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ARTICLE

Sustainable Dyeing of Polyamide 6 Fabrics Using Waste Pods of *Cassia fistula* as a Novel Source of Natural Colourants

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ABSTRACT

Environmental concerns over synthetic dyes, including water pollution and high energy demands, have driven interest in sustainable alternatives. This research investigates the colouration of polyamide 6 (nylon 6) textiles using a natural dye derived from the mature pods of *Cassia fistula*, which serve as a source of anthraquinone-based pigments. The study systematically evaluated the influence of dyeing parameters-namely temperature (30–90 °C), duration (10–60 min), pH range (4–11), dye concentration (10%–70% owf), and post-mordanting using alum, ferrous sulfate, and stannous chloride-on the resulting colour strength (K/S) and CIE Lab* coordinates. The fastness characteristics of polyamide 6 fabric were assessed, with the corresponding results detailed in the subsequent sections. Maximum dye absorption was achieved at 90 °C for 60 minutes under acidic conditions (pH 4), and from the conditions was given K/S 2.242. An increase in dye concentration led to higher K/S values, which were further augmented by mordanting, with aluminum potassium sulfate and stannous chloride yielding the greatest results. Colour fastness assessments indicated good to excellent resistance to washing, water exposure, rubbing, and perspiration, all of the properties were up to 4. Whereas resistance to light was

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found from 1 to 2. The findings confirm *Cassia fistula* extract as a renewable, eco-friendly dye for polyamide 6, offering commercially viable colour strength and fastness while supporting sustainable textile processing.
Keywords: Natural Dye; *Cassia Fistula* Waste; Polyamide; Mordant

1. Introduction

The use of natural dyes dates back thousands of years, with archaeological evidence linking their application to ancient civilizations including Mesopotamia, Egypt, and India [1]. Throughout history, natural colourants have served various purposes, from colouring human body parts (such as hair and fingernails) to decorating caves, leather, pharmaceuticals, animal furs, feathers, and textiles-particularly before the advent of modern civilization [2]. The advent of synthetic dyes in 1856, initiated by William Henry Perkin's accidental discovery of mauveine, represented a significant milestone in the evolution of dye technology. Due to their affordability, extensive colour range, ease of manufacture, and uniformity in shade, synthetic dyes rapidly gained preference, contributing to the decline in natural dye utilization [3]. Nevertheless, by the late twentieth century, growing awareness of the adverse environmental impacts associated with synthetic dye production-including water contamination, chemical toxicity, and high energy demands-prompted increasing concern [1]. In recent years, the unsustainable use of synthetic dyes, coupled with growing awareness of their adverse impacts on human health and the global environment, as well as the implementation of strict environmental regulations, has revived interest in the extraction and utilization of natural dyes [2,4,5]. Consequently, these and other contributing factors have intensified recent advocacy for substituting synthetic dyes with natural alternatives across various human activities, with the aim of safeguarding environmental sustainability [6]. Natural dyes hold significant potential for application across multiple sectors, including food colouring, cosmetics, leather processing, dye-sensitized materials, medicinal plants, textile dyeing, and printing [7–9]. Among these, plant-derived colourants are particularly preferred owing to the widespread availability of plant resources at minimal cost and their capacity to produce a broad spectrum of hues [10]. The majority of natural dyes exhibit low substantivity toward textile fibres and therefore require the use of mordanting agents to enhance dye–fibre affinity [11]. These agents, typically metallic salts, facilitate the binding of dye molecules to the fibre. Commonly employed mordants include alum, chrome, stannous chloride, and ferrous sulfate [12].

