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Single bath two-step dyeing of 50/50 acrylic/cotton blends: an industrial scale investigation

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Although one-bath dyeing of acrylic/cotton blend fabrics has been investigated at laboratory scale, its industrial application remains poorly understood. This study provides mechanistic insights into dye-fibre interactions, pH and ionic effects, and efficiency limitations, defining the operational boundaries for industrial implementation. Laboratory-scale trials were conducted for one-bath two-step dyeing of acrylic/cotton blends, followed by industrial-scale trials. Results reveal that light- and medium-shade fabrics achieve satisfactory fastness and levelness, whereas dark shades exhibit substantial fastness deterioration under industrial conditions due primarily to uncontrolled dye interactions and insufficient reductive clearing. Experiments, performed by dyeing acrylic first and cotton second without draining the bath, gave successful results in light-medium shades, demonstrating the conditions under which one-bath two-step dyeing is feasible. These findings provide a framework for industrial process decision-making rather than a universally applicable dyeing method.

Key words: Acrylic/cotton, Cationic dye, Fastness, Industrial-scale dyeing, One-bath two-step dyeing

1 Introduction

Blending of textile fibres is carried out to achieve desired aesthetic effects, reduce production costs, and enhance the performance properties of the final textile products[1]. The term “blend” refers to a combination of two or more fibres with different physical or chemical characteristics[2]. Fibre blends are of considerable importance in the textile industry because they can provide properties that are unattainable with a single fibre type. However, blend dyeing is a complex process that requires careful consideration of fibre-dye interactions, dye class compatibility, and process conditions[3].

Among various blends, acrylic/cellulose combinations are particularly significant. The cellulose component contributes moisture absorption and antistatic properties, whereas acrylic provides thermal insulation, wrinkle resistance, and abrasion resistance, especially for outerwear applications. Acrylic/cotton blends are widely used in sportswear and leisure clothing, with yarns blended in ratios from 80:20 to 50:50. These blends are employed in light woven fabrics, dress fabrics, sportswear, knitted undergarments, and leisure wear[4].

Two primary methods are employed for dyeing fibre blends: one-bath and two-bath processes. In one-bath dyeing, both fibre types are dyed in the same bath, whereas in two-bath dyeing, each fibre type is dyed sequentially in separate baths. The one-bath method is applicable when the chosen dyes are compatible and have similar dyeing conditions, offering advantages such as reduced processing time, lower energy and water consumption, and decreased chemical usage. However, limitations include restricted dye selection and lower fastness, particularly for dark shades. In contrast, the two-bath method allows greater dye choice and higher fastness, albeit with longer processing time and higher cost[5].

Selecting dyes for acrylic/cellulose blends presents additional challenges. Disperse dyes exhibit poor build-up and limited fastness on acrylic fibres, necessitating the use of basic (cationic) dyes in most cases. The most economical approach for pale shades is a one-bath application of disperse and direct dyes. Cellulosic/acrylic blends can be dyed in pale to medium depths using a one-bath process with direct and basic (cationic) dyes, although there is a risk of co-precipitation between the two dye classes. Reactive dyes provide improved fastness for the cellulosic component, while bright, high wet-fastness shades typically require a combination of cationic

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dyes for acrylic and reactive dyes for cotton. Due to their instability under alkaline fixation, cationic dyes often require two-bath processes for dark shades[4].

Typically, acrylic fibres are dyed first with cationic dyes, followed by reactive dyeing of the cotton component. Among textile dyes, reactive dyes account for approximately 30-50% of the market. Cationic dyes, on the other hand, offer high brightness and colour intensity, even at low concentrations, making them suitable for acrylic fibres[6]. Despite the wide use of acrylic/cellulose blends, studies on their dyeing with cationic/reactive dye combinations are limited. Below, previous studies on the dyeing of acrylic/cellulose blends are summarized in chronological order.

Lee et al. investigated the staining of cotton by cationic dyes, the stability of cationic dyes, and the fastness properties under various conditions, in order to study the dyeing behaviour of acrylic/cotton blends with cationic and reactive dyes. Cationic oxazine dyes exhibited better stability compared with cationic azo dyes. Staining of cationic dyes on cotton increased gradually with pH and neutral salt concentration, but decreased with longer dyeing time and higher temperature[7].

Shokry et al. explored the achievement of union dyeing for knitted cotton/acrylic blend fabrics using a single cationic dye in one bath, following chemical treatment of the cotton with an anionic agent (tannic acid). The optimum dyeing conditions were determined as 4% dye concentration, 6 g/L Na_2SO_4, pH 6 at 90 °C for 75 minutes. The fastness properties of the dyed cotton/acrylic blended fabrics, treated with tannic acid and dyed with three different cationic dyes under the optimum conditions, were subsequently evaluated[8].

