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Research on overdyeing process of indigo and turmeric on nylon knitted fabrics

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This study investigated the overdyeing process of nylon knitted fabrics using two natural plant dyes—indigo and turmeric—to address the high pollution associated with synthetic dyes and the limited color gamut of natural dyes. Through single-factor experiments, the dyeing parameters were optimized to achieve yellow-green and blue-green hues. The dyeing performance, color fastness, and antibacterial properties of the dyed fabrics were evaluated. The optimal conditions for yellow-green shades were: indigo 5 g/L, glucose 10 g/L, NaOH 1 g/L, liquor ratio 1:50, reduction at 60 °C for 30 min, oxidation at room temperature for 30 min; followed by turmeric 1.2 g/L, liquor ratio 1:60, dyeing at 80 °C for 20 min. For blue-green shades: indigo 10 g/L, turmeric 0.8 g/L, dyeing at 50 °C, with other parameters identical. Both overdyed fabrics exhibited color fastness of grade 4 or higher, meeting apparel requirements. Antibacterial rates against *Staphylococcus aureus* and *Escherichia coli* reached 99% and 98%, respectively. These results confirm the feasibility of applying natural plant dyes to nylon fabrics and provide a reference for sustainable textile dyeing.

Keywords Indigo, Turmeric, Overdyeing, Nylon fabric, Natural dye, Antibacterial property

Plant dyeing technology is an ancient craft that utilizes botanical dyes to impart color to textiles. Its fundamental principle involves extracting pigments from plant roots, stems, leaves, flowers, and fruits, and then applying specific dyeing processes to bind these pigments to the textile fibers. Fabrics dyed using this method are non-toxic, harmless, and exhibit favorable environmental compatibility, along with various healthcare benefits[1].In the context of growing environmental concerns, natural dyes have regained attention as sustainable alternatives to synthetic dyes, which are often associated with high pollution loads and toxic effluents.

Overdyeing, as a plant dyeing technique capable of imparting rich visual depth to textiles, operates on the principle of applying multiple dye baths of different colors sequentially to the fabric. Each application deposits a new color layer on the textile surface, progressively creating a more varied and layered visual effect. Achieving this result hinges on the precise selection and scientific combination of dye baths, as well as strict control over the dyeing sequence.The overdyeing process effectively compensates for the limited color gamut of single plant dyes. It offers several pathways for enhanced color expression: first, multiple colored dye baths can be applied successively according to specific color design requirements. Second, it can utilize the color-shifting properties of mordants by applying a single plant dye bath, followed by overdyeing with different mordants. Third, these approaches can be flexibly combined, thereby enabling the creation of diverse color patterns and achieving a more expansive color palette[2].

In the research and practice of overdyeing techniques, numerous scholars have achieved valuable results. Zhao Yongjun et al. employed indigo and pagoda tree buds to overdye cotton/Modal knitted fabrics, successfully obtaining green-tinted fabrics, thereby providing a practical case for achieving green hues in textiles using natural dye overdyeing[3]. Kocaturk and Lu Yanhua et al. applied turmeric and natural indigo in the overdyeing of wool or tussah silk, and conducted a systematic evaluation of the resulting fabrics' color gamut and color fastness properties[4,5]. Liu Liu et al. utilized gardenia and natural indigo to overdye cotton fabrics, while also testing multiple color fastness properties such as resistance to soaping, rubbing, and sunlight, thus offering data support for the application of overdyeing techniques on cotton fabrics[6].

