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ORIGINAL ARTICLE

An eco-friendly dyeing of woolen yarn by *Terminalia chebula* extract with evaluations of kinetic and adsorption characteristics

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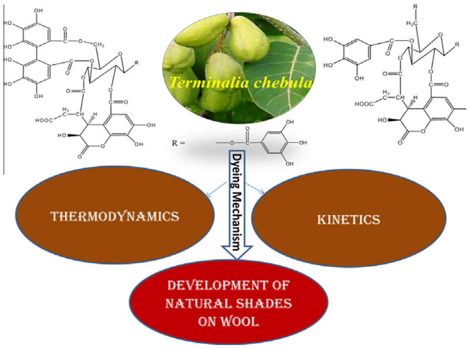
GRAPHICAL ABSTRACT



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ABSTRACT

In the present study *Terminalia chebula* was used as an eco-friendly natural colorant for sustainable textile coloration of woolen yarn with primary emphasis on thermodynamic and kinetic adsorption aspects of dyeing processes. Polyphenols and ellagitannins are the main coloring components of the dye extract. Assessment of the effect of pH on dye adsorption showed an increase in adsorption capacity with decreasing pH. Effect of temperature on dye adsorption

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showed 80 °C as optimum temperature for wool dyeing with *T. chebula* dye extract. Two kinetic equations, namely pseudo first-order and pseudo second-order equations, were employed to investigate the adsorption rates. Pseudo second-order model provided the best fit ($R^2 = 0.9908$) to the experimental data. The equilibrium adsorption data were fitted by Freundlich and Langmuir isotherm models. The adsorption behavior accorded well ($R^2 = 0.9937$) with Langmuir isotherm model. Variety of eco-friendly and sustainable shades were developed in combination with small amount of metallic mordants and assessed in terms of colorimetric (CIEL$^*a^*b^*$ and K/S) properties measured using spectrophotometer under D65 illuminant (10° standard observer). The fastness properties of dyed woolen yarn against light, washing, dry and wet rubbing were also evaluated.

Introduction

Natural dyes have been used for coloration of synthetic as well as natural textile materials such as wool, cotton, silk, nylon, fur and leather since prehistoric times. With the advent of synthetic dyes in the middle of nineteenth century, use of natural dyes declined to great extent and practically becomes unused in the beginning of 20th century [1,2]. An international awareness about environment, ecology and pollution control creates an upsurge in the use of natural dyes in the middle of 20th century. During the last few decades, increasing attention has been paid by the researchers all over the globe towards various aspects of natural dye applications [2,3].

Natural dyes/colorants derived from flora and fauna are believed to be an eco-friendly, safe and viable substitute to synthetic colorants because of their non-toxic, non-carcinogenic and biodegradable nature [4,5]. Moreover, natural dyes do not cause pollution and waste water problems. As per present trend of meeting peoples demand keeping in view ecological concerns of synthetic colorants, natural dyes are used for textile functional treatments with antimicrobial, UV-protection, de-odorizing, anti-allergic, anti-feedants, fluorescence and some other functional finishing properties [6–12]. Therefore, constantly increasing demand and new source of natural dyes are to be explored suitably and systematically for sustainable coloration of synthetic and natural textile material.

Terminalia chebula, commonly called as chebulic myrobalan/harda, belongs to family *Combretaceae* of genus *Terminalia* grown in Asian continent. *T. chebula* is a popular traditional medicine not only used in India but also in other countries of Asia and Africa. It possesses laxative, diuretic, cardiotonics, hypoglycemic, anti-bacterial [13], anti-fungal [14], antioxidant [15,16] and anticancer [17] properties. Hydrolysable tannins, chebulagic acid, chebulinic acid, gallic acid, and ellagic acid are the major tannin constituents present in myrobalans [18]. Besides the complex tannin mixture of myrobalans is also known to yield a dye C.I. Natural Red 5. Yellow dye obtained from *T. chebula* fruits can be applied to textile substrate with or without mordants to get a large range of shades of reasonable colorimetric (CIEL$^*a^*b^*$ and K/S) and fastness properties [19]. To achieve present day sophisticated demands of people, lot of research has been undertaken in the field of natural dyes for obtaining colorful and eco-friendly shades on textile materials [3,12,20]; but the fastness properties and reproducibility to give consistency in production are still to be solved. As a part of the approach to handle these problems, fundamental physical studies are important to understand the dyeing mechanism and improving the dyeing performance of natural dyes on variety of synthetic and natural textile materials.

Recently several investigations on dyeing properties of natural dyed textile materials have been undertaken using various functional finishing agents along with the evaluations of thermodynamic and kinetic parameters. Adsorption and kinetic aspects of honeysuckle extract on wool, tea polyphenols on wool, silk, and nylon, sodium copper chlorophyllin on silk, etc., have been investigated to understand the dyeing mechanism of natural dyes on textile materials [21–25]. The purpose of this research was to understand the dyeing mechanism of *T. chebula* natural dye onto woolen yarn with effective and sustainable coloration in combination with small amount of metallic mordants.

Experimental

Materials and chemicals

100% semi worsted woolen yarn (60 counts) was purchased from MAMB Woollens Ltd., Bhadohi, India. Commercial sample of extracted *T. chebula* dye in powder form was obtained from Sir Biotech India Ltd., Kanpur, India, and used without any further purification. Alum ($K_2Al_2(SO_4)_4$ṡ$24H_2O$), ferrous sulfate ($FeSO_4$ṡ$5H_2O$), and stannous chloride ($SnCl_2$ṡ$2H_2O$) used as mordant were of laboratory grade. Sodium hydrogen carbonate, phosphate, and sodium acetate buffer were purchased from Merck, Mumbai, India.

