

FULL PAPER

Textile dyeing with *Indigofera tinctoria*-derived dye: Exploring eco-friendly processes and expanding the colour spectrum

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Abstract

The use of natural dyes has become increasingly important as a result of their lower environmental impact and health benefits. However, developing eco-friendly dyeing processes and auxiliary products that maintain high chromatic quality remains a challenge. Natural indigo dye exemplifies this issue, as traditional industrial reduction methods using agents such as sodium dithionite are associated with significant environmental pollution. This study explored the application of fructose as a sustainable reducing agent for dyeing cotton fabrics with indigo extracted from the *Indigofera tinctoria* plant, adapting an artisanal process to industrial equipment. The most effective method involved a single-stage vat dyeing process conducted at 60°C for 60 minutes, using a 1-2-3 formulation. Results indicated that fructose emerges as an effective and environmentally friendly alternative in an industrial process compared with conventional toxic reducing agents. The study also evaluated the effect of different non-toxic auxiliary products and mordanting techniques. Pre-mordanted samples exhibited more saturated colours than post-mordanted; however, wash fastness results were lower. For example, gallnut used in the pre-mordanting process produced dark tones but showed noticeable colour change after washing, while post-mordanted samples achieved higher wash fastness. The integration of diverse auxiliaries in separate dyeing processes expanded the colour spectrum beyond the conventional blue typically associated with indigo dye, introducing a range of unique shades and hues. This study contributes to the recovery of traditional knowledge, incorporating more environmentally friendly products and adapting them to industrial equipment, while exploring a diverse chromatic palette. Such innovation supports fashion designers in creating distinctive and environmentally responsible collections.

1 | INTRODUCTION

The increasing emphasis on sustainable practices in the textile and fashion industry has underscored the significance of natural dyes due to their connection to reduced environmental impact and improved health considerations.¹ The dyeing and finishing processes

within the textile industry are notorious for their high consumption of water, energy and chemicals, leading to considerable environmental pollution.^{2,3} Furthermore, many of the products used in synthetic textile dyeing are identified as potential causes of dermatological pathologies,⁴ especially in children with sensitive or atopic skin.⁵

Natural dyes, derived from renewable resources, present a promising solution to these concerns by minimising the use of toxic substances and reducing the ecological footprint of textile production.⁶ Moreover, natural dyes can exhibit several health benefits.⁷ Ongoing research and technological advancements are creating opportunities for the development of more effective and sustainable natural dyeing processes. However, finding alternative dyeing processes and auxiliary products that align with eco-friendly principles while ensuring chromatic qualities remains challenging.⁸ The natural dye indigo, widely recognised as a blue vat dye, is one example of this challenge.⁹ Unlike most natural dyes, indigo is a vat dye, and its chemical structure makes it compatible with all natural fibres, with its largest constituent being indigotin.¹⁰

To acquire colouring capacity and become soluble, it must be in its reduced (oxygen-free) form. The reduced form of indigo is soluble in water and is called leuco-indigo.¹¹ The insolubility of indigotin makes indigo resistant to acids and bases, as well as washing and friction.^{10,12} Even so, to obtain adequate fastness to the demands of the textile industry, traditional industrial reduction processes of indigo dyes often involve the use of chemical reducing agents such as sodium dithionite, which is also known as sodium hydrosulphite ($\text{Na}_2\text{S}_2\text{O}_4$).¹³ This product has been associated with environmental pollution due to the production of harmful by-products that contaminate wastewater. This can harm ecosystems and lead to adverse health consequences.^{14,15} Because of these issues, researchers are looking for better, more eco-friendly ways to reduce indigo. Two promising alternatives are using bacteria to naturally reduce the dye or applying electrochemical methods instead of harmful chemicals.¹⁴ Moreover, organic reducing agents have been explored as possible alternatives to synthetic agents, because the use of bio-based products is also present in artisanal processes.^{16,17}

Apart from the environmental and health concerns related to the reducing agents in indigo dye and issues about colour fastness, an additional challenge emphasised is the necessity for heightened focus on the procedure. This is due to the numerous variables and stages involved, resulting in a dyeing process that is both time-consuming and requires a lot of auxiliary products.¹¹ According to Maulik et al.,¹⁵ the application of vat dyes in the textile industry often involves five basic steps (Figure 1).