Tracing the history of plant dyeing, records of dyeing techniques can be found in ancient texts. Tiangong Kaiwu details the process of dyeing with indigo plants: the plants are placed into barrels or vats, lime is added to the water, and after fermentation, the solution is used for dyeing. Once dyed, the fabric is removed and exposed

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to air, where oxidation transforms its color. In Shuowen Jiezi, the character for “green” is explained as “blue-yellow”, revealing the traditional logic behind creating green. Since green dyes cannot be directly obtained from plants or animals in nature, traditional green hues were often achieved through overdyeing with two plant dyes. The most common method involved first dyeing with plant indigo, followed by overdyeing with various yellow dyes[7]. Indigo and turmeric, as two traditional natural plant dyes, exhibit blue and yellow colors respectively. Through overdyeing techniques, they can effectively expand the color gamut within the green spectrum. Nylon knitted fabric, owing to its excellent dye uptake and wide range of applications, serves as an ideal carrier material for research on natural dyes.

Indigo, the primary component of Qingdai (natural indigo), is a natural blue dye. Concurrently, as a traditional Chinese medicinal herb, Qingdai possesses various pharmacological effects such as anti-inflammatory and anti-tumor properties. These characteristics promote its research and application in the dyeing of medical dressing materials[8]. As the main constituent of Qingdai, indigo belongs to the category of vat dyes, and its dyeing process has specific requirements: it must first be converted into its leuco form in an environment containing both a strong alkali and a strong reducing agent before it can adhere to fibers. Subsequently, oxidation treatment is required to ultimately fix the color onto the fiber surface[9].

Turmeric contains the vibrant pigment curcumin, a natural phenolic compound extracted from the rhizomes of plants in the ginger family. In the food industry, curcumin serves as a natural food colorant while also functioning as a preservative to extend the shelf life of food products[10–12]. In the medical field, the efficacy of curcumin is even more diverse. It not only promotes qi circulation, breaks blood stasis, and relieves pain by unblocking meridians, but also possesses anti-inflammatory, anti-tumor, and antioxidant properties. Furthermore, it offers protective effects on both the digestive and cardiovascular systems[13–16]. In the textile industry, curcumin is commonly used as a natural dye for textiles. Leveraging its favorable bioactivity and pharmacological effects, it can impart certain functionalities to dyed fabrics. Previous studies have successfully applied indigo and turmeric in the overdyeing of silk, achieving satisfactory dyeing results[4]. The overdyeing process combining indigo and turmeric can not only achieve the expression of rich colors such as yellow-green and blue-green but also endow textiles with special functions like antibacterial and ultraviolet protection properties[17].

This study utilizes indigo and turmeric as natural dyes to investigate the overdyeing process on nylon knitted fabrics, aiming to address the issues of pollution from synthetic dyes and the limited color gamut of natural dyes. Two indigo dyeing processes were employed to produce fabric samples in different shades of blue, which were subsequently overdyed with turmeric to achieve yellow-green and blue-green hues. The vat dyeing method was applied for indigo dyeing, followed by the direct dyeing method for turmeric overdyeing. By controlling single variables, 20 fabric samples were prepared to determine the optimal process parameters. Among these, samples #1–#9 and #11–#19 were used to explore the dyeing performance of indigo and turmeric overdyeing on nylon knitted fabrics, while samples #10 and #20, produced under the optimal dyeing conditions, were specifically tested for color fastness and antibacterial properties. This study is expected to provide an environmentally friendly dyeing solution for nylon fabrics, promote green development in the textile industry, and open new avenues for the application of natural plant dyes.

Experiment

Materials and chemicals

Nylon knitted fabric (100% nylon, 130 g/m^2, Fujian Huafeng New Material Co., Ltd.), Indigo paste (produced in Shufeng Township, Putian, Fujian), Turmeric powder (food-grade), Sodium hydroxide flakes (chemically pure), Anhydrous glucose powder (chemically pure), Sodium chloride (analytically pure), Soap powder (commercially available).

Instruments and equipment

HH-S21-4 Constant Temperature Water Bath, Y(B)571BC Crockmeter (for color fastness to rubbing), SF-600 Spectrophotometer, ZWY-240 Incubator Shaker (for antibacterial testing).