Polyamide 6 (nylon 6) is a widely utilized synthetic fibre in the textile industry, prized for the mechanical strength, resilience, and ability to form strong hydrogen bonds due to its linear polyamide backbone [13]. The presence of amide linkages (-CONH-) and terminal amino groups (-NH_2) gives polyamide 6 favorable dyeing properties, especially in acidic environments where these groups became protonated and capable of interacting with anionic dye species [13]. Conventionally, acid dyes are employed for colouring polyamide 6 due to the excellent affinity for the fibre. However, the dyeing process presents serious environmental concerns. Low dye fixation rates, high water and energy consumption, and the discharge of persistent dye residues contribute to substantial ecological harm, including elevated chemical oxygen demand (COD) and aquatic toxicity [13]. In light of increasing regulatory and sustainability pressures, there is a growing scientific and industrial interest in replacing synthetic dyes with natural, biodegradable alternatives [14]. Moreover, the application of natural dyes to synthetic fibres like polyamide 6 presents significant challenges. This study explored the application of red onion peel extract as a sustainable natural dye for nylon 6 fabrics aiming to enhance dye uptake, colour strength, and fastness while reducing environmental impact. Rich in pigments such as quercetin. The extract was applied using high-temperature, high-pressure (HTHP) dyeing with mordants including alum, copper sulfate, and potassium dichromate, each affecting shade and fastness. Ultrasonic-assisted dyeing proved especially effective, lowering dye use by 25%, cutting dyeing time by 66.7%, and saving significant energy, while also improving colour yield K/S up to 1.72 and reducing wastewater pollution by 28%. Overall, the dyed fabrics achieved moderate to good fastness to light, washing, and rubbing, confirming onion peel as a viable eco-friendly dye source for nylon [15]. Many natural dyes suffer from low substantivity and poor affinity for hydrophobic polymer matrices, resulting in limited colour strength and wash fastness.

The typically large, polar, and anionic molecular structures interact weakly with polyamide 6 through hydrogen bonding or electrostatic interactions, which are highly pH-dependent and often require mordanting to improve fixation [14].

Cassia fistula, commonly referred to as the Golden Shower tree, is a flowering species indigenous to South Asia, valued both for its ornamental appeal and its traditional medicinal applications. In recent years, it has attracted scientific attention for its potential application as a natural dye source in the textile sector. With growing concerns over the environmental impact of synthetic dyes, *Cassia fistula* offers an eco-friendly and renewable alternative for textile dyeing. The extracts have been effectively utilized on fabrics such as wool and silk, producing a variety of stable hues with favorable fastness characteristics. As interest in sustainable and biodegradable materials rises, *Cassia fistula* presents a viable botanical solution for greener textile processing.

The ripe pods (**Figure 1**) of the plant have been identified as a rich source of fistulic acid, an anthraquinone-based colouring compound, as first reported by Agarwal et al. [16]. This compound exhibits chemical properties similar to synthetic dyes, making it a suitable candidate for eco-friendly textile colouration. The potential of Golden shower as a natural dye source has been further validated through its successful application in wool and silk dyeing, as demonstrated by Bukhari et al. [17]. The findings demonstrated that, when applied in conjunction with mordants such as alum, copper sulfate, and iron, the dye was capable of producing a wide range of shades with good to excellent fastness to washing and light, thereby fulfilling essential performance requirements for commercial textile applications. Sasivatchutikool & Nakpathom [7] dyed silk with natural pigment from ripe *Cassia fistula* pods, comparing pre- and post-mordanting. Optimal dyeing occurred at 90 °C, 60 min, pH 4, yielding high colour strength and fastness. This indicates that the plant's dye compounds can effectively bind to protein-based fibres and withstand typical wear and cleaning processes.

Figure 1. *Cassia fistula* ripe pods.

In addition to its role as a natural dye, *Cassia fistula* also contributes to the environmental management side of textile manufacturing. One of the pressing issues in the industry is the treatment of textile water waste, which are often loaded with dyes, chemicals, and suspended solids. Hanif et al. [18] demonstrated that extracts from Golden shower pods possess polyelectrolytic properties, enabling them to function as natural coagulants. When applied to turbid textile wastewater, these bio-based agents significantly improved clarity and microbial quality by aggregating suspended particles and facilitating their removal. This dual capability of providing both colouration and wastewater treatment solutions underscores the plant's value in promoting sustainable textile processing. By minimizing dependence on petroleum-derived synthetic dyes and chemical coagulants, *Cassia fistula* contributes to the adoption of green chemistry principles and the advancement of circular economy practices in textile manufacturing. Its natural availability, effectiveness on animal fibres like wool, and role in effluent purification make it an important botanical resource for industries seeking both aesthetic quality and environmental responsibility.

This study investigates the dyeing of polyamide 6 fabric with a natural dye extracted from ripe *Cassia fistula* pods (**Figure 1**) using the exhaustion method. The objective was to evaluate the dyeing performance and fastness properties of polyamide 6 fabric using a dye solution obtained from the pods.

2. Materials and Methods

2.1. Materials

A plain-weave white polyamide 6 fabric was obtained from a local market in Bangkok, Thailand. The ripe pods of *Cassia fistula* were sourced from Khon Kaen Province. The dyeing experiments incorporated three mordants: alum potassium sulfate dodecahydrate ($AlK(SO_4)_2 \cdot 12H_2O$, alum), ferrous sulfate ($FeSO_4 \cdot 7H_2O$), and stannous chloride ($SnCl_2 \cdot 2H_2O$). The process employed a non-ionic soaping agent supplied by Star Tech Chemical Industrial Co., Ltd. (Thailand)[19].