Methods

FT-IR spectroscopic investigations

Fourier Transform infrared (FT-IR) spectroscopy was performed using “Perkin Elmer Spectrum RXI FT-IR System” in order to investigate and observe fiber–dye interactions with a resolution of 2 cm^{-1}. Disks were prepared by cutting dyed and undyed woolen yarn samples into fine pieces and ground with KBr, used as internal standard. Analysis of recorded FT-IR spectrum was done in accordance with the resolution of Amide I, II and III bands.

Thermal stability of T. chebula dye by thermogravimetric analysis (TGA)

Sample for thermogravimetric characterization was analyzed using Extar 6000 TGA/DTA instrument from SII Nano Technology Inc., Japan, operating under a dinitrogen atmosphere. A heating rate of 10 °C min^{-1} was used and sample was studied between 25 °C and 300 °C (Dyeing temperature range included within this interval).

Determination of dye concentration

UV–Visible spectrophotometer (T80 + UV/Vis Spectrometer, PG Instruments Ltd.) was used for measuring absorbances as well as the absorbance spectra of *T. chebula* dye solution. Concentrations of dye in solutions were determined by using a previously established absorbance versus concentration relationship (Calibration curve) at the maximum wavelength ($\lambda_{\max}$ 308 nm) of the solution using Beer–Lambert Law having a relationship of $y = 22.06x$ [21]. As shown in Fig. 1a, *T. chebula* displays two bands: an intense absorption peak at 308 nm and another broad band around 370 nm, and the percentage of exhaustion (%E) was determined using Eq. (1) [26].

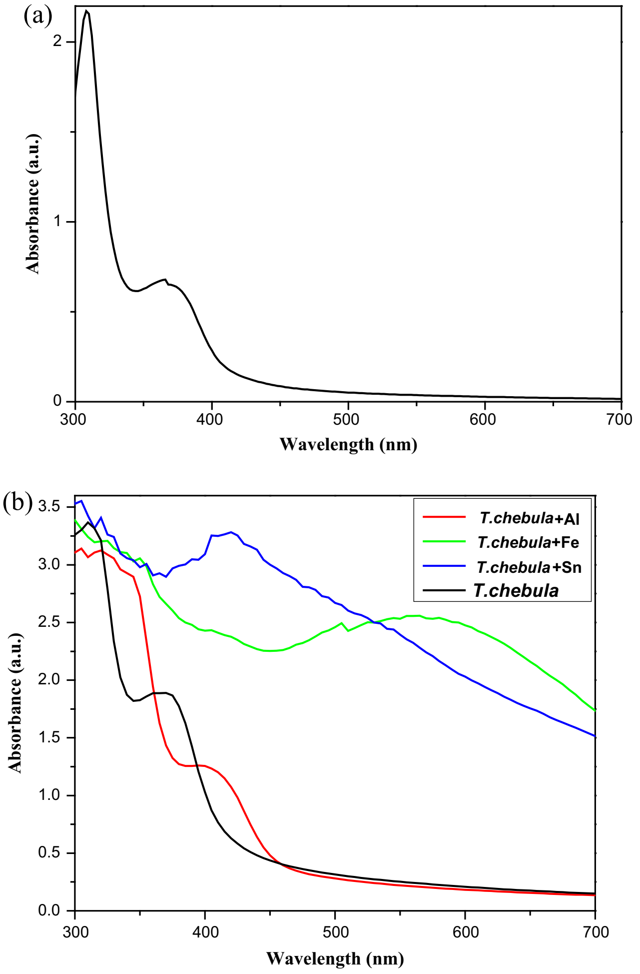


Fig. 1 (a) UV–Vis spectra of *T. chebula* natural dye. (b) UV–Visible spectra of metal treated dye solutions.

$$\%\ Dye\ uptake\ (\%E) = \frac{C_0 - C_1}{C_0} \times 100 \tag{1}$$

where C_0 and C_1 are the initial dye concentration and final dye concentration, respectively.

Effect of pH on adsorption of T. chebula extract onto woolen yarn

Woolen yarn samples were treated with 1 g L^{-1} of *T. chebula* extract at 80 °C for 60 min with material to liquor (M:L) ratio of 1:100. The treatment solution was adjusted in different pH media (pH 2–9) by means of sodium acetate, phosphate and sodium hydrogen carbonate buffer solutions. A pH/mV Meter (BD 1011) from Decibel digital technologies was used for measuring pH of dye solutions. The percentage dye uptake (%E) of *T. chebula* dye on woolen yarn was calculated according to Eq. (1).

Effect of temperature on adsorption of T. chebula extract onto woolen yarn

T. chebula dye solutions for dyeing were maintained at different temperatures (60–90 °C) for 60 min. The percentage dye uptake (%E) of *T. chebula* dye on woolen yarn was calculated as per Eq. (1).

Calculation of adsorption isotherms

The adsorption isotherms of *T. chebula* dye on woolen yarn were investigated in a series of various concentrations (0.3–2.0 g L^{-1}) at pH 4 and at 80 °C temperature for 120 min. The amount of dye adsorbed per unit weight of woolen yarn at equilibrium q_e (mg g^{-1} wool) was calculated using Eq. (2):

$$q_e = (C_0 - C_e)\frac{V}{W} \tag{2}$$

where C_0 is the initial dye concentration (mg L^{-1}), C_e is the equilibrium dye concentration (mg L^{-1}), V is the volume of dye solution (L), and W is the weight of wool fiber (g).