The first step is dye dispersion, where the dyestuff is mixed with an anionic surfactant and cold water, followed by hot water at the recommended temperature. Soft or softened water, with low concentrations of dissolved minerals such as calcium and magnesium ions, is essential for the stock vat and dyebath. Sequestering agents may be necessary to convert hard water into soft water. The next step is to reduce the vat dye, for which sodium dithionite

is typically used as a reducing agent under specific conditions for different classes of vat dyes. Careful monitoring of dyebath stability, temperature and aeration is necessary to ensure adequate reduction. The quantities of auxiliary products in the bath must be sufficient to maintain the dye in its soluble form, while also taking care not to over-reduce the dye, which can lead to irreversible changes in the dye structure. The third step is dyeing, where the leuco compound from the vat dye adsorbed onto the fibre surface and diffuses into the interior during dyeing. Auxiliary products such as sodium hydroxide and sodium dithionite are used again to deoxygenate the bath. Salts and wetting agents are also used to improve dye penetration and dyeing uniformity. In the fourth step, the dye is applied in a soluble and reduced form to impregnate textile fibres and then oxidised to convert it back into its original insoluble state. Prior to air or chemical oxidation, the products are rinsed to remove excess dye. The oxidising agent used, such as sodium perborate or hydrogen peroxide, may vary depending on factors such as time, cost, depth of desired shade, rinsing efficiency and process time. The final phase is after-treatment, which involves boiling the textile with soaping agents.

In artisanal dyeing processes, the quantity of products used is reduced, but both the bath volume and time required must be increased. One common method involves preparing an organic reduction bath, which uses only two additional ingredients besides the dye: an alkali and a reducing agent (such as sugar, fruit, plants or iron).¹⁷ According to Mohtashim et al.,¹⁸ fructose proved to be the most promising reducing sugar compared with the other sugar options. Because the entire process is conducted manually in a pan, several precautions must be observed.¹⁷ Stirring should be kept to a minimum to prevent oxygen from entering the bath, as exposure to air during dyeing can cause the leuco dye to oxidise prematurely, leading to deposits on the fibre surface.¹³ Temperature and time require careful monitoring, but due to the process being performed manually, it is challenging to replicate samples.¹⁷

The temperature and duration of the dyeing process vary depending on the method used. A higher temperature during the reduction phase is usually recommended, as it improves colour strength.¹⁹ However, while high temperatures are favoured for dye reduction, lower temperatures during the dyeing phase improve the affinity of indigo dye, leading to greater colour depth.²⁰ This explains why some processes use a two-step approach: high temperatures for reduction and lower temperatures for dyeing.

This research aims to develop a sustainable approach to cotton knit dyeing by utilising fructose as an eco-friendly reducing agent for indigo dye derived from the *Indigofera tinctoria* plant. The study proposes the adaptation of a

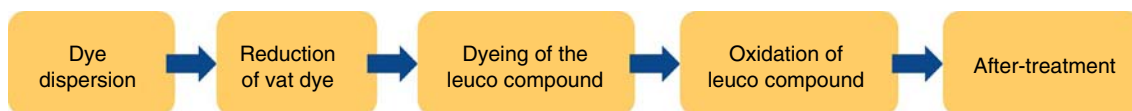


FIGURE 1 Five basic stages of the conventional industrial vat dyeing process. [Correction added on 05 August 2025, after first online publication: Figure 1 has been updated in this version.]

traditional dyeing technique for industrial equipment, combining indigo with non-toxic auxiliary agents to improve the process. These products will be applied through the three mordant methods: pre-, post- and meta-mordanting. Pre-mordanting is performed before dyeing where a bath is used for applying the auxiliary agent (mordant). In post-mordanting, the process is reversed, with dyeing performed first, followed by mordanting. In meta-mordanting, the mordant and the dye are applied together in a single bath.²¹ Key objectives include evaluating the colour strength and fastness of the dyed fabrics, exploring a broader spectrum of shades beyond the conventional blue and integrating environmentally friendly methods into industrial practices. By merging traditional knowledge with sustainable innovations, the contribution of this research is the introduction of a greener alternative to the toxic reducing agents typically used in industrial indigo dyeing and the expansion of indigo chromatic possibilities for textile and fashion design.