2.2. Equipments

The processes of mordanting and dyeing were carried out using an infrared dyeing machine (Starlet DL-6000 (Starlet-3), South Korea). Absorbance measurements were obtained with a UV-visible double beam spectrophotometer (Halo DB-20, Australia). The colour strength (K/S) and CIE Lab* coordinates of the dyed specimens were measured via spectrophotometric analysis employing a Hunter Lab Colour Quest XE (USA).

2.3. Process of Experiment

As the **Figure 2**, The process begins with the extraction of natural colour dye from *Cassia fistula***,** which is then subjected to an optimization of dyeing parameters such as temperature, time of dyeing, pH, and dye concentration. Once the optimal conditions are established, the dyed samples are evaluated for the colour values and colour strength properties. Following this, the fabrics undergo a systematic assessment of fastness characteristics, including resistance to washing, light exposure, rubbing, water, and perspiration, to determine the overall performance and durability of the dye on the textile substrate.

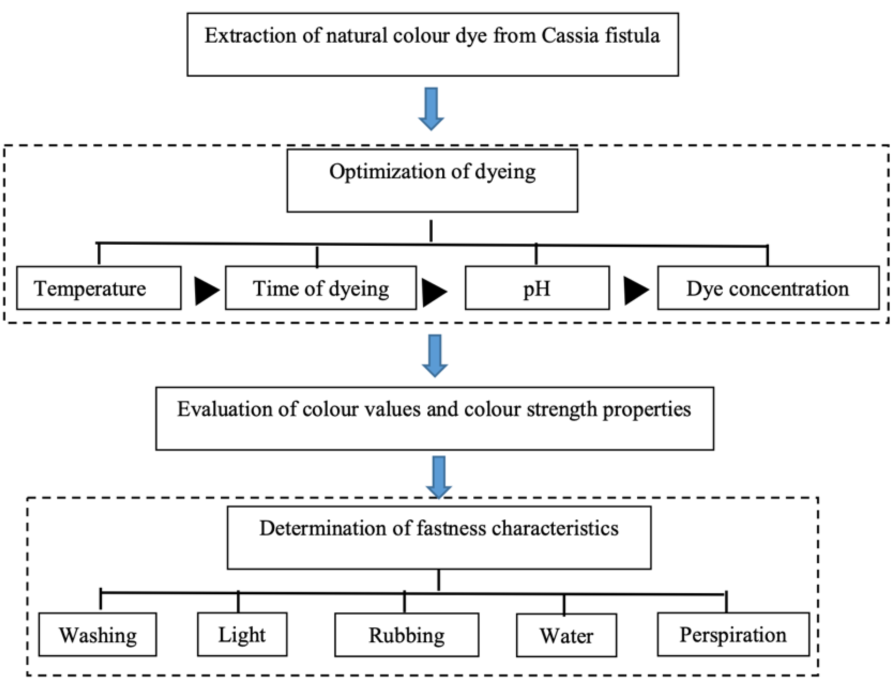

Figure 2. Experimental flowchart.

2.4. Extraction of Natural Colour Dye from *Cassia fistula*

The pods of *Cassia fistula* were blended to produce the useful material for extraction dyeing. The ground pods were mixed with distilled water was added at a weight ratio of 1:10 and boiled for a hour[7,19]. The mixture was subsequently strained to remove the solid residues, and the resulting liquid was utilized for both dyeing and evaporation processes. Crude dye extract was obtained by evaporating the solution under reduced pressure. Absorbance and. Dye concentration were correlated using a standard curve, The crude extract dissolved in distilled water. The solution showed a directed correlation between absorbance and concentration at the maximum absorption wavelength (λ_{max}) of 280 nm (**Figure 3**). Based on this calibration curve, the dye concentration was calculated to be 33.3 g/L[19].

