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Development and optimization of natural dye-based crayons from *Rumex abyssinicus* using Box-Behnken methodology

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Abstract

This study presents the first exploration of natural dye extracted from *Rumex abyssinicus* for crayon formulation, leveraging its local availability and environmental sustainability. The work focused on evaluating the effects of paraffin wax, talc, extracted dye, and temperature on the crayon's properties. Characterization techniques, including UV–vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), tensile strength testing, visibility, and durability assessments, were employed to analyze the formulated crayon. A Box-Behnken design within the Response Surface Methodology framework was used to optimize the formulation by varying paraffin wax (4, 6 and 8 g), dye (0.5, 1.25 and 2 g), talc (5, 7 and 9 g), and temperature (80, 90 and 100 °C), while keeping stearic acid (0.5 g) and beeswax (1 g) constant. UV–vis spectroscopy revealed a maximum absorbance of 0.830 at λ_{max} of 298.7 nm, indicating strong pigment retention. The crayon exhibited a tensile strength of 1.48 N/mm^2 and a percentage elongation at break of 1.34%, reflecting its durability and flexibility. These findings demonstrate the feasibility of utilizing Rumex abyssinicus dye in eco-friendly crayon production, offering a sustainable alternative with desirable mechanical and aesthetic properties.

Keywords Absorbance, Box-Behnken, Characterization, Crayon, Rumex abyssinicus, Optimization

Introduction

Crayons are widely used artistic and educational tools that support children's creativity and cognitive development. Traditionally, crayons are produced from combinations of waxes, oils, and pigments, including materials such as paraffin wax, beeswax, polyvinyl alcohol, and various organic and inorganic colorants (Bradish 1962; Harwood 2017; Sunday & Conley 2020). Although industrial and patented methods describe different formulations, the majority of these approaches rely on synthetic pigments and petroleum-derived waxes, which raise concerns regarding environmental impact, toxic chemical exposure, and waste generation (Kim et al. 2024; Lyu et al. 2022; Triana & Pamungkas 2022). These limitations have motivated a growing interest in natural pigment sources and bio-based binders that can support safer and more sustainable crayon production.

Recent studies have explored natural dyes extracted from agricultural wastes and plant materials, such as chestnut shells, dragon fruit peels, black bean hulls, and edible vegetable-based colorants (Desai et al. 2023; Renita et al. 2023; Singh et al. 2023). Compared with synthetic dyes, natural pigments generally exhibit lower

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toxicity, are biodegradable, and reduce environmental burdens during production and disposal (Dave et al. 2022; Renita et al. 2023). Several assessments in the literature have demonstrated that natural colorants have reduced ecological footprints and avoid heavy metals, aromatic amines, and halogenated compounds often present in synthetic pigments (Gürses et al. 2016; Lin et al. 2023; Periyasamy 2024; Randhawa 2024). These advantages align with global interest in cleaner production and safer children's products.

Rumex abyssinicus is a promising plant-based dye source that has not yet been investigated for crayon formulation. The plant contains high concentrations of anthraquinone derivatives such as chrysophanol, emodin, and physcion, which produce strong yellow-to-orange color shades and have excellent thermal stability (Bekele et al. 2024a; Genet et al. 2020; Mohammed et al. 2018, 2020). These pigments are known for good resistance to photodegradation, stability during heating, and compatibility with lipid-based matrices, making them suitable for wax systems used in crayons. *Rumex abyssinicus* is also widely available in Ethiopia and other African regions (Adamu et al. 2020; Yrga Adugna et al. 2022), making it a low-cost, renewable, and culturally relevant resource with socioeconomic value for local communities involved in cultivation, harvesting, or dye extraction. Its long history of traditional use in textile dyeing supports its safety profile for applications intended for children.

Only limited studies have reported natural crayon production using plant extracts, edible pigments, and bio-based wax blends (Nhi & Hanh 2024; Permatasari et al. 2024; Salunke et al. 2024), and even the available literature does not address plant dyes with high color intensity, thermal resilience, and local accessibility. Existing patents and manufacturing approaches mainly focus on improving strength, elasticity, or erasability, but do not address the need for environmentally sustainable pigment systems**.** This creates a clear technical gap in developing crayons based on locally sourced natural dyes with optimized performance. To address this gap, the present study focuses on formulating and optimizing crayons produced with natural dye extracted from *Rumex abyssinicus*. This study investigates dye extraction, dye–wax compatibility, thermal behavior during crayon formation, and the combined effect of key processing variables. Optimization was performed using the Box Behnken design of Response Surface Methodology to determine the ideal formulation for color intensity, hardness, and durability. To the best of our knowledge, this is the first study to utilize *Rumex abyssinicus* dye for crayon development and to apply systematic optimization to achieve a stable, effective, and environmentally friendly natural crayon product.