2 | MATERIALS AND METHODS

2.1 | Materials

Indigo dye extracted from the *Indigofera tinctoria* plant, and the bio-mordants myrobalan extract from the *Terminalia chebula* plant, quebracho extracted from *Schinopsis lorentzii* and gallnut extracted from oak gall, were provided by NIG Nahrungs-Ingenieurtechnik GmbH. The pomegranate bio-mordant extracted from *Punica granatum* peels was provided by Aquitex.

Fructose and calcium hydroxide ($\text{Ca}(\text{OH})_2$) were supplied by Merck Millipore; aluminium-potassium sulphate 12-hydrate ($\text{AlK}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$) was acquired from Pan-reac Química SLU; iron sulphate (FeSO_4) and aluminium acetate ($\text{C}_6\text{H}_9\text{AlO}_6$) were obtained from Green'ing-Ingrédients naturels & services. Finally, 100% cotton knit fabrics were supplied by NGS Malhas Co.

2.2 | Methods

2.2.1 | Dyeing processes

The dyeing processes phase was divided into two distinct stages. In the first stage, cotton knit fabrics were dyed

using an artisanal process for vat dyes adapted to the IBELUS IL-720 equipment, which requires fructose as a reducing agent. In the artisanal process, a 1-2-3 fructose vat is commonly used.²² This process consists of using one part natural indigo dye, two parts calcium hydroxide and three parts fructose in a pan of water. This study explored the adaptation of a 1-2-3 fructose vat to industrial equipment for an exhaust dyeing process.

Initially, the samples were washed with 1 g/L of SDC-2408 ECE Non-Phosphate Detergent (A) to remove any existing impurities. After washing, the dyeing processes started with pre-wetting samples, followed by dyeing and reduction using the artisanal 1-2-3 method. The dyeing process involved indigo concentrations of 2%, 3%, 4% and 5% (based on the weight of fibre). The process also included double the amount of calcium hydroxide and triple the amount of fructose, using a bath ratio of 1:20. An initial study with cotton fabric was conducted to test various dyebath temperatures.

Because some authors recommend a high temperature for the dye reduction process and a lower temperature for the dyeing process,^{19,20} this study tested a method where the bath temperature was maintained at 70°C for 15 minutes during the reduction phase. Two conditions were evaluated: one with the bath left at rest in a heating plate without agitation and the other using the IBELUS exhaust process. After reduction, the temperature was lowered to 30°C, and the fabric was immersed in the bath for 60 minutes in the IBELUS exhaust dyeing process (Figure 2).

Next, a combined reduction and dyeing process was tested in a single stage. In the first approach, the dyebath was maintained at 30°C for 60 minutes. In the second approach, the dyeing process began at 30°C, with the temperature gradually increasing to 60°C at a rate of 2°C per minute. The final temperature was then maintained for either 30 or 60 minutes (Figure 3). After dyeing and reduction, the samples underwent open-air oxidation, without any auxiliary product, and were rinsed in running water at room temperature. After the rinsing step, the fabrics were left to dry at room temperature. Differences in dyeing time and dye concentrations were explored.

The second stage of this phase explored the combination of the indigo dyeing process with seven non-toxic auxiliary products as mordants: alum, iron sulphate, aluminium acetate, pomegranate, myrobalan, quebracho

and gallnut. A single indigo dye concentration of 4% was chosen, and a dyeing duration of 60 minutes at 60°C was established to evaluate the application of the selected mordants using the three mordanting processes: pre-, meta- and post-mordanting. At this stage, the effect of the mordants used and the mordant methods applied were studied. The chromatic and fastness properties of the dyed samples were also explored. All dyed samples were prepared in triplicate.

2.2.2 | Wash fastness tests and colour evaluations

Wash fastness tests were performed using Washtec-P equipment in accordance with the NP EN ISO 105-C06 standard, A1S test. The fabric was stitched together with a multi-fibre fabric and then placed in a mixture of 4 g/L SDC-2408 ECE Non-Phosphate Detergent (A) at a liquor

volume of 150 mL and with the use of 10 steel balls. The samples were mechanically stirred at 40°C for 30 minutes. Following the washing process, all samples were thoroughly rinsed and air-dried at room temperature.