Calculation of adsorption kinetics

The adsorption kinetics of *T. chebula* natural dye (1 g L^{-1}) onto wool was performed at pH 4, with material to liquor (M:L) ratio of 1:100, at 80 °C for 120 min. The dye concentration C_t (mg g^{-1} wool) on the woolen yarn at time t min was calculated using Eq. (3).

$$C_t = (C_0 - C_t)\frac{V}{W} \tag{3}$$

where C_0 is initial dye concentration (mg L^{-1}), C_t is the dye concentration after t time of dyeing (mg L^{-1}), V is the volume of dye solution (L) and W is the weight of wool fiber (g).

Color measurement

The colorimetric properties of dyed woolen samples were obtained with Gretag Macbeth color-Eye 7000 A Spectrophotometer connected to a computer with installed software of MiniScan XE Plus, in terms of CIE Lab values (L^*, a^*, b^*, c^*

and $h°$) and the color strength (K/S). The color strength in visible region of spectrum (400–700 nm) was calculated based on Kubelka–Munk equation [5,9,19]:

$$\frac{K}{S}=\frac{(1-R)^2}{2R} \tag{4}$$

where (K) is absorption coefficient, (R) is reflectance of dyed samples and (S) is scattering coefficient.

The Chroma (c^*) and hue angle ($h°$) were measured by using the following equations:

$$Chroma\ (c*) = \sqrt{a^2+b^2} \tag{5}$$

$$Hue\ angle\ (h^\circ) = \tan^{-1}\left(\frac{b}{a}\right) \tag{6}$$

Results and discussion

UV–Visible characteristics of T. chebula dye extract

UV–Visible characteristics of *T. chebula* natural dye extract and different metal solutions are shown in Fig. 1b. UV–Visible spectral characteristics of metal treated *T. chebula* solutions are justifying different dye–metal interactions. Alum treated dye solution shows hypochromic shift while iron- and tin-dye solutions show hyperchromic shift with maximum shift observed in iron-dye spectrum. Iron-dye solution shows wavelength shift at 560 nm, tin at 420 nm, alum at 310 and 400 nm as compared to *T. chebula* alone at 308 and 370 nm. Similar studies were performed by Mihalick [27] to study the effect of metal ions on the color changes of tea polyphenols by the addition of iron and tin.

FT-IR analysis of wool–dye interaction

FT-IR spectra of simple and dyed woolen yarn samples are presented in Fig. 2a. Wool fiber is composed of more than 18 amino acids. The main functional groups include carboxyl (–COOH), amino (–NH2), and hydroxyl (–OH) groups. FT-IR spectra of woolen yarn samples indicate characteristic absorption peaks assigned mainly to peptide bond [8,11] determined as amide-I, amide-II, and amide-III bands [28]. The IR spectrum of pure wool fiber has distinct absorption bands: a broad one in the range of 3500–3100 cm^{-1} (–NH-stretching, –SH and –OH stretching), strong peaks at 1638, 1524, and 1226 cm^{-1} belonging to amide-I, amide-II, and –C–N stretching of amide-III, respectively [29].

All characteristic peaks of wool fiber were found in the dyed woolen yarn samples with low intensities. Low intensity and shifting of peaks relating to amide-I and C–N stretching frequency of amide-III bands of dyed woolen yarn at 3264 cm^{-1}, 1220 cm^{-1}, and 1053 cm^{-1} with an additional peak at 1399 and 2895 cm^{-1} indicate the involvement of amine groups in the interaction between fiber and dye molecules [8,11]. A probable scheme of dye–wool fiber interactions has been represented in Fig. 2b.