Islam et al. attempted to dye cotton/acrylic blend fabrics using a single-bath, single-stage method, taking into account the growing market for such blended products. Yarn-blended cotton/acrylic fabrics were produced and dyed at a 3% shade using indigo in the exhaust method, optimising the dyeing conditions by varying the amount of reducing agent, pH, and dyebath temperature. The optimum conditions were pH 6 and 120 °C for the acrylic component, and pH 11 and 90 °C for the cotton component. While yarn-blend fabrics exhibited a distinctive shadow-dyeing effect, solid dyeing was achieved with fibre-blend fabrics, highlighting the versatility of this single-bath, single-stage approach[9].

Soysal et al. examined three different approaches to dye acrylic/cellulose blends with a single dye: dyeing with cationic dyes following pre-treatment with an anionic polymer, dyeing with anionic dyes after performing cationization, and dyeing with natural dyes. The study demonstrated that pre-treatment with anionic or cationic agents could modify or improve the dyeability of both fibre components. However, because the dye uptake of both fibres changed simultaneously, achieving uniform solid colours was not possible. In contrast, marigold and pomegranate peel dyes successfully produced solid colouration on both fibre components in a single bath[10].

While one-bath dyeing of acrylic/cotton blends has been explored at laboratory scale and is employed in certain industrial practices, systematic studies that quantitatively evaluate both laboratory- and industrial-scale performance across multiple shades are scarce. In particular, the understanding of the effects of dye-fibre interactions, pH, and ionic conditions on the performance of one-bath two-step dyeing remains limited, especially at an industrial scale. The present study addresses this gap by performing controlled laboratory experiments followed by industrial-scale trials, quantifying colour yield, levelness, and fastness, and evaluating resource efficiency (water, energy, and chemical consumption). Based on these observations, the study interprets the influences of dye-fibre interactions and process parameters, and establishes operational boundaries for industrial implementation. By doing so, this work provides a data-driven framework for process optimisation, rather than merely confirming feasibility or proposing a universally applicable method, and highlights the limitations of one-bath two-step dyeing for dark shades in practical industrial settings.

2 Materials and Methods

In the present study, single-jersey fabrics composed of a 50/50% acrylic/cotton blend, spun from 30/1 ring yarn and pre-treated with a caustic soda-peroxide process, were used. Cationic and reactive dyes were selected for the acrylic and cotton components, respectively, as this combination is the most widely employed in industrial-scale applications due to its high wet and dry fastness properties. The study aimed to evaluate the feasibility of a one-bath, two-step dyeing process compared with conventional two-bath dyeing under both laboratory and industrial conditions.

2.1 Laboratory scale dyeing

Laboratory-scale dyeing trials were performed at a liquor ratio of 1:10, following a one-bath, two-step

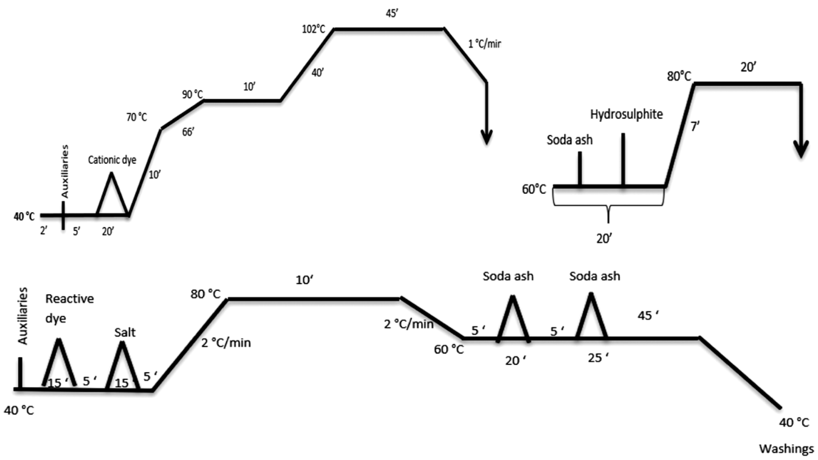


Fig. 1 — Dyeing profile for two bath dyeing

procedure, with conventional two-bath dyeing as the reference. The procedures for the two-bath and one-bath two-step dyeings are described below.