Textile colour changes were evaluated using instrumental analysis to ensure precision and consistency. The colour of both washed and unwashed fabric samples were analysed using a Datacolor International SF600 Plus—CT spectrophotometer, integrated with Datacolor TOOLS software. The analysis was performed under standardised conditions, using the D65 illuminant (representing daylight conditions) and a 10° standard observer to simulate human colour perception. Measurements were taken in three different areas of each fabric sample to account for potential variations. An average of these values was calculated, and the results were only accepted if the ΔE^* between the individual measurements was less than 1. To focus on the impact of washing, only colour change was assessed, while staining was excluded from the evaluation. Colour changes were determined based on the recorded colorimetric data, and the wash fastness assessment was expressed using a greyscale rating system. This system assigns ratings from 1 to 5, where 1 indicates poor fastness and 5 indicates excellent fastness. Additionally, colour fastness results were interpreted using CIELab colour difference (ΔE^*) values.

3 | RESULTS AND DISCUSSION

3.1 | Indigo dyeing analyses

The initial stage of the study was crucial for determining the appropriate dyeing process and the percentage of dye to be used in subsequent experiments involving the combination of indigo with different auxiliary products.

Dyeing processes, where reduction and dyeing were conducted in separate stages, did not produce satisfactory

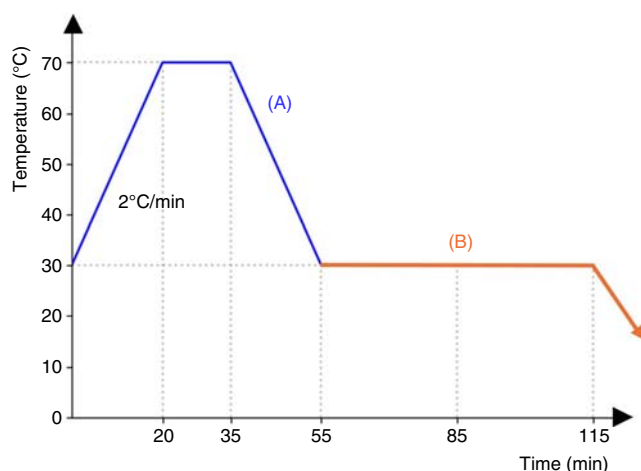


FIGURE 2 Stages of the indigo dyeing processes: A, Reduction, and B, Dyeing.

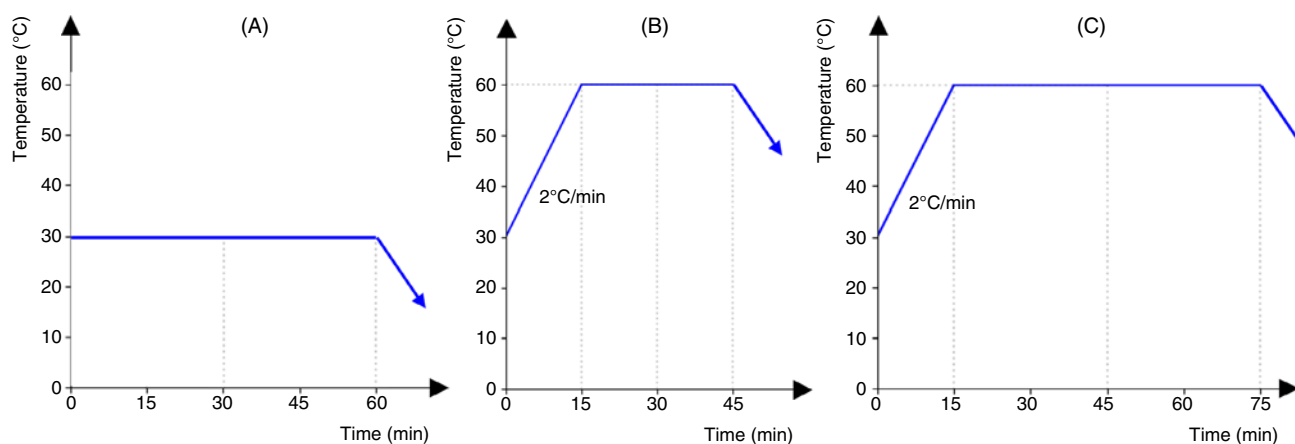


FIGURE 3 Variations in dyeing processes: A, 60 minutes at 30°C, B, 30 minutes at 60°C, and C, 60 minutes at 60°C.

results. The fabric showed staining, possibly indicating incomplete dye reduction and ineffective dye uptake (Table 1).

In the process where reduction and dyeing were performed in a single stage (Table 2), the 60-minute process

TABLE 1 Results of fabrics dyed with 4% natural indigo dye for different temperatures of dyebath and different dyeing processes.