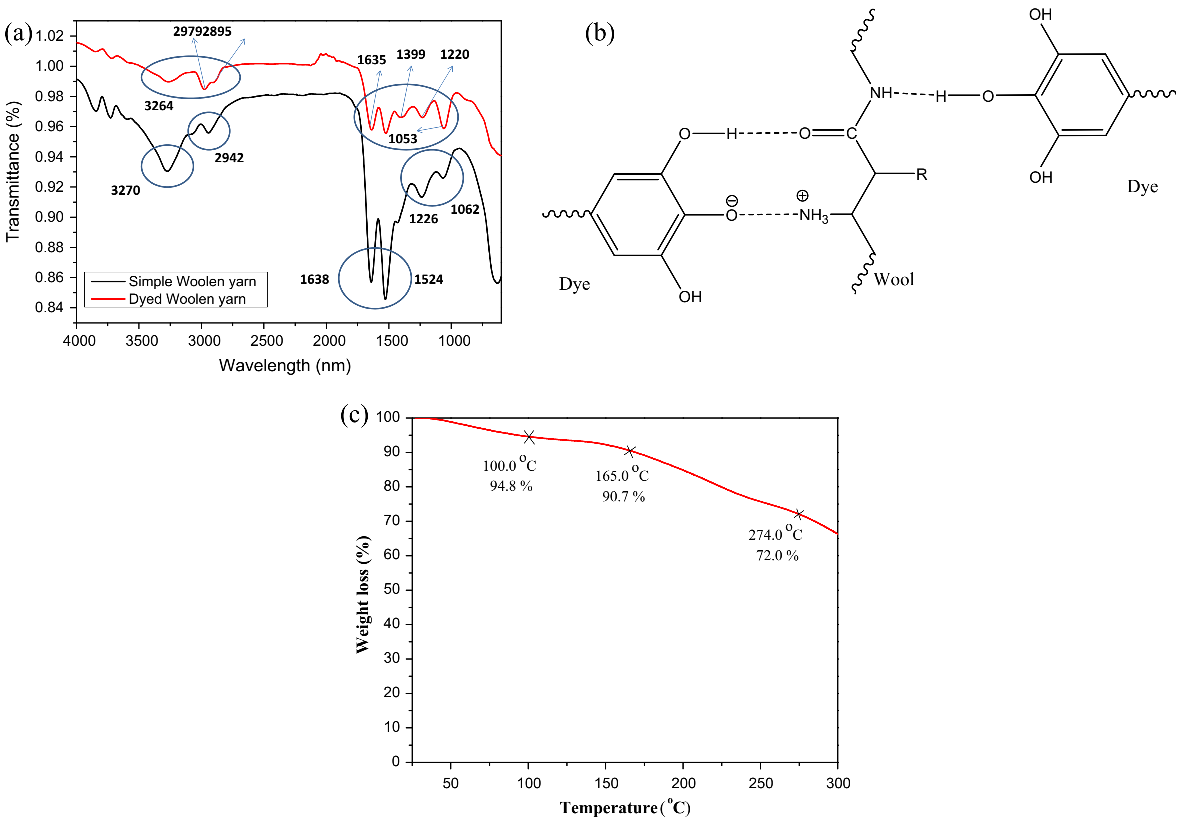


Fig. 2 (a) FT-IR spectra of undyed and dyed woolen yarn. (b) Probable scheme for interaction of dye and wool surface. (c) Thermal stability of *T. chebula* dye by thermogravimetric analysis (TGA).

Thermal stability of T. chebula dye by thermogravimetric analysis (TGA)

The thermal stability of solid sample of *T. chebula* dye was studied in terms of weight loss as a function of increasing temperature (with constant heating rate). The results of the thermogravimetric study are illustrated in Fig. 2c and confirm that the dye suffers thermal degradation at temperatures above 150 °C. A little weight loss observed in TGA graph may be attributed to water loss, adsorbed before analysis of the sample owing to the hygroscopicity of tannins [30]. It can be observed from thermogravimetric analysis, that dye compounds are enough stable up to dyeing temperature and coloring compounds as such can be utilized for adsorption on wool surface.

Effect of pH on adsorption of dye onto woolen yarn

Generally pH of dye solution plays an important role in controlling dye adsorption capacity on textile materials. *T. chebula* belongs to tannin class of natural dyes and contains hydroxyl and carboxylic acid groups. In order to find optimum dyeing pH, various dyeing experiments in the pH range of 2–9 were conducted. Inherent pH of *T. chebula* dye solution was found to be 7.41 and adjusted to 2–9 with the help of buffer solutions for dyeing shown in Fig. 3a. It indicates that adsorption capacity of woolen yarn has increased with decreasing pH from alkaline to acidic. This is mainly due to protonation of amino groups of wool in acidic pH, which is beneficial for ion–dipole interactions with hydroxyl group of color components of *T. chebula* but the carboxyl groups in the side chains are essentially unionized at lower pH values.

Effect of temperature on adsorption of dye onto woolen yarn

Temperature affects the dyeing mechanism by altering the energy of dye molecules in dye bath and swelling extent of wool and makes their interaction feasible to adsorption. The result of the study of effect of temperature on adsorption of *T. chebula* onto woolen yarn at pH 4 with initial dye concentration of 1 g L^{-1} for 60 min is shown in Fig. 3b. It can be clearly seen that with increase in temperature, percentage dye exhaustion increases first which is due to the more swelling extent of wool at high temperatures. Dye exhaustion was observed highest at 80 °C and after that with increase in temperature dye exhaustion was decreased owing to the shift of adsorption–desorption equilibrium towards right, which indicates that adsorption of *T. chebula* onto woolen yarn is controlled by exothermic process. This may be explained by the weakening of hydrogen bonds and van der Waals forces of attractions between adsorbed dye and woolen yarn at higher temperatures [21].