Table 1 Crayon production experimental design

Variables	Lower (−1)	Middle (0)	Higher (+1)
Paraffin wax amount (g)	4	6	8
Talc amount (g)	5	7	9
Dye amount (g)	0.5	1.25	2
Temperature (°C)	80	90	100

Materials and methods

Dye extraction from *Rumex abyssinicus* root

The root of *Rumex abyssinicus* was collected from Assela, Ethiopia. Paraffin wax, beeswax, stearic acid, and talc powder were purchased from local suppliers. Ethanol (analytical grade) was used as the extraction solvent. All chemicals were used as received without further purification. The natural dye used in this study was extracted based on the optimized conditions obtained from our previously published work (Bekele et al. 2024b). The roots were washed with tap water, peeled, cut into small pieces, air-dried for 2 h, and then oven-dried at 105 °C for 24 h. The dried roots were ground using a ball mill to a particle size of 0.355 mm**.** For extraction, 25 g of ground root was placed in a Soxhlet thimble containing 250 mL of ethanol. The extraction was performed at the boiling temperature of ethanol (~78 °C) for 5 h**,** which corresponds to the optimized extraction time from our previous study. After extraction, the ethanol containing the dye was concentrated using a rotary evaporator at 50 °C under reduced pressure. The extraction yield under these conditions was 53%**,** and the resulting dye solution was adjusted to 10 mg/mL for subsequent crayon formulation experiments. This approach ensured the reproducibility and efficiency of dye extraction, leveraging the previously validated Box–Behnken optimization of particle size, solid-to-liquid ratio, and extraction time.

Crayon formulation experimental design

Crayon production was optimized using a Box–Behnken Design (BBD) within Response Surface Methodology, considering four independent variables: paraffin wax amount (4, 6, 8 g), talc amount (5, 7, 9 g), dye amount (0.5, 1.25, 2 g), and processing temperature (80, 90, 100 °C). Each factor was coded at three levels (− 1, 0, + 1) as shown in Table 1. The BBD reduced the total number of experiments from 81 (full factorial) to 24 runs while maintaining statistical rigor. Color absorbance was used as the primary response variable.

Crayon preparation

Crayons were formulated by combining paraffin wax, beeswax, stearic acid, talc powder, and natural dye at the specified experimental levels. Paraffin wax was first melted at 68 °C, while beeswax was melted separately at 65 °C. The molten waxes were then combined and stirred at 300 rpm until a homogeneous mixture was obtained.

Talc powder and pre-melted stearic acid (69.3 °C) were incorporated into the mixture to enhance hardness and surface finish. Subsequently, the natural dye was added at the designated temperature (80, 90, or 100 °C) and stirred for 3 min to ensure uniform dispersion. The resulting molten blend was poured into molds and allowed to solidify at room temperature for 2 h before demolding (Mcallister et al. 2017) (Fig. 1).

Crayon characterization

Fourier Transform Infrared Spectrometer (FTIR)

Fourier Transform Infrared Spectrometer (FTIR) is an analytical technique employed to identify organic, polymeric, and, occasionally, inorganic materials. Moreover, it facilitates the study of the functional group changes in formulated crayons. The FTIR spectroscopy analysis of crayons formulated from ingredients such as paraffin wax, talc dye, stearic acid, and beeswax reveals the chemical composition and bonding arrangement of ingredients in homo-polymer, copolymer, and polymeric materials. Infrared (IR) spectroscopy, operating within the wavelength range of 4000–400 cm^{-1}), is utilized for this purpose (Mangam et al. 2024).

Double beam UV–vis spectrophotometer

In this study, UV–Vis spectra were utilized for the optimization of crayons, with absorbance serving as the response variable. The SM-1600 Spectrophotometer was employed for this purpose. Additionally, UV–Vis spectra were used to characterize both the optimized crayon and commercial crayon, comparing absorbance as a function of wavelength. Measurements of absorbance were scanned across the region from 200 to 700 nm to gather comprehensive data for analysis. The absorbance of a coloring matter solution is determined at its wavelength of maximum absorption (λ_{max}) (La Nasa et al. 2021).

Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is a thermal analyzer that depicts the mass of the sample versus temperature. TGA thermograms illustrate weight loss and derivative weight loss across a temperature range from standard (25 °C) up to 700 °C for both formulated and commercial crayons. This method yields valuable information that can be leveraged to predict material lifespan, select materials for specific end-use applications, anticipate product performance, and enhance product quality and thermal stability. In the process of thermogravimetric analysis, a small quantity of the sample (30 mg) is placed in a vial within the TGA analyzer instrument (SDT Q600 V20.9 Build 200). Thermal degradation of the isolated compounds manifests with a degradation peak, particularly noticeable in the colorant, showcasing weight loss across the temperature range from 25 °C to 700 °C (Mohammed et al. 2017).