Time and temperature	4% indigo dye	
	Total dyeing process at IBELUS	Resting bath reduction process
Reduction: 15 min at 70°C + dyeing: 60 min at 30°C		

at 30°C produced similar results to those presented previously. Increasing the temperature from 30 to 60°C led to improved results. Colour intensity was found to be

TABLE 4 Colour difference effect of one or two washing cycles of samples dyed with 4% and 5% natural indigo at 60°C for 60 minutes.

% of indigo dye	Samples		Colour change between cycles
	1 washing cycle	2 washing cycles	
4			4-5
5			5

TABLE 2 Results of fabrics dyed at different bath temperatures and natural indigo concentrations for 30 or 60 minutes of dyebath using the adapted dyeing process at IBELUS.

Indigo dye concentration				
Time at 30°C		4%		
60 min				
Time at 60°C		2%	3%	4%
30 min				
60 min				

TABLE 3 Colour coordinates and CIELab differences of samples dyed with 4% and 5% of natural indigo for 60 minutes, both unwashed and washed.

Sample	% of indigo	L^*	a^*	b^*	C^*	h	ΔE^*	Wash fastness colour change
Unwashed	4	63.0	−4.9	−10.8	11.9	245	4.0	3
Washed		66.6	−4.5	−12.5	13.2	250		
Unwashed	5	58.9	−6.1	−12.0	13.5	243	4.6	2-3
Washed		62.6	−4.7	−14.2	15.0	252		

TABLE 5 Effect of auxiliary products and mordanting methods on fabric dyed with 4% natural indigo according to the 1-2-3 dyeing process.

4% indigo dye						
	15% alum	1% iron sulphate	8% aluminium acetate	15% pomegranate	15% myrobalan	15% quebracho
Pre-mordanting						
						
						
Meta-mordanting						
Post-mordanting						

superior on fabrics dyed in a dyeing process of 60 minutes compared with 30 minutes. However, only at dye concentrations of 4% and 5% over a 60-minute bath time was the indigo effectively reduced and able to bind to the fibre, resulting in better uniformity and a more intense blue colour.

The following research analysis was conducted with samples developed by the one-stage reduction and dyeing process during 60 minutes at 60°C. As expected, increasing the concentration of indigo to 5% resulted in deeper and more vibrant colours. This is indicated by lower L^* values and lower negative b^* values, corresponding to darker and bluer colours, compared with samples with 4%. However, the higher concentration also displays slightly poorer wash fastness, with greater ΔE^* values and thus a lower fastness rating. Overall, although dyeing with 5% indigo initially provides a deeper colour, the difference diminishes significantly after the first wash. After washing, the colour of the 5% samples resembles that of the 4% indigo samples, indicating that the additional 1% dye concentration does not substantially improve long-term colour intensity (Table 3).

It was also possible to observe that the b^* (yellow-blue axis) becomes slightly more negative and that chroma

(C^*) values, which indicate colour intensity, increase slightly after washing for both concentrations, suggesting a deeper blue hue vibrancy in washed samples. The hue angle (h) shows minor increases after washing, implying a slight shift in the perceived colour tone.

The results in Table 4 show that, after two washing cycles, the colour change between washes was minimal. The ratings for the 4% and 5% indigo-dyed samples were 4-5 and 5, respectively, indicating very slight or no perceptible colour difference. This suggests that two washing cycles increase colour stability by removing excess dye from the fabric surface during the first washing cycle. Therefore, incorporating a final wash in the dyeing process may be advantageous.

3.2 | Exploration of auxiliary products

The second stage of the experimental work was conducted to analyse combinations of indigo with seven auxiliary products selected as mordants. The concentration of indigo dye used in these experiments was set at 4% (Table 5). The percentages used for mordants were

TABLE 6 CIELab differences of samples dyed with 4% natural indigo according to pre-, meta- and post-mordanting with different mordants.