2.1.1 Two-Bath Dyeing: In the conventional two-bath process, the acrylic component was dyed first with a cationic dye, followed by an after-treatment, and subsequently the cotton component was dyed with a reactive dye. Initially, the dyebath contained 1 g/L sodium acetate and 0.5 g/L acetic acid at 40 °C, to which the cationic dye was added. The temperature was then raised to 70 °C at 2 °C/min and subsequently to 90 °C at 0.3 °C/min. Dyeing continued at 90 °C for 10 minutes, followed by a rise to 102 °C at 0.3 °C/min, maintained for 45 minutes. The bath was then cooled to 90 °C at 1 °C/min. Reductive clearing was performed twice at 80 °C for 20 minutes using 2 g/L soda ash and 3 g/L sodium hydrosulfite. Neutralisation of the fabric was achieved with 0.5 g/L acetic acid (80%) at 60 °C for 20 minutes.

In the second bath, 0.4 g/L sequestering agent and 1.5 g/L anti-creasing agent were added at 40 °C, followed by reactive dye addition within 15 minutes. Salt (50 g/L NaCl) was dosed incrementally over 15 minutes. The temperature was increased to 80 °C at 2 °C/min. After a 10-minute migration phase, the temperature was reduced to 60 °C, and soda ash was added in two portions over 50 minutes. Following 45 minutes, the liquor was drained, and sequential post-dyeing treatments were performed: overflow rinse (5 min at 50 °C), acid neutralisation (6 min at 50 °C), soapings (with 0.4 g/L washing agent at 90 °C for 8 min and at 80 °C for 8 min), followed by warm rinsings (6 min at 80 °C and 6 min at 70 °C) and cold rinsing (6 min). The dyeing profile of the two-bath process for dark shades is illustrated in Figure 1.

2.1.2 One-Bath, Two-Step Dyeing: Three variants of the one-bath, two-step dyeing were conducted to assess the influence of the dye addition sequence and salt/alkali dosing on dyeing performance:

- **Method I:** Following acrylic dyeing as described above, the bath temperature was reduced to 40 °C and the pH adjusted to 7 using soda ash. Cotton dyeing was then carried out directly, followed by standard post-dyeing treatments.
- **Method II:** After adding cationic dye, the pH was adjusted to 4.5 and acrylic dyeing procedure was applied, then cotton dyeing process was started by adding the salt and alkali simultaneously (all-in method).
- **Method III:** Acrylic and cotton dyes were added together at the start, with salt included and pH adjusted to 4.5. Acrylic dyeing was applied, followed by cotton dyeing, with soda ash addition at 60 °C.

Following the one-bath, two-step dyeing, the same sequence of post-dyeing treatments as applied in the two-bath process was performed, including overflow rinsing, acid neutralisation, soaping, and warm and cold rinses. The dyeing profile of the one-bath, two-step process is shown in Figure 2.

Upon completion of post-dyeing treatments for all methods, the dyed fabric was treated with a 5% cationic fixing agent at 60 °C for 30 minutes. The cationic fixing agent applied post-dyeing markedly enhances wet fastness of reactive dyes by electrostatically neutralising anionic sulpho groups and forming stable, water-insoluble polymer-dye complexes on the fibre surface. Complementary interactions, including hydrogen bonding, van der Waals forces, and hydrophobic effects, further

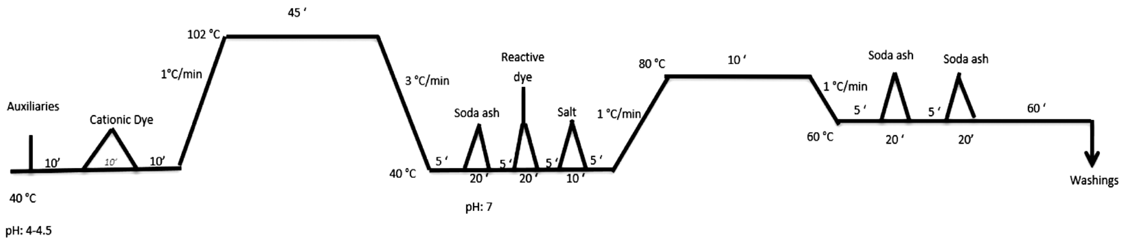


Fig. 2 — Dyeing profile for one bath dyeing

Table 1 — Dyeing recipes used for two-bath and one-bath two-step dyeing of acrylic/cotton blends in dark shades

	Black	Bordeaux
Acrylic	0.02% Setacryl Goldenyellow G	0.40% Setacryl Goldenyellow G
	0.02% Setacryl Red W-FBL	1% Setacryl Red W-FBL
	2.5% Setacryl Black FDL	0.17% Setacryl Blue W-FGRL
Cotton	0.15% Setazol Yellow SX	1% Setazol Yellow SX
	0.40% Setazol Red SX	1.6% Everzol Red ED-4B
	2.50% Setazol Black SNN	0.15% Sumifix Supra Blue BRF