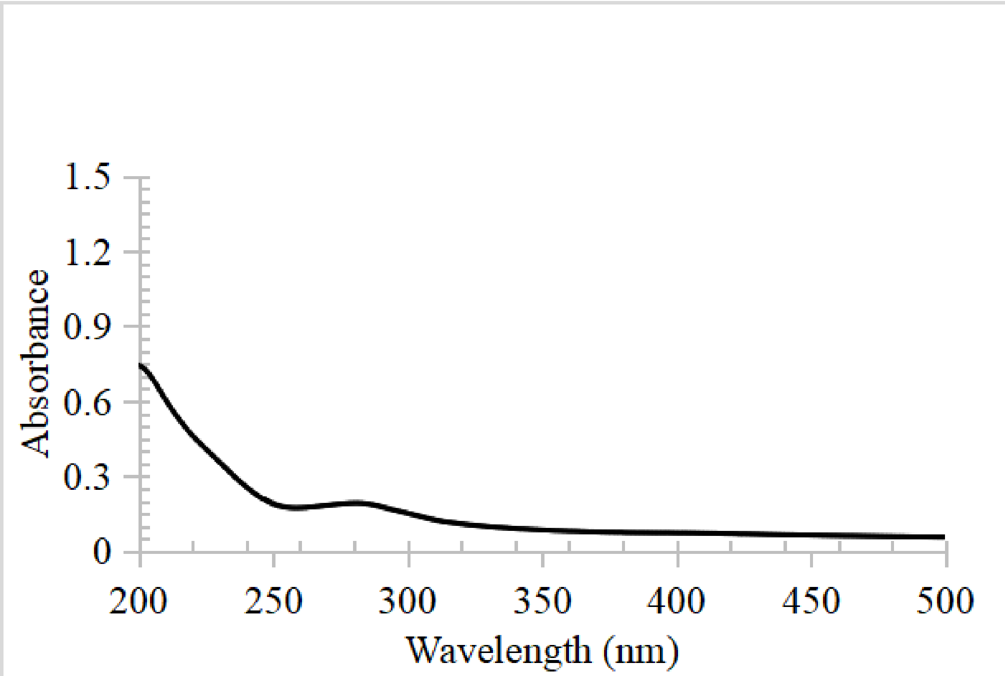

Figure 3. UV–VIS spectrum of the crude dye extract from ripe *Cassia fistula* pods dissolved in distilled water.

2.5. Optimization of Dyeing

Polyamide 6 fabric absorbed dye from *Cassia fistula* ripe pod extract under varying dyeing times, temperatures, and pH levels to optimize the dyeing conditions. Post-dyeing, the samples underwent washing with a 1 g/L non-ionic ,and then soaped with agent at 80 °C for 20 min, rinsed with purified water, drying of the samples was processed at room temperature by air.

2.5.1. Temperature

Polyamide 6 fabrics were dyed in seven separate batches with 50% on the weight of fabric of the *Cassia fistula* pods concentrate. The process dyed samples at 30, 40, 50, 60, 70, 80, and 90 °C using a bath ratio of 1:50 at the extract's native pH (5.7), with each batch dyed for 60 minutes.

2.5.2. Time of Dyeing

Polyamide 6 textiles underwent dyeing in six separate batches based on 50% of the fabric's weight of the Golden shower pod extract with the temperature maintained at 90 °C. staining process was conducted under conditions of a liquor ratio of 1:50 with pH 5.7, with dyeing duration time from 10 to 60 mins.

2.5.3. pH

Polyamide 6 textiles were soaped using 50% on the weight of fabric (owf) of *Cassia fistula* ripe pod extract in dye baths adjusted to pH 4, 5, 7, 9, and 11. Dyeing was preformed at 90 °C for 60 minutes under a bath ratio of 1:50. The pH adjustment was achieved employing the solutions of acetic acid or sodium carbonate at 5 g/L.

2.6. Effect of Dye Level and Mordanting Conditions

Polyamide 6 fabrics were dyed in infrared dyeing baths containing *Cassia fistula* ripe pod extract at concentrations of 10%, 30%, 50%, and 70% related to the weight of fabric. In **Figure 4** presented that the dyeing process was conducted at pH 4 and a bath ratio of 50:1, the process was conducted at 90 °C for 50 minutes. To enhance colour strength and fastness, Post-mordanting employed alum, ferrous sulfate, or stannous chloride at 10% on the weight of fabric. In this process, dyeing was followed by immersing the fabrics in the respective mordant baths. All treated sample fabrics have been washed at 80 °C for 20 mins in a 1 g/L aqueous non-ionic soaping agent solution, then rinsing with distilled water letting to air-dry at surrounding room temperature.