Tensile strength

Tensile strength is defined as the maximum stress a material can withstand under uniaxial tension before failure, expressed as force per unit cross-sectional area. In this study, the tensile strength of the crayons was measured using a WP 310 universal testing machine (50 kN capacity). Although tensile testing is more commonly applied to films or ductile materials, this method was adapted for solid cylindrical crayons (10 mm diameter, 85 mm height) to assess their mechanical integrity under longitudinal stress. Each crayon specimen was mounted vertically between the machine grips and subjected to a controlled, uniaxial pulling force until fracture. The maximum force at failure was recorded, and the tensile strength was calculated using Eq 1.

$$\text{Tensile strength } (\text{N/mm}^2) = \frac{Force(N)}{Area(Width \times Thickness)} \quad (1)$$

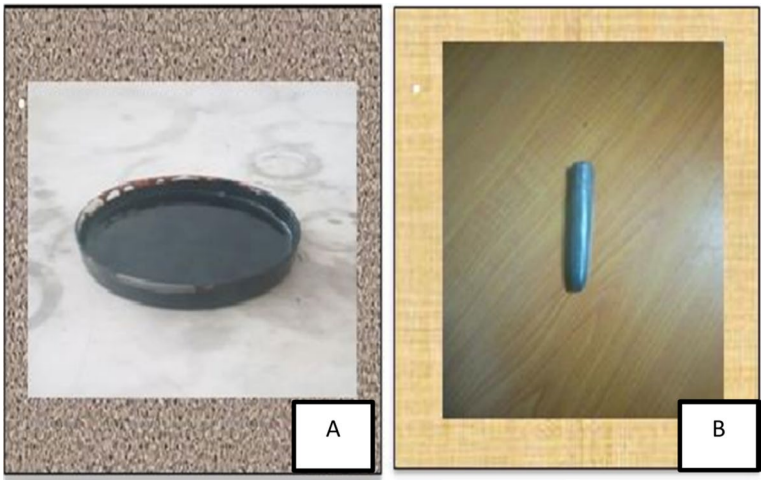


Fig. 1 Crayon production from *Rumex abyssinicus* based dye: **a** (extracted dye) and **b** (prepared crayon)

where the cross-sectional area was calculated from the specimen diameter. Percent elongation at break (%) was determined using Eq. 2.

$$\text{Percentage of strain } (\%) = \frac{finallengthatbreak - initiallength}{initiallength} \quad (2)$$

This approach, adapted from previous studies on brittle or composite cylindrical materials (Noda et al. 2016), allowed evaluation of both tensile stress and elongation at fracture, providing insights into the mechanical performance of the crayons under handling conditions.

Binding and durability test

The binding of color in formulated crayons for drawing was evaluated based on the adherence of the color to the material surface. The visibility of the color on the material indicated the effectiveness of the binding process. The durability of the color was assessed by subjecting the colored material to various environmental conditions. This included exposure to sunlight at standard temperature for 7 days, storage in a room without sunlight for 7 days, and placement in an oven at 50 °C for 2 days. These temperature variations aimed to simulate different environmental conditions and assess the color's resistance to fading or degradation. Test specimens were subjected to compression under ordinary temperature differences to evaluate the durability of the color on the material (Baliarsingh et al. 2012).

Results and discussions

Crayon characteristics

Characterization of UV–visible spectroscopy

The optical properties of the crayon samples were analyzed using a UV–Visible spectrophotometer, measuring absorbance (A) across a wavelength range of 200–800 nm. The resulting spectra (Fig. 2) were used to evaluate the absorption maxima (λmax) and infer structural characteristics of the pigments. The formulated crayon exhibited a distinct absorption maximum (λmax = 298.7 nm) with an absorbance of 0.8303. This strong UV absorption is attributed to the presence of conjugated double bonds and anthraquinone chromophores in the *Rumex abyssinicus* dye, including chrysophanol, emodin, and physcion. These chromophores possess extended π-electron systems that facilitate electronic transitions ($\pi \rightarrow \pi^*$) under UV irradiation, which is responsible for the observed λmax and contributes to the vivid coloration of the crayon. The relatively high