Table 2 — Dyeing recipes used for two-bath and one-bath two-step dyeing of acrylic/cotton blends in light to medium shades

	Brick-colour	Pink	Blue
	0.09% Setacryl Golden Yellow GL	0.009% Setacryl Golden Yellow GL	0.024% Setacryl Golden Yellow GL
Acrylic	0.09% Setacryl Red W-FBL	0.090% Setacryl Red W-FBL	0.020% Setacryl Red W-FBL
	0.02% Setacryl Blue FGRL	0.006% Setacryl Blue FGRL	0.140% Setacryl Blue FGRL
	0.95% Avitera Gold SE	0.09% Avitera Gold SE	0.10% Avitera Gold SE
Cotton	0.72% Avitera Red SE	0.70% Avitera Red SE	0.20% Avitera Light Red SE
	0.063% Avitera Light Blue SE	0.01% Avitera Light Blue SE	0.80% Avitera Light Blue SE

reinforce dye fixation and reduce dye leaching. This dual action ensures improved fastness performance, particularly under washing and perspiration conditions, without compromising fibre integrity[11].

Laboratory-scale trials were initially conducted for two dark shades, black and bordeaux (Table 1). Dyeing recipes are given in Table 1.

Subsequently, light to medium shades such as brick, pink, and blue were dyed on the cotton component using trifunctional Avitera reactive dyes (Huntsman), selected for their industrial relevance and high wet fastness (Table 2). The dye concentrations and shade selections in Tables 1 and 2 were chosen to reflect industrial practice. Differences in dye proportions between shades, particularly for blue dyes, help explain the observed variations in colour yield and K/S values across the samples.

In the two-bath process, reductive clearing is applied twice to remove residual unfixed cationic dyes from acrylic fibres, ensuring uniform colouration and optimal wet fastness for subsequent cotton dyeing. In the one-bath, two-step process, however, reductive clearing was not applied because it is inherently incompatible with simultaneous or sequential cationic and reactive dyeing. Removing unfixed cationic dye from acrylic fibres would inevitably extract reactive dye from cotton.

2.2 Industrial Scale Dyeing

Industrial-scale trials were performed on 20 kg fabric samples dyed in black, bordeaux, and brick shades using the one-bath, two-step method (acrylic followed by cotton) in a jet dyeing machine (HT Thies), following the laboratory-scale procedures described above. Fabric circulation was maintained at 2 cycles/min. The colour yield (K/S) and CIE L*a*b* values of the dyed samples were measured, and total colour difference (ΔE) values were calculated. Levelness of dyeing was also evaluated. In addition, washing, rubbing, water and perspiration (acidic and alkali) fastness tests were performed on the samples.

Post-dyeing treatments included impregnation with 20 g/L cationic fixing agent on a foulard (pick-up 80%) and drying in a stenter at 120 °C. Additionally, a cost comparison between one-bath and two-bath methods for black dyeing was performed.

2.3 Determination of colour yield and CIEL*a*b* values

In order to determine the colour yield after dyeing, the reflectance (R%) values of samples were measured with spectro photometer (D 65/10°) in the spectral region of 400-700 nm. K/S values were calculated using the Kubelka-Munk equation:

$K/S = (1-R)^2 / 2R$

R: Reflectance value at maximum absorption wavelength
K: Absorption coefficient
S: Scattering coefficient
CIE L*a*b* C*h° values of the samples were also measured.
L*: Lightness/darkness value (100: ideal white, 0: ideal black)
a*: Redness/greenness value (+ redder, - greener)
b*: Yellowness/blueness value (+ more yellow, - more blue)
C*: Chroma
h: Hue

The total colour difference (ΔE) values of the dyeings were calculated according to the following formula;

$\Delta E = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}$

ΔL*: Lightness-darkness value difference
Δa*: difference in redness (+a*) - greenness (-a*)
Δb*: difference in yellowness (+b*) - blueness (-b*)

- Dyeing levelness: Levelness values (L) were calculated via colour efficiency values obtained from 30 different parts of the fabric by using the following equation[12]:

$$L = \left(1 - \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{\frac{K}{S}i}{\frac{K}{S}} - 1\right)^2}{n-1}}\right) \times 100 \quad (3)$$

L = Dyeing levelness (%) (L=100 indicates totally (100%) uniform dyeing, L=0 indicates totally uneven dyeing)
K/S = Colour yield
n = Number of measurements

2.4 Fastness tests

Washing, rubbing, perspiration (acidic and alkaline), water and light fastness tests were performed according to ISO 105-C06 (subvariant A1M)[13], ISO 105-X12[14], ISO 105-E04[15], ISO 105-E01[16]and ISO 105-B02[17], respectively.

