature
- Predictive modeling of ΔE using statistical or machine learning techniques
- Integration of automated dosing and digital compacting control systems

Such advancements can further enhance shade reproducibility and move knit dyeing processes toward smart manufacturing and Industry 4.0 integration.

10. References

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