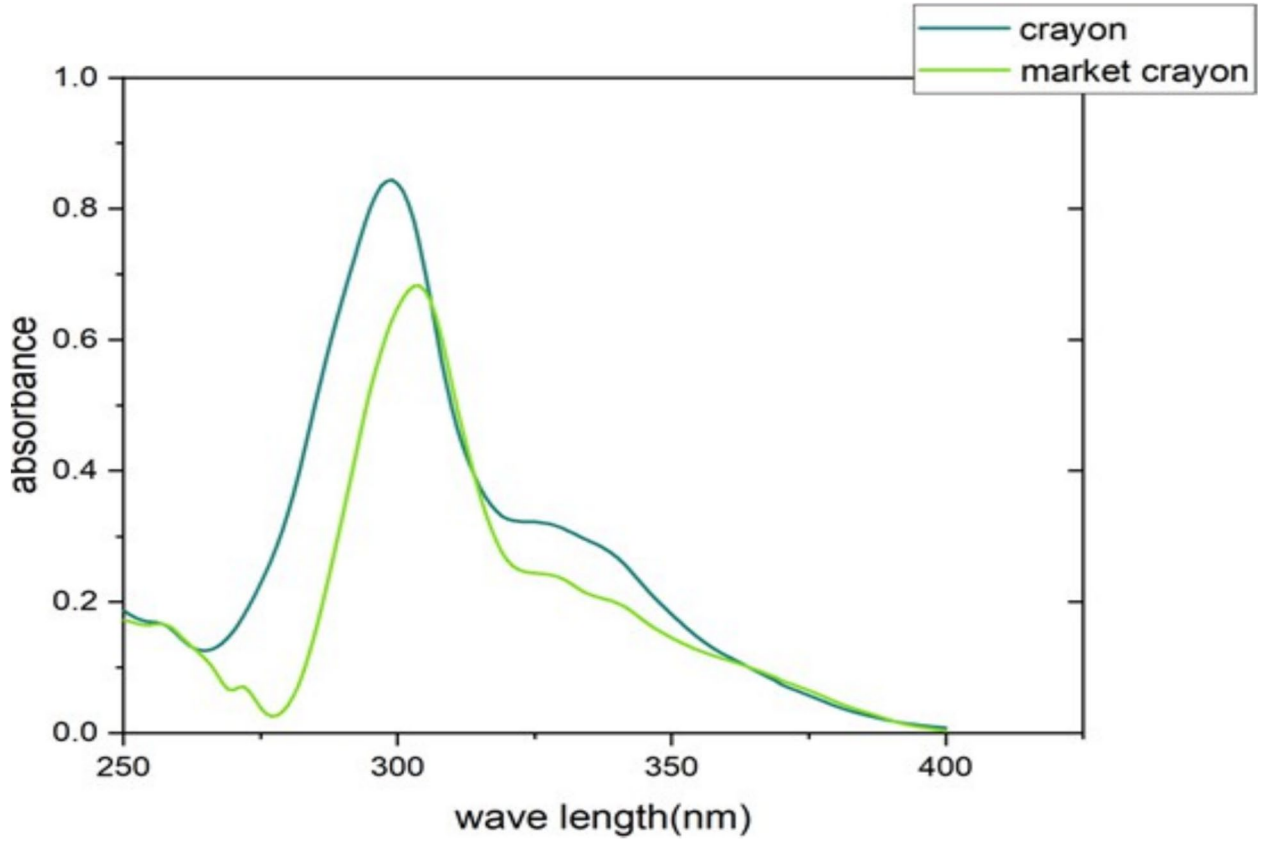


Fig. 2 UV–Visible Spectroscopy for formulated and commercial crayons

absorbance also reflects the effective incorporation and concentration of the natural pigment in the wax matrix.

In comparison, the commercial crayon displayed a maximum absorbance at λmax = 305.5 nm with an absorbance of 0.68. The commercial product contained a moderate concentration of black synthetic pigment, which primarily absorbs in the near-UV to visible region. While black pigments absorb broadly across the visible spectrum, the near-UV absorption observed here corresponds to the aromatic or conjugated structures present in the synthetic dye. Essentially, the spectral comparison demonstrates that the naturally dyed crayon exhibits stronger UV absorption at its λmax, consistent with the presence of conjugated anthraquinone structures, whereas the commercial crayon shows lower absorbance due to its pigment composition. These results align with reported UV–Visible characteristics of natural and synthetic dyes, highlighting the effective light absorption and potential color intensity of the *Rumex abyssinicus*-based crayon (Kafle et al. 2014).

Fourier transformation infrared (FT-IR) analysis of crayon

Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the functional groups present in the formulated crayon, as illustrated in Fig. 3. The absorption peak at 3697.91 cm^{-1} corresponds to N–H stretching vibrations, while the broad peak observed at 3390.00 cm^{-1} is indicative of hydrogen-bonded –OH stretching, characteristic of alcohols and phenols, which may arise from components such as the natural dye, talc, and stearic acid. The peak at 2939.79 cm^{-1} is attributed to C–H stretching vibrations of alkanes, confirming the presence of paraffin wax. A nearby peak at 2849.90 cm^{-1} corresponds to C–H stretching in aldehydes. The absorption band at 1627.42 cm^{-1} signifies C = C bending vibrations of alkenes and is associated with the beeswax component. A peak at 1497.65 cm^{-1} suggests the presence of aromatic C = C stretching, which may also be contributed by stearic acid. The signal at 1002.44 cm^{-1} indicates C–F stretching of alkyl fluorides. Additionally, the peak at 675.39 cm^{-1} is consistent with disubstituted cis-2R–2H bending, while the band at 490.64 cm^{-1} corresponds to C–I stretching vibrations in alkyl halides. These spectral features confirm the successful incorporation of both wax matrices and natural organic dye components in the crayon formulation (Rotich et al. 2022; Sabyrkhanova et al. 2022).