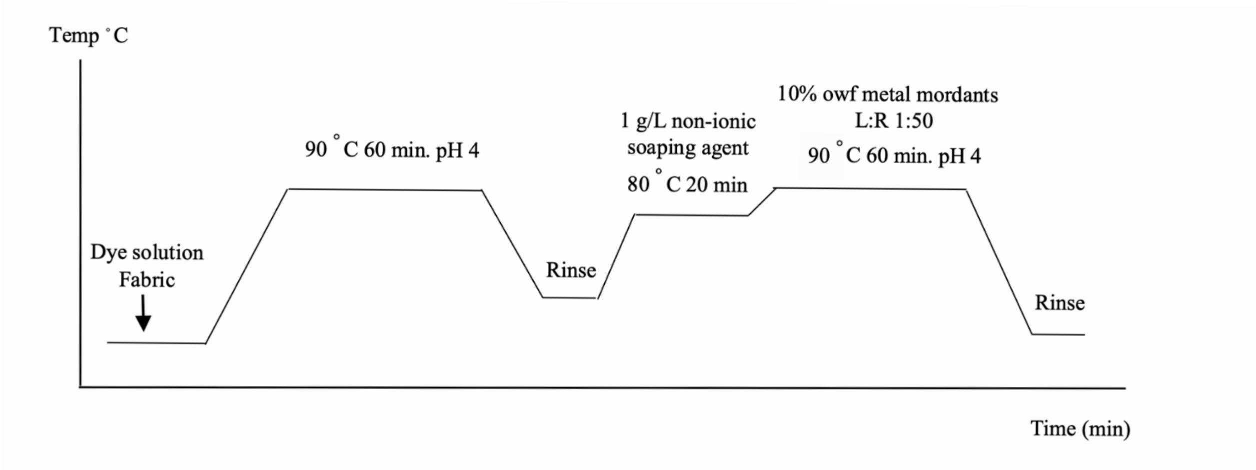

Figure 4. Dyeing condition diagram.

2.7. Evaluation of Colour Values and Colour Strength Properties

Colour values (CIE Lab*) and strength (K/S) of the *Cassia fistula* ripe pod dyed fabrics were analyzed with a reflectance spectrophotometer, employing illuminant D65 and the 10° standard observer. *colour values were expressed in the CIE Lab space, where L* represents lightness (0 = black, 100 = white), a* for the red–green axis (+a* = red, −a* = green), and b* for the yellow–blue axis (+b* = yellow, −b* = blue)[20–22]. The K/S values, which indicate Colour strength (K/S) was calculated using the Kubelka–Munk equation, $K/S = (1 - R)^2 / 2R$, where R is reflectance, K the absorption coefficient, and S the scattering coefficient[23,24]. All analyzed samples exhibited. a consistent absorption wavelength at 400 nm.

2.8. Determination of Fastness Characteristics

Colour fastness to washing, light, rubbing, water, and perspiration was evaluated in accordance with the following ISO standards: ISO 105-C06 A1S:2010 Colour fastness to domestic and commercial laundering[25], ISO 105-B02:2014 Colour fastness to artificial light: Xenon arc fading lamp test[26], ISO 105-X12:2016 Colour fastness to rubbing[27], ISO 105-E01:2013 Colour fastness to water[28], and ISO 105-E04:2013 Colour fastness to perspiration in acid and alkaline[29].

3. Results and Discussion

3.1. Effect of Dyeing Temperature

The influence of dyeing temperature (30–90 °C) on the dyeability of polyamide 6 fabric with *Cassia fistula* extract is shown in **Table 1**. It is evident from **Table 1** that K/S values increased substantially from 0.380 at 30 °C to 2.240 at 90 °C, accompanied by a clear decrease in lightness (L*) values from 88.44 to 69.80, indicating darker and more saturated shades. This enhancement is attributed to the thermal swelling of polyamide 6 fibres, which increases porosity and facilitates dye diffusion into internal regions of the fibre structure[7,17,22]. Higher temperatures also enhance molecular motion and reduce viscosity of the dye solution, further promoting dye-fibre interactions. The dyed polyamide 6 fabric displayed a yellowish-brown shade.

Table 1. Colour values, strength, and appearance of polyamide 6 fabrics dyed with *Cassia fistula* extract at 30–90 °C (50% owf dye concentration, liquor ratio 1:50, pH 4, 60 min).