Effect of initial dye concentration on adsorption of dye onto woolen yarn

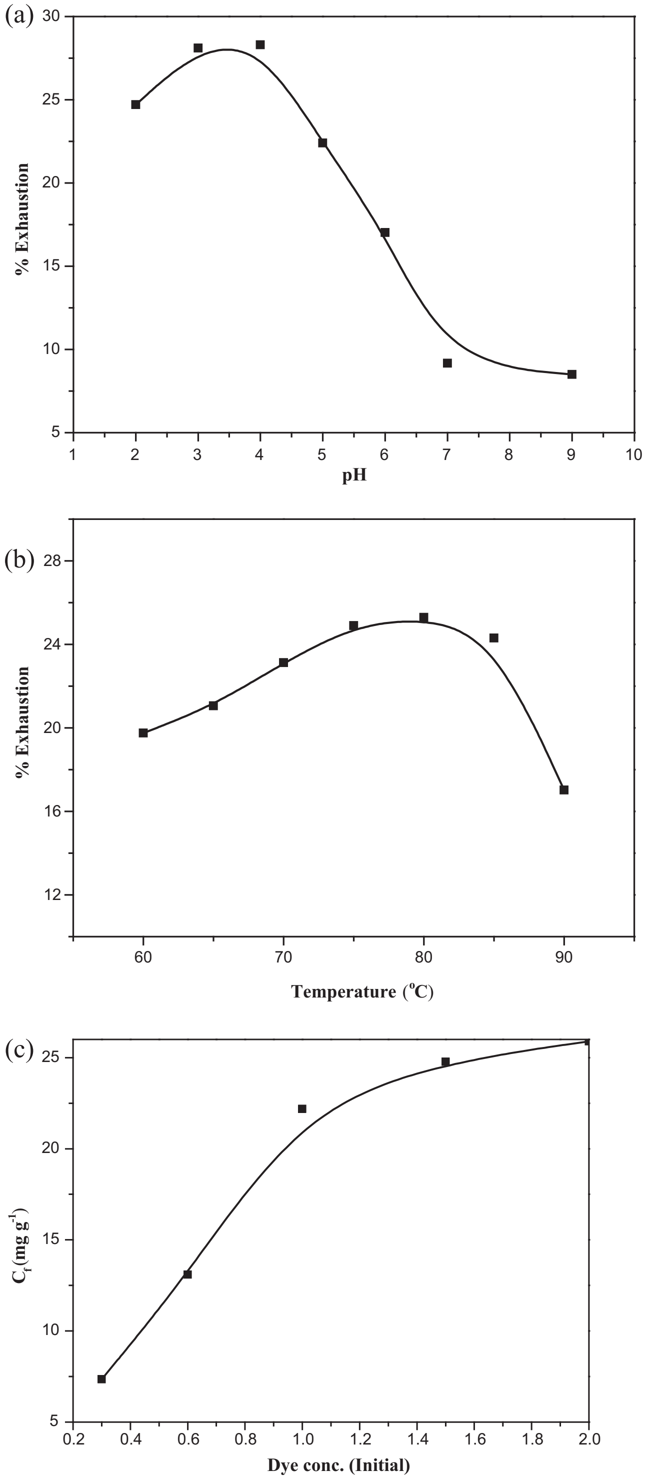


Fig. 3 (a) Dye exhaustion at different pH. (b) Dye exhaustion at different temperature. (c) Variation of adsorption capacity with initial dye concentration.

The adsorption of *T. chebula* dye at different initial dye concentrations ranging from 0.3 to 2.0 g L^{-1} onto woolen yarn is presented in Fig. 3c. It was found that adsorption capacity was concentration dependent and increased with increase in the initial concentration of *T. chebula* dye up to 1 g L^{-1}. This may be a result of an increase in the driving force of the concentration gradient with the increase in the initial dye concentration [31]. Further increase in dye concentration does not increase adsorption capacity significantly.

An initial dye concentration of 1 g L^{-1}, pH of 4 and temperature of 80 °C were used as optimized condition for determining adsorption characteristics of *T. chebula* natural dye onto woolen yarn.

Adsorption isotherm

The equilibrium adsorption isotherm is fundamental in describing the adsorbate–adsorbent interactions and is important in the design of an adsorption system. Langmuir and Freundlich isotherms were used to fit the equilibrium adsorption data of *T. chebula* dye onto woolen yarn. Fig. 4a represents adsorption isotherm curves of *T. chebula* onto woolen yarn at 80 °C and pH 4 with initial dye concentration of 1 g L^{-1}.

Langmuir isotherm

Most widely used two variable equation for determining adsorption characteristics is Langmuir isotherm. The Langmuir adsorption isotherm model has been successfully applied to many other real sorption processes [8]. Graphically, it is characterized by a plateau and an equilibrium saturation point where no further adsorption can take place, once a molecule occupies a particular site [32,33]. Moreover, Langmuir theory has related rapid decrease of intermolecular forces of attraction with increase in distance. Theoretically, a saturation value is reached beyond which no further sorption can take place. The saturated monolayer curve can be represented by the following expression [34]:

$$\frac{1}{C_f}=\frac{1}{S_c}+\frac{1}{S_cK_lC_s} \tag{7}$$

where C_f and C_s are the amount of dye adsorbed per gram of wool fiber (mg g^{-1}) and dye concentration (mg mL^{-1}) in dye bath at equilibrium, respectively. S_c (mg g^{-1} wool) is the maximum dye adsorbed per unit weight of wool fiber for complete monolayer adsorption. K_L is Langmuir constant related to affinity of binding sites (mL mg^{-1}).

Fig. 4b represents Langmuir isotherm of *T. chebula* dye onto woolen yarn at 80 °C. The values of S_c and K_l are obtained from the slope and intercept of plot between $1/C_f$ versus $1/C_s$. A linear plot with high regression coefficient (R^2 = 0.9937) suggests that adsorption mechanism could be described by Langmuir isotherm, indicating that dye molecules interact with ionic sites of fibers through ionic interactions.

Further, description of Langmuir isotherm can be also be expressed in terms of the dimensionless constant separation factor for equilibrium parameter, R_L [35,36], defined as follows:

$$R_L=\frac{1}{1+K_LC_O} \tag{8}$$

where C_0 is the initial dye concentration (mg L^{-1}) and K_L is Langmuir constant.

R_L value indicates the type of isotherm to be irreversible (R_L = 0), favorable (1 > R_L > 0), linear (R_L = 1) or unfavorable (R_L > 1) [37]. In the present study of dyeing properties of *T. chebula* onto woolen yarn, value of R_L was observed very close to 1 (0.999), indicating that the adsorption of *T. chebula* natural dye on wool fiber is favorable and linear.