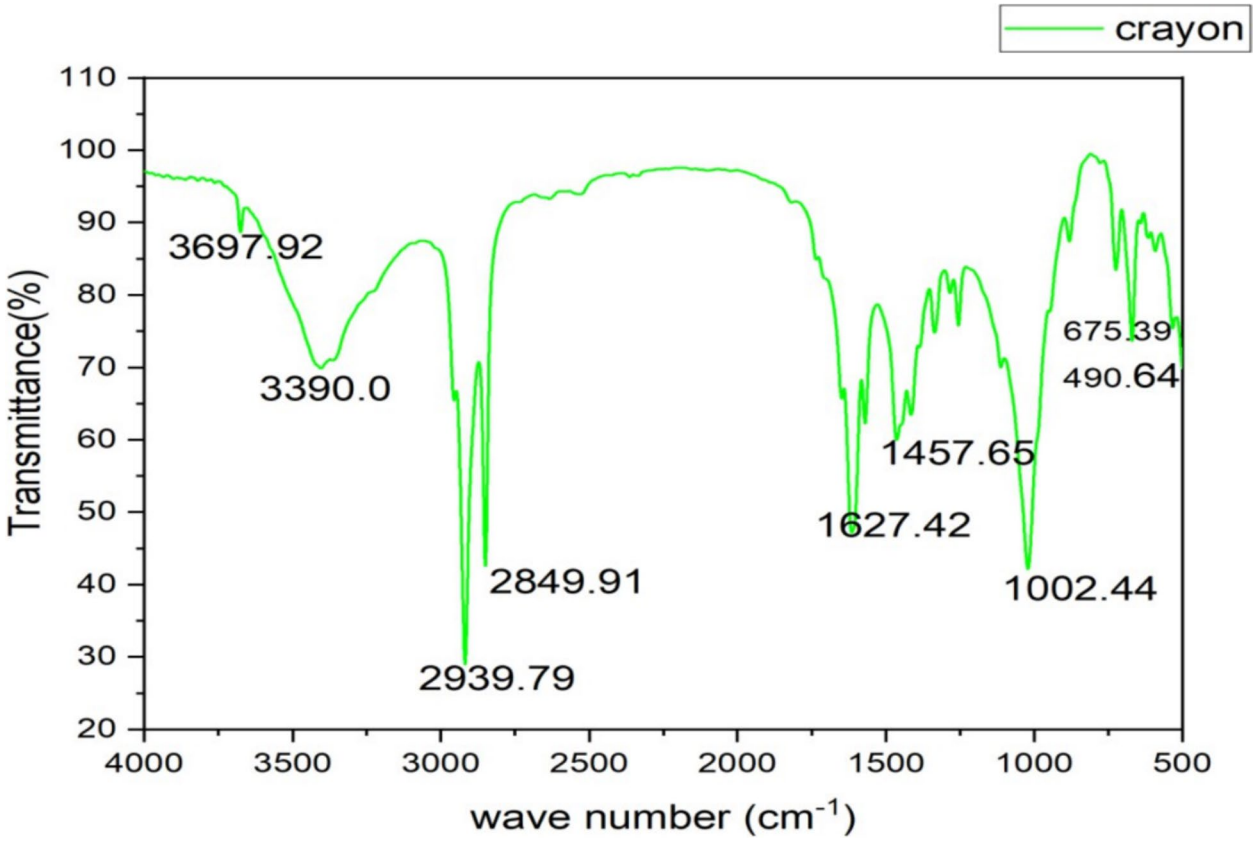


Fig. 3 FTIR analysis of crayon

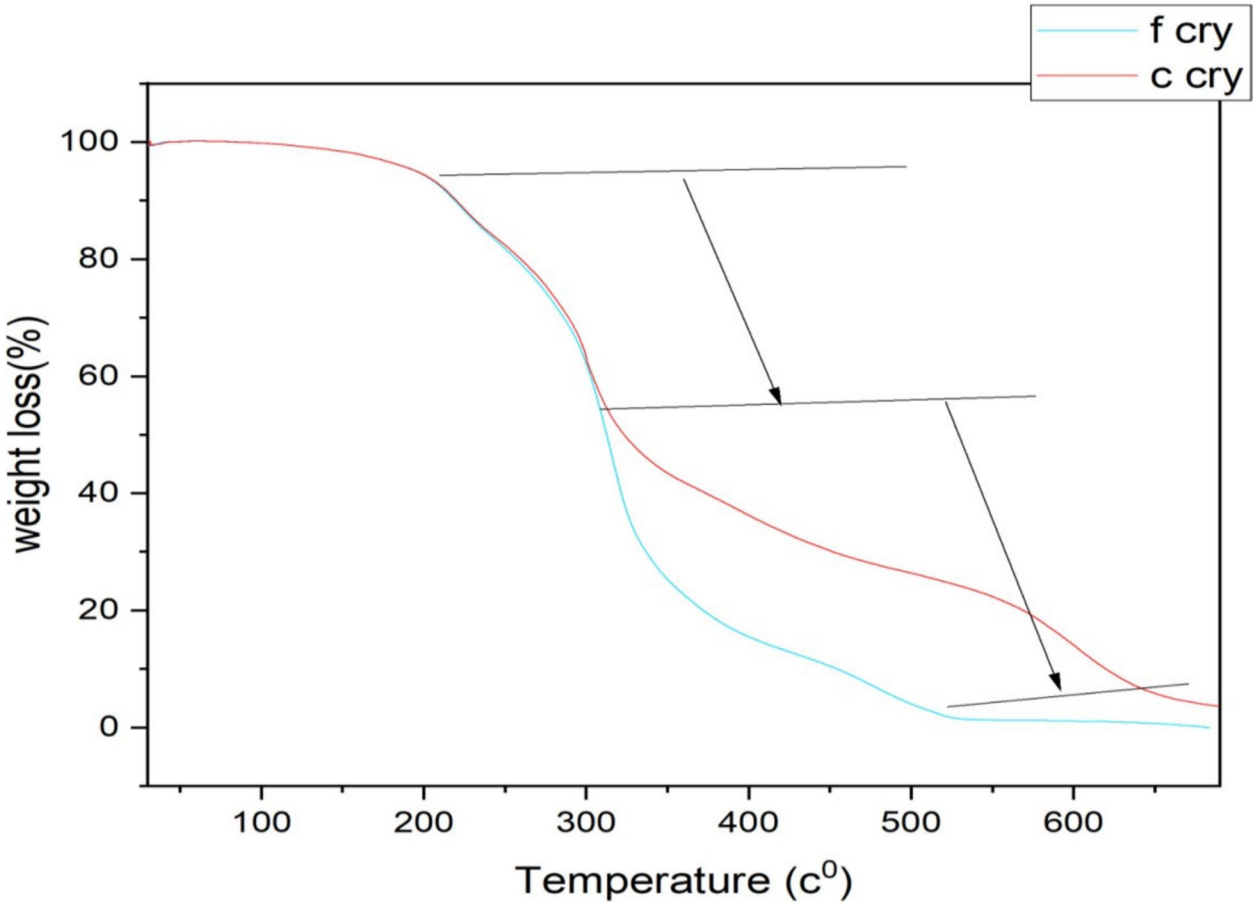


Fig. 4 TGA for formulated (f cry) and commercial crayons (c cry)