Optimization of dyeing process

The Qingdai and turmeric over-dyeing process is shown in Fig. 1. Preliminary Trials were conducted to establish baseline conditions for yellowish-green and bluish-green shades.

Indigo Dyeing (Vat Dyeing Method): Fabric was immersed in the indigo bath containing indigo, glucose (reducing agent), and NaOH. The reduction was carried out at specified temperature and time under controlled pH (10–11). Glucose acts as the reducing agent, converting insoluble indigo to soluble leuco-indigo. After reduction, the fabric was oxidized in air.

Turmeric Overdyeing (Direct Dyeing Method): The indigo-dyed fabric was then immersed in a turmeric dye bath at varying concentrations, temperatures, and times.

Parameter Design: Single-factor experiments were conducted to optimize turmeric concentration, dyeing temperature, and dyeing time for both target shades. The detailed parameters for sample preparation are listed in Table 1.

Post-treatment: All dyed samples were washed, soaped, and air-dried before testing.

Dyeing performance testing

The colorimetric parameters L*, a*, b*, and the K/S values of the dyed fabrics were measured using an SF-600 spectrophotometer under D65 illuminant at a 10° observer. Three measurements were taken from different areas of each sample and averaged. The L* value indicates the lightness/darkness of the color; a higher L* value corresponds to a lighter fabric color, while a lower L* value indicates a darker color. The a* value represents the color tendency between red (+a) and green (− a). The b* value represents the color tendency between yellow

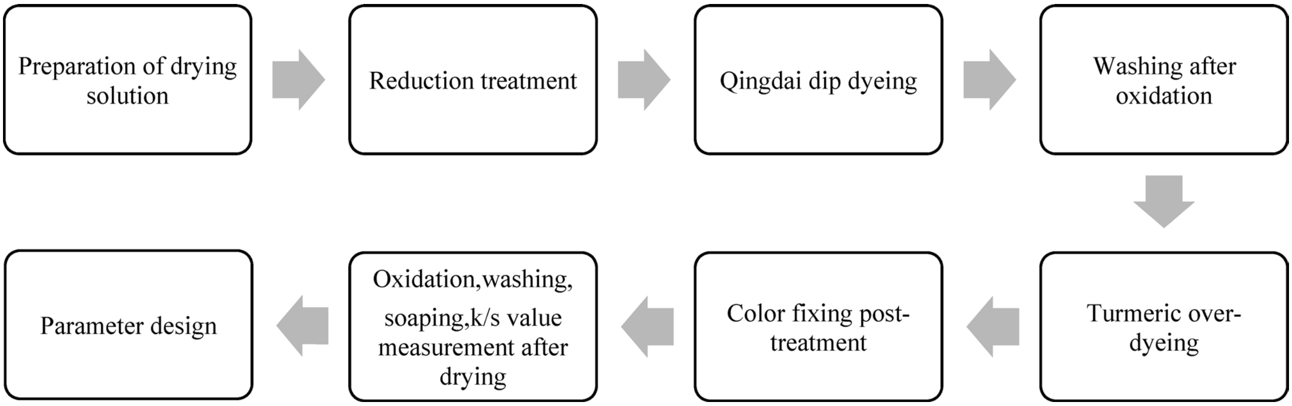

Fig. 1. Qingdai and turmeric over-dyeing process.