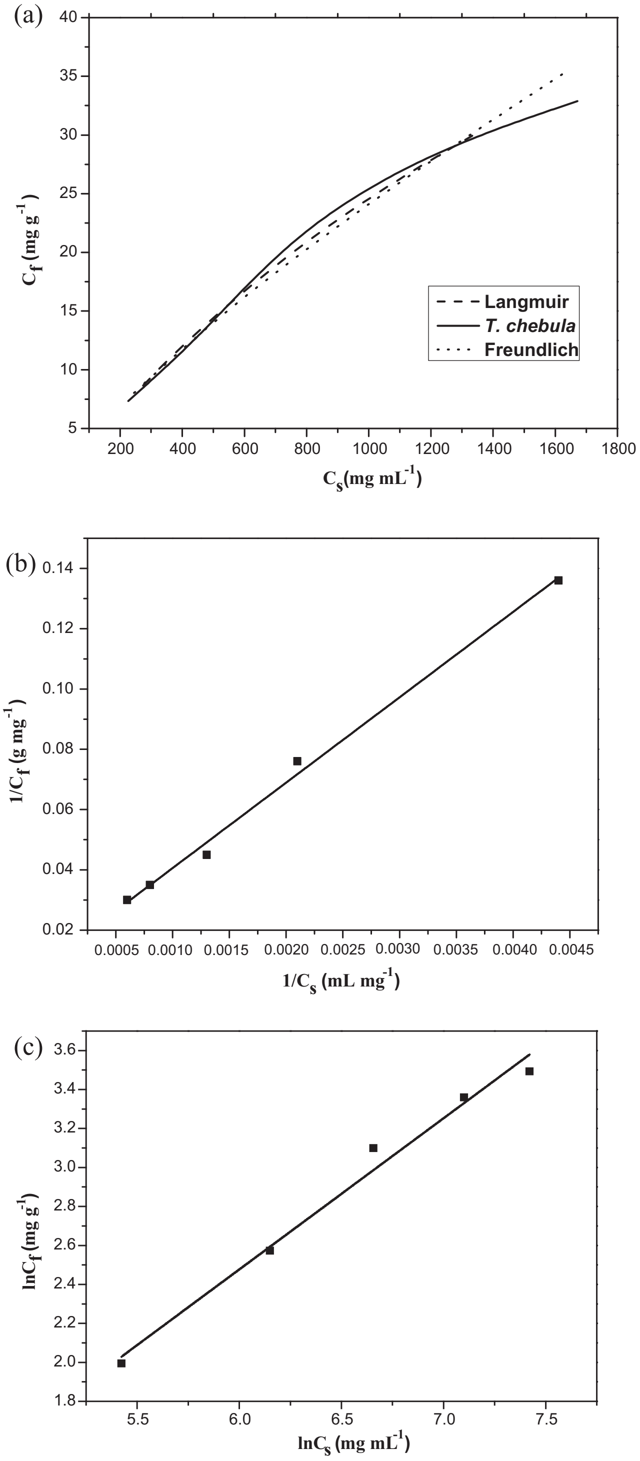


Fig. 4 (a) Sorption isotherms of *T. chebula* onto woolen yarn at pH 4 and temperature 80 °C with initial dye concentration 1 g L^{-1}. (b) Langmuir adsorption isotherm. (c) Freundlich adsorption isotherm.

Freundlich isotherm

Another adsorption isotherm is Freundlich isotherm used to describe interactions between adsorbate and adsorbent where multilayer adsorption takes place with non-uniform distribution of adsorption heat and affinities over the heterogeneous surface. Linear form of Freundlich equation can be represented as follows [34]:

$$\ln\ C_f = \ln\ K_f + 1/n \ln\ C_s \tag{9}$$

where C_f and C_s are the amount of dye adsorbed per gram of wool fiber (mg g^{-1}) and dye concentration (mg mL^{-1}) in dye bath at equilibrium respectively. K_f is the Freundlich adsorption constant and n is that of the adsorption intensity. K_f and n can be determined from slope and intercept of linear plot ($R^2 = 0.9802$) of ln C_f versus ln C_s (Fig. 4c). The magnitude of the exponent $1/n$ gives an indication of the favorability of adsorption. The value of $n > 1$ represents favorable adsorption.

Non-linear least-squares fitting procedure was used to find out most appropriate model for adsorption behavior of *T. chebula* onto woolen yarn. The adsorption characteristics for Langmuir and Freundlich models are summarized in Table 1 and results showed that Langmuir model gave the best fit to adsorption data for *T. chebula* onto woolen yarn.

Adsorption kinetics

The adsorption rate curves of *T. chebula* extract onto woolen yarn is shown in Fig. 5a. In order to examine the mechanism of adsorption process pseudo first-order and pseudo second-order equations were applied to test the experimental data. A simple kinetic analysis of adsorption is the pseudo first-order reaction which is represented as follows [38]:

$$\ln\ (C_f - C_t) = \ln\ C_f - K_1 t \tag{10}$$

where C_f and C_t are the amount of dye adsorbed per gram of woolen yarn (mg g^{-1}) at equilibrium and at any time t respectively. K_1 is the rate constant of pseudo first-order rate expression.

A straight line in the plot of ln(C_f – C$_t$) versus t determines the applicability of the kinetic model to fit the experimental data (Fig. 5b). First-order rate constant and equilibrium adsorption density C_f can be determined from the slope and intercept of the plot and are listed in Table 2, with a comparison of results in terms of correlation coefficient. Correlation coefficient for pseudo-first order reaction is 0.988.