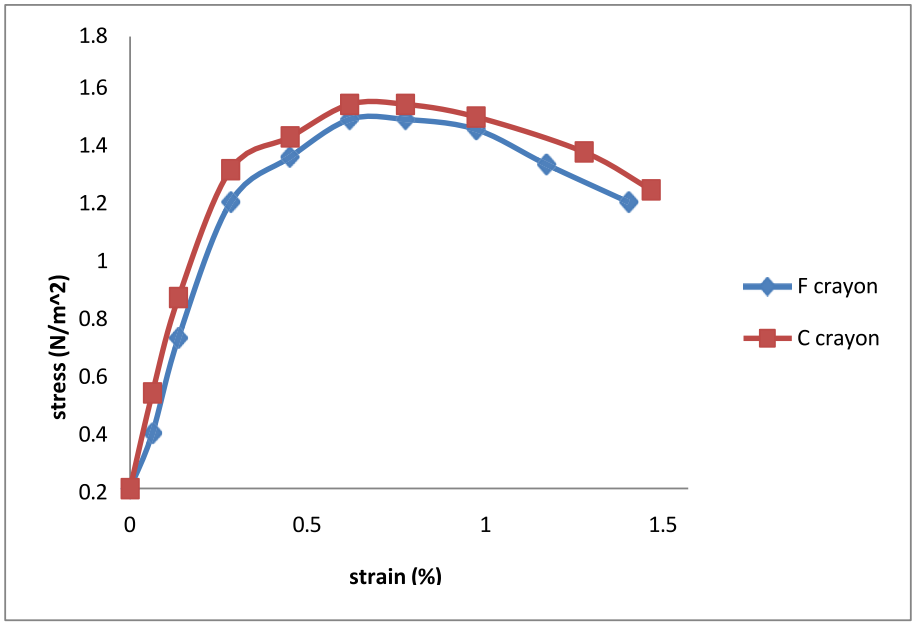


Fig. 5 Graph of stress versus elongation of break test for commercial and formulated crayons