Temperature (°C)	Colour Value			Colour Strength (K/S)	Colour Obtained
	L*	a*	b*		
30	88.44	−3.24	21.37	0.380	
40	86.80	−3.79	29.26	0.416	
50	83.78	−2.41	37.97	0.513	
60	80.69	1.07	41.88	0.627	
70	78.23	4.57	37.27	0.871	
80	74.94	5.72	36.59	1.001	
90	69.80	6.15	33.80	2.240	

The anthraquinone-based colourants in *Cassia fistula* notably rhein and aloe-emodin are thermally stable, enabling efficient dyeing at elevated temperatures without structural breakdown. Additionally, the presence of amide (-CONH-) functional groups in polyamide 6 allows for hydrogen bonding and polar interactions with the hydroxyl and carboxylic groups in the dye, particularly under heat-assisted conditions [7,17].

3.2. Influence of Dyeing Time

The influence of dyeing time (10–60 min) on the dyeability of polyamide 6 fabric with *Cassia fistula* extract is shown in **Table 2**. It can be observed that, dyeing time significantly affected the depth of shade on polyamide 6 fabric. K/S values increased from 1.176 at 10 min to 2.242 at 60 min, indicating a time-dependent diffusion mechanism.

Table 2. Colour values, colour strength, and appearance of polyamide 6 fabrics dyed with *Cassia fistula* extract at dyeing times from 10 to 60 min at 90 °C, at a liquor ratio of 1:50, pH 4 and 50% owf dye concentration.

Time (min)	Colour Value			Colour Strength (K/S)	Colour Obtained
	L*	a*	b*		
10	73.01	7.34	30.71	1.176	
20	72.86	7.47	31.02	1.342	
30	72.11	7.71	31.46	1.395	
40	70.23	7.61	32.84	2.093	
50	70.08	6.95	32.40	2.126	
60	69.80	6.15	33.80	2.242	

This trend suggests that dye exhaustion approaches equilibrium by 60 min, as no substantial increase was observed beyond this point. The extended dyeing time allows dye molecules sufficient opportunity to interact with the polyamide 6 matrix through hydrogen bonds and van der Waals forces, resulting in enhanced fixation [7,17]. The observed decrease in L* and increase in a*/b* values over time confirms improved colour saturation and chromatic development. This finding indicates that a dyeing duration of 60 min at elevated temperature is optimal for dye–fiber interaction, achieving both practical efficiency and maximum colour strength.

3.3. Effect of pH in the Dyeing Process

The effect of dye bath pH (4–11) on the dyeability of polyamide 6 fabric with *Cassia fistula* extract is shown in **Table 3**. From **Table 3**, it can be observed that the highest K/S value (2.242) was obtained at pH 4, while dye affinity decreased sharply at neutral and alkaline pH. Polyamide 6 exhibits amphoteric properties, and under acidic conditions, the terminal amino groups (-NH_2) become protonated (-NH_3^+) [30,31].

This cationic charge promotes electrostatic attraction with the anionic groups in the dye molecules such as deprotonated hydroxyl and carboxyl groups facilitating improved dye uptake. At higher pH levels, these amino groups are no longer protonated, resulting in reduced affinity for anionic dyes and consequently lower K/S values. These results affirm the importance of maintaining mildly acidic dye baths when applying natural dyes to polyamide 6 fibres, consistent with findings from previous natural dye studies [32].

Table 3. Colour values, colour strength, and appearance of polyamide 6 fabrics dyed with *Cassia fistula* extract at different pH values (4, 5, 7, 9 and 11) at a liquor ratio of 1:50, 90 °C for 60 min, and 50% owf dye concentration.

pH	Colour Value			Colour Strength (K/S)	Colour Obtained
	L*	a*	b*		
4	69.80	6.15	33.80	2.242	
5	68.54	8.61	31.23	2.180	
7	79.90	6.72	10.06	0.470	
9	81.08	5.55	9.40	0.408	
11	90.10	2.05	−1.14	0.071	

3.4. Influence of Dye Concentration on Colour Strength (K/S)

Polyamide 6 fabrics were dyed using the post-mordanting method, with alum, ferrous sulfate, and stannous chloride utilized as mordants. **Table 4** presents the colour values and colour strength of the fabrics dyed with golden shower ripe pod extract. As observed in **Table 4**, increasing dye concentration from 10% to 70% owf led to a proportional increase in K/S values across all mordanting conditions. Without any agent, the colour strength reached 2.30, while mordanted samples demonstrated even stronger dye fixation 2.395 with $AlK(SO_4)_2$, 2.249 with $FeSO_4$, and 2.363 with $SnCl_2$ at higher dye concentrations.