<table>
<tr><th>Sample</th><th>Number of samples</th><th>Turmeric concentration/(g/L)</th><th>Dyeing temperature/℃</th><th>Dyeing time/min</th><th>Liquor ratio</th><th>Fabric weight/g</th></tr>
<tr><td rowspan="10">5 g/L Qingdai-dyed polyamide knitted fabric</td><td>1#</td><td>0.8</td><td rowspan="3">70</td><td rowspan="3">20</td><td rowspan="20">1:60</td><td rowspan="20">10</td></tr>
<tr><td>2#</td><td>1.0</td></tr>
<tr><td>3#</td><td>1.2</td></tr>
<tr><td>4#</td><td rowspan="3">0.8</td><td>70</td><td rowspan="3">20</td></tr>
<tr><td>5#</td><td>80</td></tr>
<tr><td>6#</td><td>90</td></tr>
<tr><td>7#</td><td rowspan="3">0.8</td><td rowspan="3">70</td><td>10</td></tr>
<tr><td>8#</td><td>20</td></tr>
<tr><td>9#</td><td>30</td></tr>
<tr><td>10#</td><td>1.2</td><td>80</td><td>20</td></tr>
<tr><td rowspan="10">10 g/L Qingdai-dyed polyamide knitted fabric</td><td>11#</td><td>0.6</td><td rowspan="3">60</td><td rowspan="3">20</td></tr>
<tr><td>12#</td><td>0.7</td></tr>
<tr><td>13#</td><td>0.8</td></tr>
<tr><td>14#</td><td rowspan="3">0.7</td><td>40</td><td rowspan="3">20</td></tr>
<tr><td>15#</td><td>50</td></tr>
<tr><td>16#</td><td>60</td></tr>
<tr><td>17#</td><td rowspan="3">0.7</td><td rowspan="3">60</td><td>10</td></tr>
<tr><td>18#</td><td>20</td></tr>
<tr><td>19#</td><td>30</td></tr>
<tr><td>20#</td><td>0.8</td><td>50</td><td>20</td></tr>
</table>

Specific parameters of Qingdai and turmeric over-dyeing sample.

(+ b) and blue (-b). The K/S value characterizes the dyeing depth and the fiber-dye interaction; a higher K/S value indicates a stronger light absorption capacity of the dye, whereas a lower value indicates weaker light absorption.

Color fastness testing

Rubbing Fastness(dry/wet): Tested according to Chinese National Standard GB/T 3920 —2008, "Textiles—Tests for color fastness—Color fastness to rubbing." The samples were graded under D65 illuminant using the grey scales for assessing change in color (GB/T 250–2008) and staining (GB/T 251–2008).

Washing Fastness: Tested according to Chinese National Standard GB/T 3921—2008, "Textiles – Tests for color fastness—Color fastness to washing with soap or soap and soda." The test specimen was stitched together with specified standard adjacent fabrics and treated in a solution containing soap or soap and sodium carbonate at 40 °C with mechanical agitation for 30 min, followed by rinsing and drying. Using the original sample as a reference, the samples were graded under D65 illuminant using the grey scales for assessing change in color (GB/T 250–2008) and staining (GB/T 251–2008).

Antibacterial performance testing

Test strains: Staphylococcus aureus, Escherichia coli, and Candida albicans. C. albicans was included to assess antifungal potential, relevant for hygienic textile applications. Antibacterial rates were determined using the shake flask method (AATCC 100). Untreated nylon fabric served as the control.

Fig. 2. Photographs of yellow-green trial-dyed process samples.

Fig. 3. Photographs of blue-green trial dyeing process samples.

Test Methods: The antibacterial rate was determined using the colony counting method with reference to AATCC 100 standard. Antibacterial durability was evaluated via the shake flask method (containing 0.3% Tween 80), simulating 50 standard wash cycles (GB/T 12490).

Results and discussion

Preliminary overdyeing trials

Based on the results of the preliminary dyeing trials, it was found that for the yellowish-green dyeing process, a reduction in both the indigo concentration and the dyeing temperature is required. Conversely, for the bluish-green dyeing process, a reduction in the indigo concentration and an increase in the dyeing temperature are necessary.The test-dyed samples are presented in Figs. 2 and 3.

Dyeing mechanism analysis

The formation of green on nylon via sequential indigo-turmeric dyeing is based on distinct dye-fiber interactions and optical color mixing.