2.5 Statistical evaluation

Statistical analysis of the colour yield (K/S) values was performed using Minitab 22 software. A general linear model (GLM) was applied to evaluate the effects of colour and dyeing method (one bath and two bath) on K/S values. Each experiment was conducted in triplicate. The analysis of variance (ANOVA) was used to test for significant differences among groups at a significance level of $p<0.05$. The ANOVA results, including degrees of freedom (DF), adjusted sum of squares (Adj SS), mean squares (Adj MS), F-values, and p-values, are presented in tables.

3 Results and Discussion

3.1 Results of laboratory scale dyeings

The effectiveness of the one-bath dyeing process can vary between dark and light-medium shades. Therefore, dark colours were examined first. For this purpose, PAC/CO blend fabrics were dyed in black (BL) and bordeaux (BO) using a cationic dye for the acrylic component and a reactive dye for the cotton component. Conventional two-bath dyeing (Reference: R) was applied as a control. Three one-bath, two-step variants were evaluated:

I. Acrylic dyeing followed by cotton dyeing (two-step method, coded as I);

II. Acrylic dyeing followed by cotton dyeing with all-in addition of salt and alkali (all-in method, coded as II);

III. Simultaneous addition of cationic and reactive dyes with salt, followed by cotton dyeing with alkali adjustment (coded as III).

Colour yield (K/S), CIE L*a*b*, and total colour difference (ΔE) values of the dyed fabrics are presented in Table 3, and photographic images of the samples are shown in Figure 3. To better interpret the observed differences in colour yield, statistical

Table 3 — Colour yield (K/S), CIE L*a*b* and total colour difference (ΔE) values of fabric samples dyed in dark shades

Sample	L*	a*	b*	ΔE	C*	h°	K/S
BLR	16.2	0.6	-1.3	-	1.4	293	25.7
BLI	17.5	0.7	-0.9	1.4	1.1	309	23.5
BLII	16.7	0.7	-0.7	0.8	1.0	317	25.6
BLIII	17.9	0.9	-0.7	1.9	1.1	325	25.4
BOR	23.1	28.3	9.4	-	29.8	18	31.0
BOI	24.7	29.3	9.9	2.0	30.9	19	27.3
BOII	25.9	30.4	9.8	3.5	31.6	18	25.1
BOIII	27.7	33.2	13.5	7.9	35.8	22.1	25.2

analysis was also performed. Table 4 presents the ANOVA results for colour yield (K/S) values of fabrics dyed in dark-shades.

The ANOVA results indicate that neither the colour nor the dyeing method had a statistically significant effect on the K/S values ($p > 0.05$), suggesting that differences in colour yield among the tested methods and shades are not significant under the applied conditions. Nevertheless, examination of the K/S values indicates that two-bath dyed samples are slightly darker than the one-bath dyed samples for both black and bordeaux shades. This reduction in colour yield in one-bath dyeing is likely due to interactions between anionic (reactive) and cationic (basic) dyes within the same bath, which can limit the dye absorption efficiency. Additionally, the subsequent dyeing of cotton after acrylic dyeing and reductive washing allows cotton to absorb reactive dyes more effectively, compensating for initial dye interactions.

Fig. 3 — Photographs of fabric samples dyed in dark shades

Figure 3 presents photographic images of the acrylic/cotton blend fabrics dyed in dark shades by two-bath and one-bath two-step methods. Visual inspection confirms the colourimetric data reported in Table 3. Fabrics dyed by the one-bath method appear slightly lighter, particularly for the bordeaux shade, which is consistent with their ΔE values. The a* and b* values of the samples increased in the order: two-bath < one-bath I < one-bath II < one-bath III, indicating a shift towards redder and more yellowish nuances in one-bath variants. Considering ΔE values, the two-step one-bath method (I) consistently gave the closest match to the two-bath reference, suggesting optimal dye sequence and reduced interference. Dyeing levelness was uniform across all samples.Washing and rubbing fastness values are given in Table 5.

The results show that one-bath two-step dyeing achieved comparable washing and rubbing fastness to conventional two-bath dyeing. Although a slight reduction in colour yield was observed, one-bath dyeing is considered feasible for industrial application, as it does not compromise fastness or levelness, and the small decrease in yield is acceptable given the savings in water, energy, and time.