Mordants enhance dye-fibre affinity by forming coordination complexes, forming a connection between fibre and dye molecules. In particular, ferrous sulfate ($FeSO_4$) creates a tight chemical link between the dye and the fibre [31]. This often results in deeper and duller shades due to iron's interaction with phenolic and anthraquinone compounds [32,33]. Meanwhile, stannous chloride ($SnCl_2$), although forming weaker complexes, yielded unexpectedly high K/S values in this study, suggesting favorable interaction with polyamide 6 under optimized conditions [22]. These outcomes indicate that metal mordants not only improve colour yield but also affect final shade, confirming their practical value in polyamide 6 dyeing using plant-based extracts.

Table 4. Colour values and strength of polyamide 6 fabric dyed with *Cassia fistula* extract (10%–70% owf) using post-mordanting with 10% owf metal mordants (liquor ratio 1:50, 90 °C, 60 min, pH 4).

Type of Mordant	Dye/ Concentration (% o.w.f.)	Colour Strength (K/S)	Colour Value			Colour Obtained
			*L**	*a**	*b**	
-	Undyed	0.043	93.69	3.89	−13.50	-
Without mordanting	10	0.511	79.56	5.48	11.34	
	30	1.075	74.81	6.44	21.09	
	50	2.24	69.90	6.15	37.80	
	70	2.30	67.10	7.21	33.84	
$AlK(SO_4)_2$ (Al)	10	0.537	80.24	4.17	1387	
	30	1.370	72.00	7.47	23.81	
	50	2.269	68.44	8.65	30.93	
	70	2.395	66.07	9.75	28.73	
$FeSO_4$ (Fe)	10	0.662	77.57	3.53	13.71	
	30	1.429	70.79	5.97	22.39	
	50	2.153	65.60	8.02	25.48	
	70	2.249	66.97	7.49	29.02	
$SnCl_2$ (Sn)	10	0.494	81.06	4.85	11.78	
	30	1.376	72.48	7.57	23.31	
	50	2.218	67.27	9.88	29.12	
	70	2.363	68.31	9.12	31.49	

3.5. Evaluation of Fastness Properties

As **Tables 5–7** presented the colour fastness ratings of polyamide 6 fabrics dyed with and without mordants, using 70% owf dye and 10% owf mordant. The results were assessed in accordance with ISO standards and tools. Which was the gray scale (1–5; 1 = very poor, 5 = excellent) was used for washing, water, perspiration, and rubbing fastness, And the blue wool scale (1–8; 1 = very poor, 8 = excellent) was applied for light fastness[34].

Table 5. Colour fastness to washing at 40 °C (ISO 105-C06 A1S: 2010) and colour fastness to water (ISO 105-E01: 2013).

Fastness	Washing				Water			
	W	Al	Fe	Sn	W	Al	Fe	Sn
Colour change	4	4	4	4	4–5	4–5	4–5	4–5
Colour staining								
-Acetate	4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
-Cotton	4–5	4–5	4–5	4–5	4	4	4	4
-Nylon	4	4	4	4	4	4	4	4
-Polyester	4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
-Acrylic	4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
-Wool	4	4	4	4	4	4	4	4

Note: W = without mordant, Al = $AlK(SO_4)_2$, Fe = $FeSO_4$, Sn = $SnCl_2$.

As presented in **Table 5**, washing fastness was rated at 4, and colour staining across multifibre strips was 4 to 4–5, indicating strong dye fixation and resistance to detergent action. Similarly, water fastness ratings remained consistently high. These performances are associated with the presence of tannins and anthraquinones, which bind strongly to polyamide chains through multiple interaction sites, including hydrogen bonding and metal-assisted coordination[34,35].

As shown in **Table 6**, rubbing fastness was equally favorable with dry and wet ratings of 4 to 4–5. This mechanical stability confirms that dye molecules were not only absorbed into the fibre surface but also strongly retained within the fibre structure, minimizing frictional release. light fastness remained a limitation**.** Unmordanted fabric scored 1, and mordanted samples slightly improved to rating 2. Similar with one research that using bitter bean pods dying with cotton wastes, there showed the lightness result was lower as well[36]. These values reflect the inherent photosensitivity of natural anthraquinone dyes, which are prone to photooxidation and photolytic degradation upon prolonged exposure to UV light[7,37,38]. While mordants like $FeSO_4$ may marginally enhance light stability by absorbing UV radiation, additional measures such as post-treatment with UV absorbers may be necessary for outdoor or light-exposed textile applications. This study demonstrated that natural sources can be effectively provided UV absorbers for textiles. Specifically, an extract from Areca catechu was applied to nylon fabrics, where it acted as a sustainable, eco-friendly ultraviolet blocker[39].