Indigo Dyeing: In the alkaline reducing bath (with glucose facilitating reduction), indigo is converted to leuco-indigo, which adsorbs onto nylon fibers via hydrogen bonding and van der Waals forces with amide groups. Subsequent oxidation reforms insoluble indigo microcrystals trapped within the fiber, creating a blue base layer.

Turmeric Overdyeing: Curcumin molecules, applied under milder conditions, attach to the fiber and the indigo-coated surface primarily through hydrogen bonding (via its phenolic -OH and carbonyl groups) and hydrophobic interactions. This forms a yellow outer layer.

Color Formation: The perceived green results from subtractive color mixing. Light passes through the outer curcumin layer (which absorbs blue-violet light) and the inner indigo layer (which absorbs red light), allowing the middle green wavelengths to dominate the reflection.

Dye-Fabric Interaction: The proposed mechanism involves a hierarchical structure within the fiber: an inner core of physically fixed indigo and an outer shell of curcumin molecules attached by secondary forces.

Study on the compound dyeing properties of indigo and turmeric for yellowish-green shades on nylon knitted fabric

The colorimetric parameters L*, a*, b*, and the K/S values of the nylon knitted fabrics were measured according to the method described in “1.4 Dyeing Performance Testing.” The specific parameters are listed in Table 2.

Samples 1#-3#: effect of turmeric concentration

A single-factor experiment was conducted by varying the turmeric concentration to 0.8 g/L, 1 g/L, and 1.2 g/L. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 2. With the increase in turmeric concentration, the L* value gradually increased, indicating a lighter fabric shade. The a* values were

Number of samples	L^*	a^*	b^*	K/S	Fabric sample photos
1#	− 1.02	− 0.04	2.10	4.523	
2#	− 0.52	− 0.41	3.64	4.6585	
3#	− 0.12	− 0.11	0.53	5.4517	
4#	− 0.50	− 0.52	5.68	4.1061	
5#	− 7.58	− 3.01	7.39	4.4162	
6#	− 10.00	− 4.13	1.31	2.9311	
7#	− 7.76	− 0.39	2.39	3.4213	
8#	− 7.17	− 0.91	9.32	4.8623	
9#	− 9.11	− 1.93	8.49	4.1286	

Table 2. Colorimetric parameters of nylon knitted fabric in yellowish-green shades dyed with indigo and turmeric under the influence of turmeric concentration, dyeing temperature, and dyeing time.

predominantly negative, showing a trend of first decreasing and then increasing, which suggests the fabric color shifted towards green, with the green component initially intensifying and then diminishing. The b* values were predominantly positive, exhibiting a pattern of first increasing and then decreasing, indicating a shift towards yellow, where the yellow component first increased and then decreased. The K/S value increased significantly with rising turmeric concentration, leading to a gradual deepening of the fabric color. The K/S value reached its maximum at a turmeric concentration of 1.2 g/L, indicating optimal dyeing depth.

Samples 4#-6#: effect of dyeing temperature
A single-factor experiment was conducted by varying the dyeing temperature to 70 °C, 80 °C, and 90 °C. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 2. As the dyeing temperature increased, the L* value gradually decreased, resulting in a darker fabric shade. The a* values were predominantly negative and gradually decreased, signifying a stronger green bias and a progressive increase in the green component of the fabric. The b* values were predominantly positive, first increasing and then decreasing, indicating a yellow bias where the yellow component initially increased and subsequently decreased. The K/S value first increased and then decreased, corresponding to an initial deepening and subsequent lightening of the fabric color. The K/S value reached its maximum at a dyeing temperature of 80 °C, indicating optimal dyeing depth.

Samples 7#-9#: effect of dyeing time
A single-factor experiment was conducted by varying the dyeing time to 10 min, 20 min, and 30 min. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 2. With increasing dyeing time, the L* value first increased and then decreased, meaning the fabric color first lightened and then darkened. The a* values were predominantly negative and gradually decreased, indicating a stronger green bias and an increase in the green component of the fabric color. The b* values were predominantly positive, first increasing and then decreasing, suggesting a yellow bias where the yellow component initially increased and then decreased. The K/S value first increased and then decreased, leading to an initial darkening followed by a lightening of the fabric color. The K/S value reached its maximum at a dyeing time of 20 min, indicating optimal dyeing depth.