Light to medium shades (brick, pink, and blue) were also investigated at laboratory scale. Conventional two-bath dyeing was applied, and one-bath, two-step dyeing of the acrylic followed by cotton component was performed using trifunctional reactive dyes. Colour yield (K/S), CIE L*a*b*, and ΔE values are presented in Table 6, along with sample images in Figure 4. To better interpret the observed differences in colour yield,

Table 4 — ANOVA results for colour yield (K/S) values of fabrics dyed in dark-shades by different methods

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Colour	1	8,820	8,820	2,10	0,243
Method	3	13,510	4,503	1,07	0,478
Error	3	12,590	4,197		
Total	7	34,920			

Table 5 — Washing and rubbing fastness values of fabric samples dyed in dark shades

Sample	Washing (Staining)						Rubbing	
	WO	PAC	PES	PA	CO	CA	Dry	Wet
BLR	3	4-5	4-5	3	4	3-4	4	3
BLI	3	4-5	4-5	2-3	4	3	4	3
BLII	3	4-5	4-5	2-3	4	3	4	3
BLIII	3	4-5	4-5	2-3	4	3	4	3
BOR	3	4-5	4-5	3	4	3	3-4	3
BOI	3	4-5	4-5	3	4	3	3-4	3
BOII	3	4-5	4-5	3	4	3	3-4	3
BOIII	3	4-5	4-5	3	4	3	3-4	3

Table 6 — Colour yield (K/S), CIE L*a*b* and total colour difference (ΔE) values of fabrics dyed in light to medium shades and their photographs

Sample	Photograph	L*	a*	b*	ΔE	C*	h°	K/S
BRAR		42.1	23.0	26.7	-	35.3	49	9.7
BRA		43.9	23.4	26.4	1.9	35.3	48	8.3
PAR		49.3	31.8	2.7	-	31.9	5	5.5
PA		49.3	31.8	2.4	0.4	31.9	4	5.5
BAR		34.9	-1.9	-17.1	-	17.2	264	6.7
BA		37.7	-2.1	-16.0	3.0	16.2	262	5.5

Table 7 — ANOVA results for colour yield (K/S) values of fabrics dyed in light to medium shades by different methods

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Colour	2	14,0133	7,0067	24,44	0,039
Method	1	1,1267	1,1267	3,93	0,186
Error	2	0,5733	0,2867		
Total	5	15,7133			

Fig. 4 — Photographs of fabric samples dyed in light to medium shades

statistical analysis was also performed. Table 7 presents the ANOVA results for colour yield (K/S) values of fabrics dyed in light to medium shades.

Examination of the K/S values in Table 6 shows that fabrics dyed using the two-bath method generally exhibit higher colour intensity, as reflected by lower L* values. However, ANOVA results indicate that the dyeing method did not significantly affect colour ($p > 0.05$), suggesting that the observed differences between one-bath and two-bath methods are not statistically meaningful under the tested conditions. Slight variations in a* and b* values between the methods indicate minor hue differences in addition to lightness changes.

As illustrated in Figure 4, these minor colourimetric differences are not visually perceptible for light to medium shades, supporting the industrial feasibility of the one-bath two-step process for such colour depths. Specifically, for the pink shade, ΔE values were below 1, which is within typical industrial acceptance thresholds, confirming that one-bath two-step dyeing produces a colour equivalent to the two-bath reference. Overall, while the one-bath, two-step process (first dyeing the acrylic component, then the cotton with trifunctional reactive dyes) yields slightly lower colour intensity than the conventional two-bath method, the marginal increase in dye usage is acceptable considering the substantial savings in processing time and water consumption. Among the three shades studied, the one-bath process was most effective for pink and least effective for blue. Inspection of the dye recipes (Table 2) shows that the blue component is highest in the blue shade and lowest in pink, indicating that the reduced colour yield in single-bath dyeing is primarily attributable to the blue dyes. Additionally, well-documented factors such as hydrolysis and aggregation of reactive blue dyes, as well as competitive interactions with cationic dyes in the mixed-bath system, may contribute to the observed effect. These aspects should be carefully considered when designing single-bath processes for recipes dominated by blue components. Washing and rubbing fastness values of light-medium shades are shown in Table 8.

Fastness results indicate that one-bath two-step dyeing achieves comparable performance to two-bath dyeing. Slightly higher wet rubbing fastness in one-bath samples is attributed to lighter colour shades rather than improved fixation, as lighter shades inherently exhibit better wet fastness. Overall, one-bath two-step dyeing provides satisfactory fastness across all shades.