Table 7 presented the result of dyed polyamide 6 fabrics was good to very good fastness to perspiration under both acidic and alkaline conditions, with colour change ratings of 4 and staining ratings of 4 to 5. These results underscore the stability of the dye-fibre-mordant complexes even in the presence of salt and pH fluctuations found in sweat. Thus, *Cassia fistula* contains high levels of tannins, which are water-soluble plant compounds with many hydroxyl and carbonyl groups that readily bind to fibers and dyes improving natural dye fixation on polyamide 6, thereby enhancing the fixation of natural dyes to the fibers[7,17,33].

Table 6. Colour fastness to light (ISO 105-B02: 1994) and rubbing (ISO105- X12: 2001).

Mordant Type	Light (Colour Change)	Rubbing (Colour Staining)			
		Warp		Weft	
		Dry	Wet	Dry	Wet
Without	1	4–5	4	4–5	4
$AlK(SO_4)_2$	2	4–5	4–5	4–5	4–5
$FeSO_4$	2	4–5	4–5	4–5	4–5
$SnCl_2$	2	4–5	4	4–5	4

Table 7. Colour fastness to perspiration (ISO 105-E04: 2013).

Fastness	Acid				Alkaline			
	W	Al	Fe	Sn	W	Al	Fe	Sn
Colour change	4	4	4	4	4	4	4	4
Colour staining								
-Acetate	4–5	4–5	4	4–5	4	4	4	4–5
-Cotton	4–5	4–5	4–5	4–5	4	4	4	4–5
-Nylon	4	4	4–5	4–5	4	4	4	4–5
-Polyester	4–5	4–5	4	4–5	4–5	4–5	4–5	4–5
-Acrylic	4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
-Wool	4	4	4	4	4	4	4	4

Note: W = without mordant, Al = $AlK(SO_4)_2$, Fe = $FeSO_4$, Sn = $SnCl_2$.

4. Conclusions

This study demonstrated the effectiveness of *Cassia fistula* ripe pod extract as a natural, sustainable dye for polyamide 6 (nylon 6) fabrics. Optimization experiments revealed that dyeing temperature, time, pH, dye concentration, and mordant type significantly affect dye uptake and final shade quality. The highest colour strength (K/S) was achieved at 90 °C for 60 min under acidic conditions (pH 4), where protonation of nylon's amino groups enhanced electrostatic attraction with anionic dye molecules. Increasing dye concentration (10%–70% owf) proportionally improved K/S values, with post-mordanting using alum, ferrous sulfate, or stannous chloride further enhancing dye fixation through coordination complex formation. Alum and stannous chloride yielded the highest K/S values, while ferrous sulfate produced deeper, duller tones due to its interaction with phenolic and anthraquinone dye structures.

Colour fastness testing showed good to excellent resistance (ratings 4–5) to washing, water, rubbing, and perspiration, indicating strong dye–fiber interactions. However, light fastness remained low (ratings 1–2), reflecting the photosensitivity of anthraquinone-based dyes and highlighting the need for UV protection treatments in light-exposed applications.The findings confirm *Cassia fistula* extract as a renewable, eco-friendly alternative to synthetic dyes for nylon, offering competitive colour performance under optimized conditions. Beyond its dyeing potential, the plant's documented coagulant properties present opportunities for integrated use in sustainable textile production and wastewater treatment. Future work should focus on enhancing light fastness, expanding shade range, and scaling production for industrial adoption.

Importantly, this study reports for the application of *Cassia fistula* pod waste to nylon 6, establishing a novel route for transforming agricultural residues into value-added natural dyes. By demonstrating efficient dye uptake and strong fastness performance, this work contributes to advancing sustainable dyeing practices and reducing dependence on petroleum-based synthetic dyes. From an industrial perspective, the abundant availability of *Cassia fistula* waste and the dual role as both dye source and water treatment. Future work should focus on enhancing light fastness, expanding shade range, and conducting scaling experiments to demonstrate practical viability and support industry-wide implementation.

Author Contributions

Conceptualization, T.R. and R.M.; methodology, S.U.; investigation, T.R.; resources, H.S.; data curation, J.S.; writing—original draft preparation, J.D.; writing—review and editing, K.V.; visualization, J.W.; supervision, T.R. and K.V.; project administration, K.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All data generated during this study are included in this published article.

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Conflicts of Interest

The authors declare no conflicts of interest.

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