In summary, the optimal dyeing process parameters for achieving yellowish-green shades on nylon knitted fabric via compound dyeing with indigo and turmeric are as follows: liquor ratio of 1:60, turmeric concentration of 1.2 g/L, dyeing temperature of 80 °C, and dyeing time of 20 min.

Study on the compound dyeing properties of indigo and turmeric for bluish-green shades on nylon knitted fabric

The colorimetric parameters L*, a*, b*, and the K/S values of the nylon knitted fabrics were measured according to the method described in "1.4, Dyeing Performance Testing. "The specific parameters are listed in Table 3.

Number of samples	L*	a*	b*	K/S	Fabric sample photos
11#	− 0.86	− 2.19	− 3.22	3.5943	
12#	− 1.81	− 1.11	− 1.47	3.6307	
13#	− 0.98	− 1.57	− 2.99	4.7079	
14#	− 2.78	− 2.94	− 12.94	2.9994	
15#	− 2.34	− 2.96	− 6.40	3.8689	
16#	− 1.20	− 0.87	− 3.22	3.4773	
17#	− 1.38	− 2.71	− 4.80	3.2611	
18#	− 1.48	− 1.58	− 0.39	3.9208	
19#	− 3.59	− 0.06	− 0.46	3.3726	

Table 3. Colorimetric parameters of nylon knitted fabric in bluish-green shades dyed with indigo and turmeric under the influence of turmeric concentration, dyeing temperature, and dyeing time.

Samples 11#-13#: effect of turmeric concentration

A single-factor experiment was conducted by varying the turmeric concentration to 0.6 g/L, 0.7 g/L, and 0.8 g/L. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 3. With the increase in turmeric concentration, the L* value first decreased and then increased, indicating the fabric color darkened initially and then lightened. The a* values were predominantly negative, showing a trend of first increasing and then decreasing. This suggests the fabric color shifted towards green, with the green component initially decreasing and then increasing. The b* values were predominantly negative, exhibiting a pattern of first increasing and then decreasing, indicating a shift towards blue, where the blue component first decreased and then increased. The K/S value increased significantly with rising turmeric concentration, leading to a gradual deepening of the fabric color. The K/S value reached its maximum at a turmeric concentration of 0.8 g/L, indicating optimal dyeing depth.

Samples 14#-16#: effect of dyeing temperature

A single-factor experiment was conducted by varying the dyeing temperature to 40 °C, 50 °C, and 60 °C. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 3. As the dyeing temperature increased, the L* value gradually increased, resulting in a lighter fabric shade. The a* values were predominantly negative, first decreasing and then increasing. This signifies a green bias where the green component in the fabric first increased and then subsequently decreased. The b* values were predominantly negative and gradually increased, indicating a blue bias where the blue component of the fabric color continuously decreased. The K/S value first increased and then decreased, corresponding to an initial deepening and subsequent lightening of the fabric color. The K/S value reached its maximum at a dyeing temperature of 50 °C, indicating optimal dyeing depth.

Samples 17#-19#: effect of dyeing time

A single-factor experiment was conducted by varying the dyeing time to 10 min, 20 min, and 30 min. The L*, a*, b*, and K/S values of the dyed fabrics were measured, as shown in Table 3. With increasing dyeing time, the L* value gradually decreased, meaning the fabric color progressively darkened. The a* values were predominantly negative and gradually increased, indicating a reduction in the green component of the fabric color. The b* values were predominantly negative, first increasing and then decreasing, suggesting a blue bias where the blue component initially decreased and then increased. The K/S value first increased and then decreased, leading to an initial darkening followed by a lightening of the fabric color. The K/S value reached its maximum at a dyeing time of 20 min, indicating optimal dyeing depth.