3.2 Results of industrial scale dyeings

Following laboratory-scale trials, industrial-scale dyeing was performed on PAC/CO blend fabrics in black, bordeaux, and brick shades, using both

Table 8 — Washing and rubbing fastness values of fabric samples dyed in light to medium shades

	Washing (Staining)						Rubbing	
Sample	WO	PAC	PES	PA	CO	CA	Dry	Wet
BRAR	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3
BRA	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3-4
PAR	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3
PA	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3-4
BAR	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3-4
BA	4-5	4-5	4-5	4-5	4-5	4-5	4-5	4

Table 9 — Colour yield (K/S), CIE L*a*b*, total colour difference (ΔE) and levelness (%) values of dyed fabric samples under operating conditions and photographs of dyed fabric samples

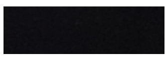
Sample	Photo	L*	a*	b*	ΔE	C*	h°	K/S	Levelness (%)
BLR		14.9	-0.8	-2.6	-	2.7	254	28.4	98,74
BLO		16.1	-0.6	1.3	4.1	1.5	116	26.2	99,29
BOR		22.6	29.3	10.7	-	31.1	20	34.1	99,22
BOO		23.4	29.4	12.3	1.7	31.9	23	31.2	97,83
BRR		43.7	23.4	27.9	-	36.4	50	9.0	99,02
BRO		44.3	23.2	27.4	0.8	35.9	50	8.4	98,96

Table 10 — ANOVA results for colour yield (K/S) values of dyed fabrics under operating conditions

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Colour	2	632,123	316,062	454,76	0,002
Method	1	5,415	5,415	7,79	0,108
Error	2	1,390	0,695		
Total	5	638,928			

conventional two-bath dyeing (Reference: R) and one-bath, two-step dyeing (O). Colour yield (K/S), CIE L*a*b*, ΔE values, and sample photographs are presented in Table 9. To better interpret the observed differences in colour yield under the studied operating conditions, statistical analysis was also performed. Table 10 presents the ANOVA results for colour yield (K/S) values of dyed fabrics.

The ANOVA results show that the fabric colour had a statistically significant effect on K/S values ($p<0.05$), while the dyeing method did not ($p>0.05$). This indicates that variations in colour yield are primarily driven by the shade itself rather than the dyeing process used under the applied operating conditions. Nevertheless, even though the effect of the dyeing method is not statistically significant, small practical differences between one-bath and two-bath dyed fabrics are still observable. K/S values indicate that two-bath dyed fabrics are consistently darker, with correspondingly lower L* values. Differences in a* values were minor, whereas b* values were higher in one-bath dyed dark shades, indicating a slightly more yellowish nuance. ΔE values for medium shades (brick) remained below 1, consistent with standard perceptibility limits used in industrial practice. Therefore, the colour differences between one-bath and two-bath dyed fabrics are visually negligible and acceptable for commercial applications. For dark shades, ΔE differences were more pronounced. However, these can be mitigated by recipe adjustments. Although such adjustments may slightly increase dye consumption, the resulting time and water savings compensate for the additional cost, particularly considering environmental benefits.

The levelness values of the dyed fabrics, presented in Table 9, were consistently high across all shades, ranging from 97.83% to 99.29%. These results indicate excellent uniformity in colour distribution, both within and across fabric lengths and widths. Visual inspection confirmed this observation, as no streaks, bands, or other signs of uneven dyeing were detected. It is well established that the human eye cannot easily detect shade differences smaller than 4%[18] and the observed variations in levelness are

Table 11 — Washing, rubbing and light fastness values of industrial scale dyed fabric samples

Sample	Washing (Staining)						Rubbing		Light
	WO	PAC	PES	PA	CO	CA	Dry	Wet	
BLR	4-5	4-5	4-5	3	4	4	4-5	3	4
BLO	2	4	3-4	1-2	2-3	2	4-5	3	3
BOR	2-3	4-5	4-5	3	3	3	4	2-3	4
BOO	2	4-5	4-5	2	2-3	2-3	4	2-3	3-4
BRR	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3-4	4
BRO	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3-4	4

Table 12 — Water fastness values of industrial scale dyed fabric samples

Sample	WO	PAC	PES	PA	CO	CA
BLR	4	4-5	4-5	3-4	4	3-4
BLO	1	2-3	2-3	1	1-2	1
BOR	4	4-5	4-5	4-5	4	3-4
BOO	2	4	4	2-3	3	2
BRR	4-5	4-5	4-5	4-5	4-5	4-5
BRO	4-5	4-5	4-5	4-5	4-5	4-5

Table 13 — Acidic perspiration fastness values of industrial scale dyed fabric samples

Sample	WO	PAC	PES	PA	CO	CA
BLR	2	3-4	4	2	3	2-3
BLO	1	2-3	2-3	1	1-2	1
BOR	2-3	4	4-5	3-4	4	3
BOO	1-2	3-4	4	2	3	1-2
BRR	4-5	4-5	4-5	4-5	4-5	4-5
BRO	4-5	4-5	4-5	4-5	4-5	4-5

Table 14 — Alkali perspiration fastness values of industrial scale dyed fabric samples

Sample	WO	PAC	PES	PA	CO	CA
BLR	2	3-4	4	2-3	3	2-3
BLO	1	2-3	2-3	1	1-2	1
BOR	2-3	4	4-5	3-4	3-4	3
BOO	1-2	3-4	4	2	3	1-2
BRR	4-5	4-5	4-5	4-5	4-5	4-5
BRO	4-5	4-5	4-5	4-5	4-5	4-5

below this threshold. Therefore, the uniformity achieved in the dyed samples can be considered fully acceptable for industrial applications. Fastness test results are provided in Tables 11-14.