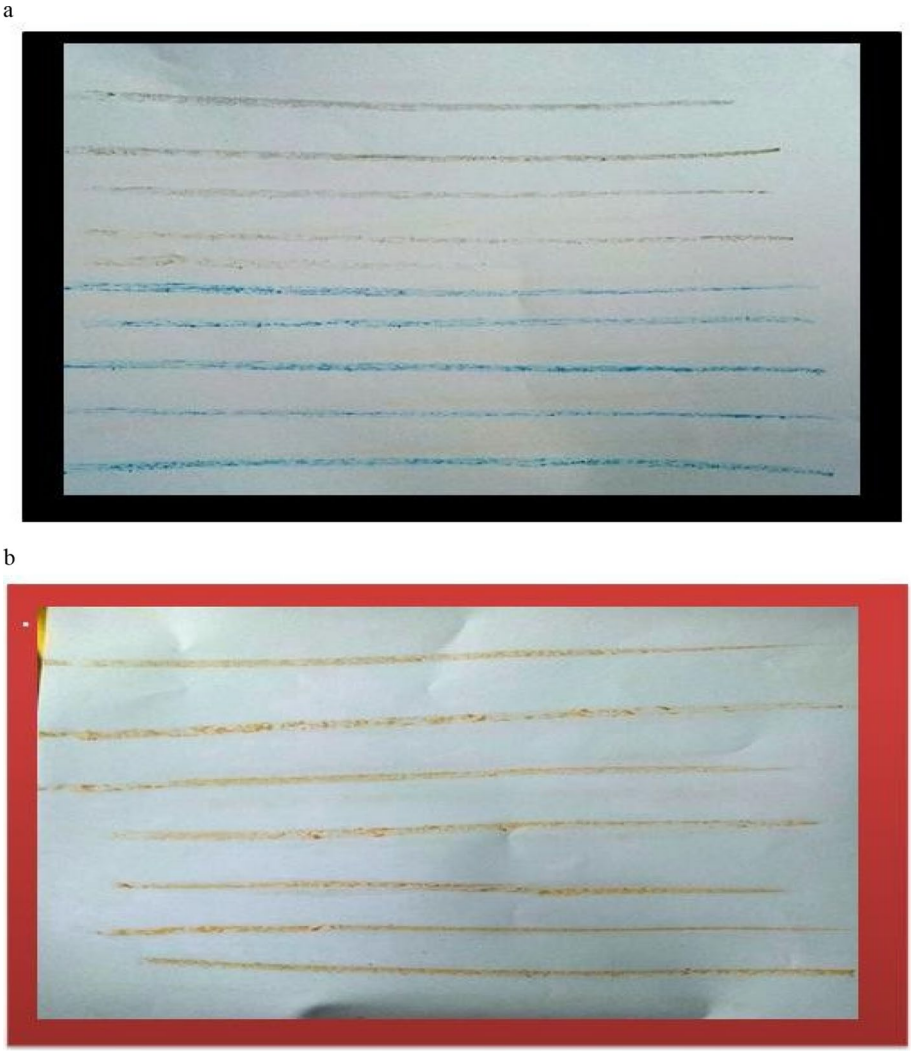


Fig. 6 Color of commercial crayon on paper (**a**) and formulated crayon (**b**)

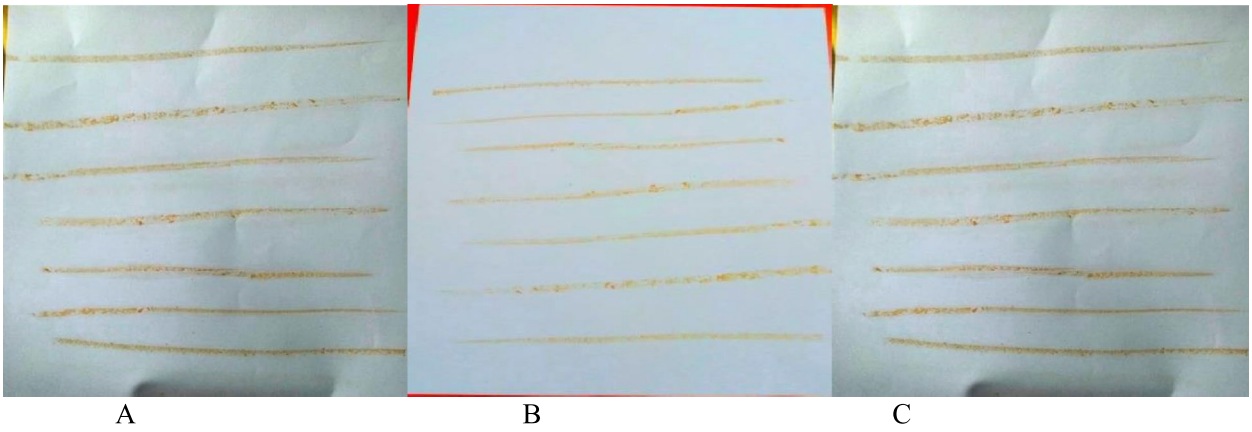


Fig. 7 Durability test of the formulated crayon: (**A**) for 7 days (sunlight), (**B**) for 7 days (indoors), and (**C**) for 2 days (in an oven)