Sample	Mordanting process	L^*	a^*	b^*	C^*	h
Indigo + alum	Pre-	59.6	-5.6	-13.7	14.8	248
	Meta-	69.5	-2.5	-5.7	6.3	246
	Post-	62.2	-4.7	-12.0	12.9	249
Indigo + iron sulphate	Pre-	59.2	-5.5	-11.6	12.8	245
	Meta-	63.3	-6.3	-7.2	9.6	229
	Post-	59.8	-6.5	-2.5	6.9	201
Indigo + aluminium acetate	Pre-	67.4	-5.3	-7.6	9.3	235
	Meta-	-	-	-	-	-
	Post-	62.4	-5.6	-10.7	12.1	243
Indigo + pomegranate	Pre-	55.1	-5.6	11.1	12.4	117
	Meta-	77.2	-0.7	8.8	8.8	95
	Post-	63.3	-4.2	5.0	6.5	130
Indigo + myrobalan	Pre-	53.6	-4.5	10.0	11.1	114
	Meta-	81.6	-0.6	7.6	7.6	94
	Post-	56.4	-5.2	5.6	7.6	133
Indigo + quebracho	Pre-	52.7	-1.4	0.3	1.4	170
	Meta-	76.6	-3.9	-2.8	4.8	216
	Post-	56.4	-3.4	-2.4	4.2	215
Indigo + gallnut	Pre-	55.9	-6.6	9.2	11.3	126
	Meta-	71.9	0.1	21.8	21.8	90
	Post-	60.1	-5.4	-7.7	9.4	235

TABLE 7 Wash fastness of samples dyed with 4% natural indigo and diverse auxiliary products according to the 1-2-3 dyeing process. [Correction added on 05 August 2025, after first online publication: Table 7 has been updated in this version.]

4% indigo dye									
		15% alum	1% iron sulphate	15% pomegranate	15% myrobalan	15% quebracho	15% gallnut		
Pre-mordanting	Unwashed								
	Washed								
ΔE^*		6.5	7.3	17.2	18.7	6.9	19.8		
Colour change		2	2	1	1	2	1		
Meta-mordanting	Unwashed								
	Washed	-		-	-	-			
ΔE^*			7.3				21.7		
Colour change			2				1		

TABLE 7 (Continued)

4% indigo dye		15% alum	1% iron sulphate	15% pomegranate	15% myrobalan	15% quebracho	15% gallnut
Post-mordanting	Unwashed						
	Washed						
ΔE^*		5.1	3.2	8.8	12.6	5.5	3.8
Colour change		2-3	4-5	1-2	1	2-3	3

carefully selected based on their effectiveness and environmental impact: 15% for bio-mordants to ensure sufficient dye fixation, 8% for aluminium acetate due to its efficacy as a mordant at lower concentrations and 1% for iron sulphate to minimise its environmental footprint and avoid adverse health effects.¹⁷

Alum mordanting improves the blue tone of indigo, with pre-mordanting achieving the deepest and most saturated blue shades. Iron sulphate consistently darkens the indigo tone, with pre-mordanting and post-mordanting resulting in darker shades compared with meta-mordanting. On the other hand, aluminium acetate showed little uniformity in all mordanting processes and did not obtain satisfactory results.

Myrobalan and pomegranate make greenish tones across all mordanting methods, with pre-mordanting producing the darkest and most uniform shade. Quebracho mordant results in greyish tones with subtle blue undertones, showing the highest uniformity in pre-mordanting. Gallnut mordant shifts the tone towards green or yellow-green, with pre-mordanting creating a deeper shade. The colour variation depending on the mordant method is particularly evident when indigo is combined with gallnut.

Overall, pre-mordanting consistently results in darker and more saturated colours (lower L^* , more pronounced b^*) compared with post-mordanting. Meta-mordanting indicates weaker dye adherence, and in most cases, it is evident that indigo was not effectively reduced (Table 6).

To evaluate colour fastness to washing, all samples dyed using the meta-mordanting method were excluded, except for those treated with iron sulphate and gallnut, as they showed the most promising results. Additionally, all processes involving aluminium acetate were eliminated because of poor colour uniformity (Table 7).