Fastness analysis shows that one-bath dyeing of dark shades exhibits slightly lower performance compared with two-bath dyeing, especially in wet fastness, due to the absence of reductive clearing between acrylic and cotton dyeing steps. In two-bath processes, residual unfixed dyes on the acrylic surface are removed before cotton dyeing, improving wet fastness. Fastness values for medium shades (brick) were comparable between one- and two-bath methods. Fastness deterioration observed in dark shades during industrial-scale one-bath dyeing is attributed to enhanced bath circulation and greater fibre exposure, which increase the migration of unfixed cationic dyes on acrylic surfaces prior to cotton dyeing. Differences between laboratory- and industrial-scale results can be explained by these scale-dependent process factors. Despite the slight fastness reduction for dark shades, one-bath dyeing of light-medium shades remains effective, offering significant savings in water, energy, and chemical usage.

For black and bordeaux shades, samples dyed by the one-bath two-step method exhibited slightly lower light fastness ratings compared to their two-bath counterparts. This difference is primarily attributed to the higher lightness (L*) values of the one-bath dyed samples, indicating lighter colour shades. It is well established that lighter shades generally show lower apparent light fastness due to reduced dye concentration on the fibre surface. Therefore, the

Table 15 — A cost comparison of one- and two-bath methods for black colour dyeing

Method	Time (h)	Electricity (kwh)	Natural Gas (sm³)	Water (L)
Two bath	13.15	144.65	6.25	1710
One bath-two step	8.9	97.9	4.588	1140
Saving (%)	47.75	47.75	36.14	50.00

observed decrease in light fastness for dark shades dyed by the one-bath method is related to shade depth rather than an inherent deficiency of the dyeing process itself. In contrast, for the brick shade, the one-bath and two-bath dyed fabrics exhibited very similar colour depth and tone, as evidenced by close K/S values and an acceptable total colour difference (ΔE = 0.8). Consequently, both dyeing methods resulted in identical light fastness ratings (Grade 4). This confirms that when comparable shade depth and colourimetric properties are achieved, the light fastness performance of one-bath two-step dyeing is equivalent to that of the conventional two-bath process. These results further support the applicability of the one-bath two-step method for light to medium shades under industrial conditions.

A cost analysis was performed for black shade dyeing, as it represents the darkest and most resource-intensive shade and serves as a representative example to illustrate potential savings (Table 15).

The analysis shows reductions in electricity, natural gas, and water consumption of 47.75, 47.75, 36.14 and 50.00, respectively, for black shade dyeing under the conditions studied. While these values may differ for other shades or process conditions, they illustrate the potential for operational and environmental savings in the specific scenario examined.

4 Conclusion

Within the scope of this study, one-bath, two-step dyeing of acrylic/cotton blended fabrics was investigated at both laboratory and industrial scales. Laboratory-scale trials, in which the acrylic component was dyed first followed by the cotton component without draining the bath, demonstrated satisfactory fastness and uniformity for light-medium shades, with only a minor reduction in colour yield. Industrial-scale trials confirmed these results for light-medium shades but revealed notable fastness limitations for dark shades, highlighting practical constraints for large-scale implementation. The study also provides a quantitative assessment of resource savings, including reductions in water, energy, and chemical consumption. Overall, the findings establish operational boundaries for industrial application of one-bath two-step dyeing, offering a data-supported basis for process selection and optimisation, while recognising that dark shades are better processed using conventional two-bath methods to ensure optimal colour yield and fastness.

Based on these findings, one-bath, two-step dyeing is recommended only for light- and medium-shade PAC/CO blended fabrics to achieve satisfactory fastness and levelness, while also realising cost and resource efficiencies. Dark shades are unsuitable for industrial-scale application with this method and should be dyed using conventional two-bath processes to ensure optimal colour yield and fastness. The study thus defines the operational boundaries of one-bath two-step dyeing rather than presenting it as a universally applicable solution. Furthermore, it is important to note that the results obtained in this study are valid specifically for 50/50 acrylic/cotton fabrics. Future work could extend these findings to other blend ratios to further assess the generality of the observed dyeing mechanisms and industrial applicability.

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