Rate law equation for pseudo second-order kinetics is represented as follows [39]:

$$\frac{t}{C_t} = \frac{1}{K_2 C_f^2} + \frac{1}{C_f} t \tag{11}$$

where C_f and C_t are the amount of dye adsorbed per gram of wool fiber (mg g^{-1}) at equilibrium and at any time t respectively. K_2 is the rate constant of pseudo second-order adsorption.

From Table 2, it is considered that pseudo-second order reaction fits best to experimental data of *T. chebula* dyeing

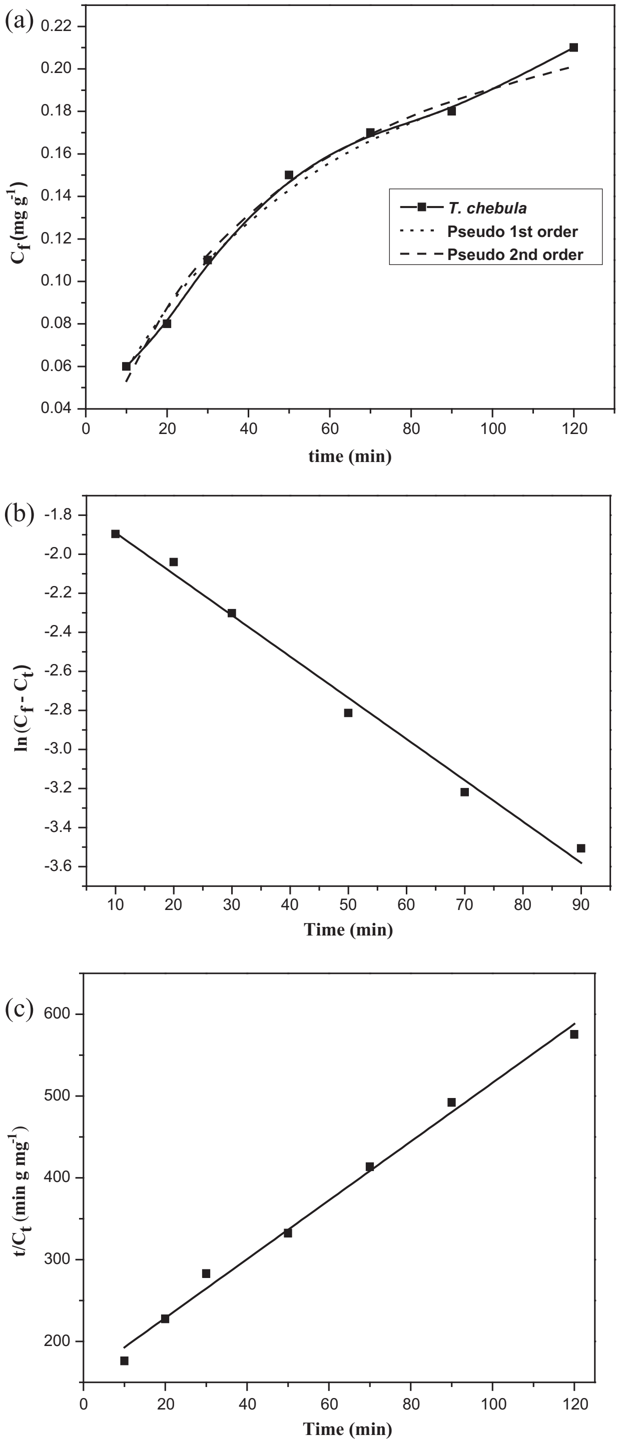


Fig. 5 (a) Adsorption kinetic curve of *T. chebula* onto woolen yarn at pH 4 and temperature 80 °C with initial dye concentration 1 g L^{-1}. (b) Pseudo first-order kinetic model. (c) Pseudo second-order kinetic model.

Table 1 Isotherm parameters for wool dyeing with *T. chebula*.

Temp. (°C)	Langmuir isotherm				Freundlich isotherm		
	S_c	K_l	R_l	R^2	K_f	n	R^2
80	81.30	4.4×10^{-4}	0.99	0.9937	8.846	1.288	0.9802

Table 2 Kinetic parameters for wool dyeing with *T. chebula*.

Temp. (°C)	Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
	C_f	K_1	R^2	C_f	K_2	R^2
80	5.354	0.021	0.9888	0.278	0.082	0.9908

onto woolen yarn with high regression coefficient of 0.9908 (Fig. 5c). Rate constant and adsorption capacity of woolen yarn calculated through fitting of pseudo second-order are given in Table 2. High correlation coefficient of pseudo second-order model suggests that overall mechanism of adsorption of *T. chebula* onto woolen yarn is controlled by chemisorption process involving valency forces through the sharing or exchange of electrons between the adsorbent and adsorbate as covalent force and ion exchange [21]. The possible interactions for chemisorptions may be H-Bonding and ionic interactions between fiber surface and dye molecules shown in Fig. 2b.