Analysis of the table reveals that indigo exhibits superior resistance to washing compared with auxiliary products. This is evident in the prevalence of the blue tones after washing. Samples that initially exhibited a green hue, such as the gallnut pre-mordanted sample, significantly reduced the colour of the auxiliary product during washing, resulting in a shift to a more pronounced blue shade. The application of pre-mordanting tends to produce more vibrant colours, as indicated by lower L^* values, but these colours demonstrated poorer resistance to washing and higher ΔE^* values. On the other hand, post-mordanting generally improves wash fastness, particularly when using iron sulphate, quebracho and gallnut mordants. Iron sulphate (in meta-mordanting) and gallnut (in post-mordanting) show the most effective results in terms of

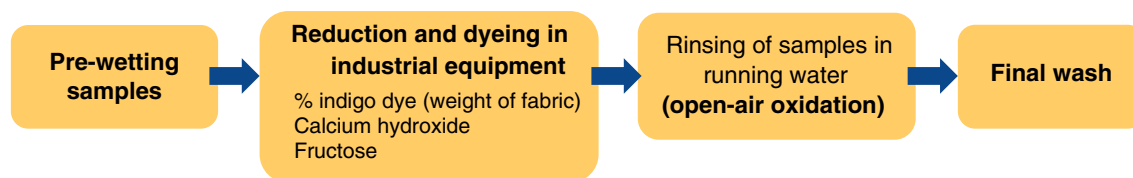


FIGURE 4 Stages of the vat dyeing process adapted to the industrial equipment.

wash fastness, achieving ratings of 4-5 and 3, respectively.

Because indigo dyeing with auxiliary products using the meta-mordant method does not produce satisfactory results, it may be beneficial to introduce an additional step to incorporate the auxiliary product through either pre- or post-mordanting. However, based on the results obtained, adding an auxiliary product exclusively to improve the chromatic and fastness properties of indigo dyeing is unnecessary. Indigo alone demonstrates greater uniformity and superior wash fastness compared with its combination with mordants such as alum, iron sulphate and aluminium acetate, all of which produced blue tones.

On the other hand, mordants are important to expand the colour palette of indigo. For example, gallnut allows for the creation of three distinct colours depending on the mordanting method used, while pomegranate, myrobalan and quebracho produce different tones of green. However, after washing, dyed fabrics tend to revert to blue. This phenomenon presents an opportunity for designers to experiment with intentional colour variations, creating dynamic and evolving garments that improve their aesthetic appeal.

Overall, the results indicate that a simpler indigo dyeing process demonstrates satisfactory outcomes when applied to industrial equipment (Figure 4). Compared with the conventional industrial process (Figure 1), this approach involves fewer and less complex steps and depends on lower-impact materials. This makes it a safer, more sustainable and cost-effective alternative for coloration with indigo in textile fashion design, offering designers greater flexibility in achieving unique shades while maintaining an eco-conscious choice.

4 | CONCLUSIONS

This study highlights the potential of fructose as a sustainable and eco-friendly reducing agent for industrial indigo dyeing. It validates the effectiveness of the 1-2-3 formulation—natural indigo dye, fructose and calcium hydroxide—when applied in a single-stage process at 60°C using industrial equipment. This innovative process simplifies the dyeing process and improves its

environmental profile while expanding the achievable colour spectrum. By integrating traditional dyeing knowledge with modern, environmentally conscious practices, the proposed approach contributes to sustainable advances in the textile and fashion industry.

The study further demonstrates the significant impact of mordant choice and mordanting methods on the final colour and uniformity of indigo-dyed fabrics. Pre-mordanting generally produces darker and more uniform results, while post-mordanting improves wash fastness properties. This is evident in the use of gallnut as a mordant, where the pre-mordanting process initially produced a darker and more uniform colour compared with post-mordanting. However, after washing, the pre-mordanted fabric displayed a significant colour shift, with a colour change rating of 1, whereas the post-mordanted sample maintained greater stability, with a colour change rating of 3. This improved fastness may be associated with lower colour saturation compared with pre-mordanting. Tannin-based mordants, such as pomegranate, quebracho and myrobalan, create unique undertones that interact with indigo dye, expanding the traditional blue into a wider range of shades, such as greenish, yellow and greyish tones. However, variations in colour measurements may arise due to non-homogeneous dye distribution, emphasising the need for careful consideration of dye uniformity when analysing colour data to ensure accuracy and reliability.

Future research should focus on assessment and optimisation of wash and rub fastness, validation of the proposed vat dyeing process in an industrial environment and exploration of the indigo dyeing combination with other natural dyes. This will further diversify the colour spectrum and add value to fashion products. These efforts will support the continued development of sustainable and innovative textile dyeing solutions while opening new possibilities for fashion design. By adopting this approach, designers can create visually distinct, ethically produced garments that align with the growing consumer demand for sustainability. Intentional colour variations can be incorporated into collections to increase aesthetic aspects while maintaining an environmentally responsible approach.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest regarding the publication of this article.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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