Fiber resistance to rubbing color fastness		Soaping resistance color fastness						
Dry friction	Wet friction	Color change	Wool	Acrylic fiber	Polyester fiber	Polyamide	Cotton	Acrylic fiber
4	4	4–5	4–5	4–5	4–5	4–5	4–5	4–5

Table 4. Rubbing fastness and washing fastness of nylon knitted fabric in yellowish-green shades dyed with indigo and turmeric.

Fiber resistance to rubbing color fastness		Soaping resistance color fastness						
Dry friction	Wet friction	Color change	Wool	Acrylic fiber	Polyester fiber	Polyamide	Cotton	Acrylic fiber
4–5	4	4–5	4–5	4–5	4–5	4–5	4–5	4–5

Table 5. Rubbing fastness and washing fastness of nylon knitted fabric in bluish-green shades dyed with indigo and turmeric.

Bacterial colony name	Antibacterial rate (%)
Golden Staphylococcus	99
Escherichia coli	98
Candida albicans	90

Table 6. Antibacterial rate of nylon knitted fabric in yellowish-green shades dyed with indigo and turmeric.

Bacterial colony name	Antibacterial rate (%)
Golden Staphylococcus	99
Escherichia coli	99
Candida albicans	89

Table 7. Antibacterial rate of nylon knitted fabric in bluish-green shades dyed with indigo and turmeric.

In summary, the optimal dyeing process parameters for achieving bluish-green shades on nylon knitted fabric via compound dyeing with indigo and turmeric are as follows: liquor ratio of 1:60, turmeric concentration of 0.8 g/L, dyeing temperature of 50 °C, and dyeing time of 20 min.

Color fastness

Nylon knitted fabrics were dyed under the respective optimal dyeing process conditions described above to obtain samples 10# and 20#. The rubbing fastness and washing fastness of the fabrics were measured according to the methods specified in Sect. 1.5, Rubbing Fastness Test and Washing Fastness Test. The test results are presented in Tables 4 and 5.

Antibacterial performance

Nylon knitted fabrics were dyed under the aforementioned optimal dyeing process conditions to obtain samples 10# and 20#. The antibacterial rates of the fabrics were measured according to the method described in Section"Antibacterial performance testing", Antibacterial Performance Testing. The test results are presented in Tables 6 and 7.

Environmental implication

Compared to conventional synthetic dyeing of nylon, which often uses acid or disperse dyes requiring harsh chemicals and generating colored effluent, this natural dye overdyeing process utilizes milder, biodegradable materials. Although the reducing step involves alkali, the overall process reduces the reliance on petrochemical-based, potentially toxic dyes, aligning with greener production goals.

Conclusion

This study successfully developed yellow-green and blue-green shades on nylon knitted fabrics via overdyeing with indigo and turmeric. Optimal parameters were established through single-factor experiments. The dyed fabrics exhibited color fastness of grade 4 or higher and excellent antibacterial properties, with inhibition rates up to 99% against S. aureus. These results demonstrate the viability of natural dye overdyeing on synthetic fibers and support its application in sustainable and functional textile production.

Outlook

Future work should focus on: (1) Evaluating the durability of color and antibacterial properties under repeated washing and light exposure; (2) Scaling up the process for industrial trial production; (3) Exploring the application of this overdyeing strategy to other synthetic fibers; (4) Conducting a comprehensive lifecycle assessment to quantify the environmental benefits compared to synthetic dyeing processes.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

Xiaohong Yuan assisted with testing antibacterial properties, which also provided supervision for paper writing. Yanqi Wu, Xinru Chen, Xin Li and Xinyan Shi wrote the main manuscript text, which also prepared Figs. 1, 2 and 3; Table 1-7.3. Feng Dong and Junfeng Zhang provided fabric raw materials and also reviewed the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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