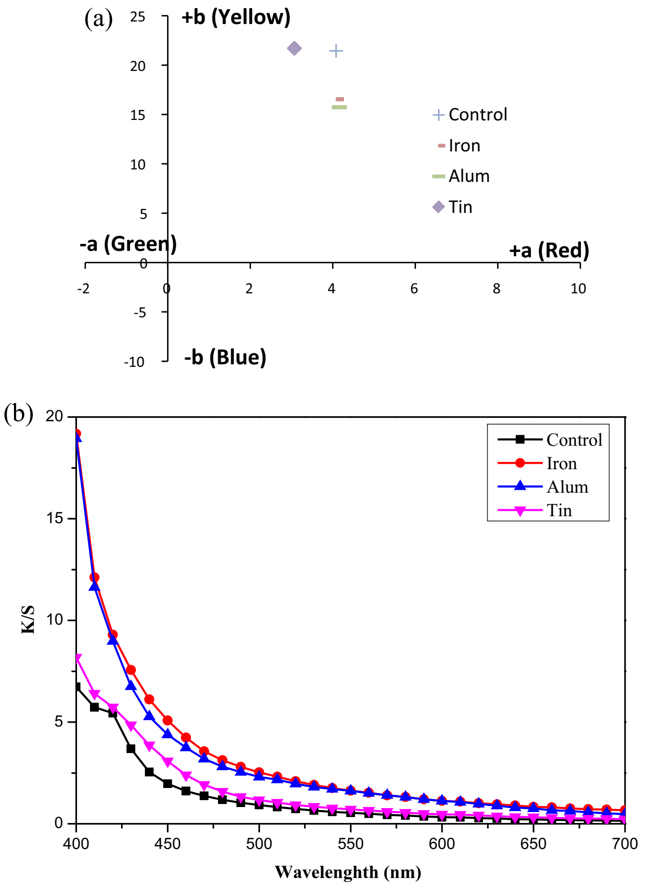


Fig. 6 (a) a^*b^* plot of *T. chebul*a dyed woolen yarn. (b) Effect of metal salts on the color strength woolen yarn dyed with 1 g L^{-1} of *T. chebula* dye.

Colorimetric properties

In practical dyeing and finishing processes, dyeing time cannot be as long as that of thermodynamic studies. Therefore, optimal conditions for assessment of colorimetric properties were considered as 80 °C temperature and pH 4 for 60 min. The colorimetric properties of *T. chebula* dyed woolen yarn depend on its affinity to wool fiber and dyeing mechanism, which are of great importance for practical use and efficient dyeing processes. From a^*–b^* plots (Fig. 6a and Table 3), it is evident that woolen yarn samples dyed with *T. chebula* extract showed yellowish color in the red-yellow coordinate of color space diagram, hue angle ranging between 74° and 90° for unmordanted as well as mordanted samples with high lightness (L^*) and low chroma (C^*) indicating light and bright shades. Mordanting has appreciable effect on colorimetric properties with large shifts observed in L^*, a^*, b^*, c^* and $h°$ values. Shift toward yellow co-ordinate was higher in case of alum mordanted samples. Mordanted samples show higher K/S values as compared to unmordanted ones. The mordant activity sequence was found to be $FeSO_4$ > Alum > $SnCl_2$ > control (Fig. 6b). Metal mordants especially d-block elements have coordination complex forming ability and therefore readily chelate with the dye molecules forming ternary complexes eventually resulting in higher color strength values [40].

Fastness properties

Fastness properties of *T. chebula* dyed woolen yarn are shown in Table 4. Control dyed as well as mordanted samples show good light fastness rating of 5 except tin mordanted samples showing light fastness of 3–4. *T. chebula* showed color change

Table 3 CIEL$^*a^*b^*$ values of *T. chebula* dyed woolen yarn.

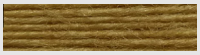
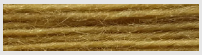
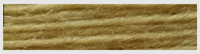
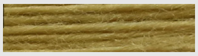
Dye conc.	Mordant	L^*	a^*	b^*	c^*	$h°$	Shades obtained
1 g L^{-1}	Control	60.69	4.08	21.44	21.82	79.22	
	$FeSO_4$	44.43	4.09	16.54	17.03	76.11	
	Alum	44.94	4.16	15.73	16.27	75.18	
	$SnCl_2$	56.60	3.07	21.70	21.91	89.91	

Table 4 Fastness properties of *T. chebula* dyed woolen yarn.

Dye (*T. chebula*)	Mordant	Light fastness	Wash fastness			Rub fastness	
			c.c.	c.s.	c.w.	Dry	Wet
1 g L^{-1}	Control	5	4–5	5	5	4–5	4–5
	Iron	5	3–4	5	5	4–5	4–5
	Alum	5	5	5	5	3–4	3–4
	Tin	3–4	4	5	5	4–5	4–5

c.c. = color change; c.s. = staining on cotton; c.w. = staining on wool.

and staining of 3–4 and 5 on adjacent cotton and wool fabrics, respectively. Dry and wet rub fastness ratings were found in the range of 4–5 for control, iron and tin mordanted samples while alum mordanted samples possess 3–4 dry and wet rub fastness. Rub fastness data indicate that mordanting has increased resistance of transfer of color to adjacent fabrics.

Conclusions

This study is the first to investigate thermodynamic and kinetic aspects of dyeing of *T. chebula* dye onto woolen yarn. Percentage dye exhaustions were significantly affected by pH and temperature. It was seen that dye exhaustion was more at lower temperatures, hence proving exothermic nature of *T. chebula* dyeing on woolen yarn. Kinetic and thermodynamic aspects of this study revealed fitting of experimental data to pseudo second-order and Langmuir isotherm model. a^*–b^* plots of control dyed and mordanted woolen yarn were found in the red-yellow coordinate of color space diagram. Mordants effectively increased color strength of dyed woolen yarn by increasing wool–dye interaction by chelation. Wash and rub fastness data indicate that mordanting has increased resistance of color transfer to adjacent fabrics.

Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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