Thermo gravimetric analysis of crayon

Thermogravimetric analysis (TGA) was conducted to evaluate the thermal stability and decomposition behavior of both the formulated natural-dye crayons and commercial crayons (Fig. 4). TGA allows quantitative assessment of mass changes associated with moisture loss, thermal degradation, and char formation. The TGA curves revealed three distinct stages of mass loss for both samples. The first stage (up to ~ 112 °C) corresponded to the evaporation of surface-bound moisture and low-boiling volatiles. In the second stage, representing the primary degradation phase, the formulated crayon exhibited major weight loss between 207.72 °C and 528.41 °C, with a Tmax (maximum degradation rate) at 312.5 °C**,** while the commercial crayon showed substantial degradation from 207.72 °C to 660.81 °C**,** with T_{max} at 374.3 °C. The onset degradation temperature (T_{onset}) was 205.8 °C for the formulated crayon and 206.1 °C for the commercial sample. The third stage involved final decomposition and conversion to char, starting at 528.41 °C for the formulated crayon and 660.81 °C for the commercial one. The residual char percentage at 700 °C was 12.5% for the formulated crayon and 19.3% for the commercial crayon. The broader degradation range and higher Tmax of the commercial crayon indicate enhanced thermal resistance, likely due to its synthetic constituents compared to the naturally derived *Rumex abyssinicus* pigment. Generally, the TGA results quantitatively demonstrate the differences in thermal stability between the natural and commercial crayons, providing insight into how compositional variations affect decomposition behavior (Apaydın Varol & Mutlu 2023; Castro et al. 2023).

Table 2 Optimization results for the absorbance of the formulated crayon

Run Number	Talc amount (g)	Dye amount (g)	Paraffin wax amount (g)	Temperature (°C)	Absorbance
1	5	2	6	90	0.615
2	7	0.5	6	80	0.629
3	7	2	6	80	0.687
4	7	2	4	90	0.816
5	7	0.5	8	90	0.517
6	7	0.5	4	90	0.729
7	9	2	6	90	0.8
8	5	1.25	6	80	0.566
9	5	0.5	6	90	0.53
10	7	1.25	4	80	0.77
11	7	1.25	4	100	0.785
12	5	1.25	4	90	0.673
13	7	2	6	100	0.701
14	9	0.5	6	90	0.715
15	5	1.25	6	100	0.577
16	7	1.25	8	100	0.554
17	9	1.25	6	80	0.742
18	5	1.25	8	90	0.504
19	7	0.5	6	100	0.643
20	7	1.25	8	80	0.542
21	7	2	8	90	0.589
22	9	1.25	8	90	0.658
23	9	1.25	6	100	0.756
24	9	1.25	8	90	0.83

Tensile strength test

Tensile strength testing was performed using a screwdriver-type tensile testing machine, where shaped crayon samples were clamped between stationary and movable fixtures. Tension was applied until fracture occurred, with real-time measurements of applied force and elongation recorded via the system's computer interface. The breaking strength was defined as the force at fracture (Perez 2004), whereas tensile strength referred to the maximum load sustained prior to fracture initiation. As shown in Fig. 5, the formulated crayon exhibited a maximum tensile strength of 1.48 N/mm^2, while the commercial crayon reached 1.53 N/mm^2, indicating better mechanical integrity in the commercial product, likely due to reduced decomposition and fewer internal defects. Tensile strength values increased from 0 N/mm^2 to their respective maxima in both crayons. Filler content also influenced mechanical performance; higher filler loading resulted in decreased tensile strength, dropping from 1.43 N/mm^2 to 1.14 N/mm^2 in the formulated crayon and from 1.48 N/mm^2 to 1.19 N/mm^2 in the commercial crayon. Elongation at break, reflecting the material's ductility, was 1.34% for the formulated crayon and 1.4% for the commercial counterpart. The stress–strain behavior indicated an initial elastic region followed by a plastic region, where permanent deformation and fracture occurred.

Binding and durability of color

The color-binding performance of the formulated crayon was assessed in comparison to a commercial crayon by evaluating the visibility and adhesion of the color on paper surfaces. As shown in Fig. 6, both the formulated and commercial crayons exhibited effective color adherence, with clearly visible marks on the material surface. Durability was further examined under various conditions, including prolonged sunlight exposure, ambient room conditions, and oven heating. The formulated crayon demonstrated excellent color stability, showing no significant fading or degradation when exposed to these conditions. As illustrated in Fig. 7, the crayon retained its vibrancy and adhesion, comparable to the commercial counterpart. These findings confirm that the formulated crayon possesses reliable color durability and quality,

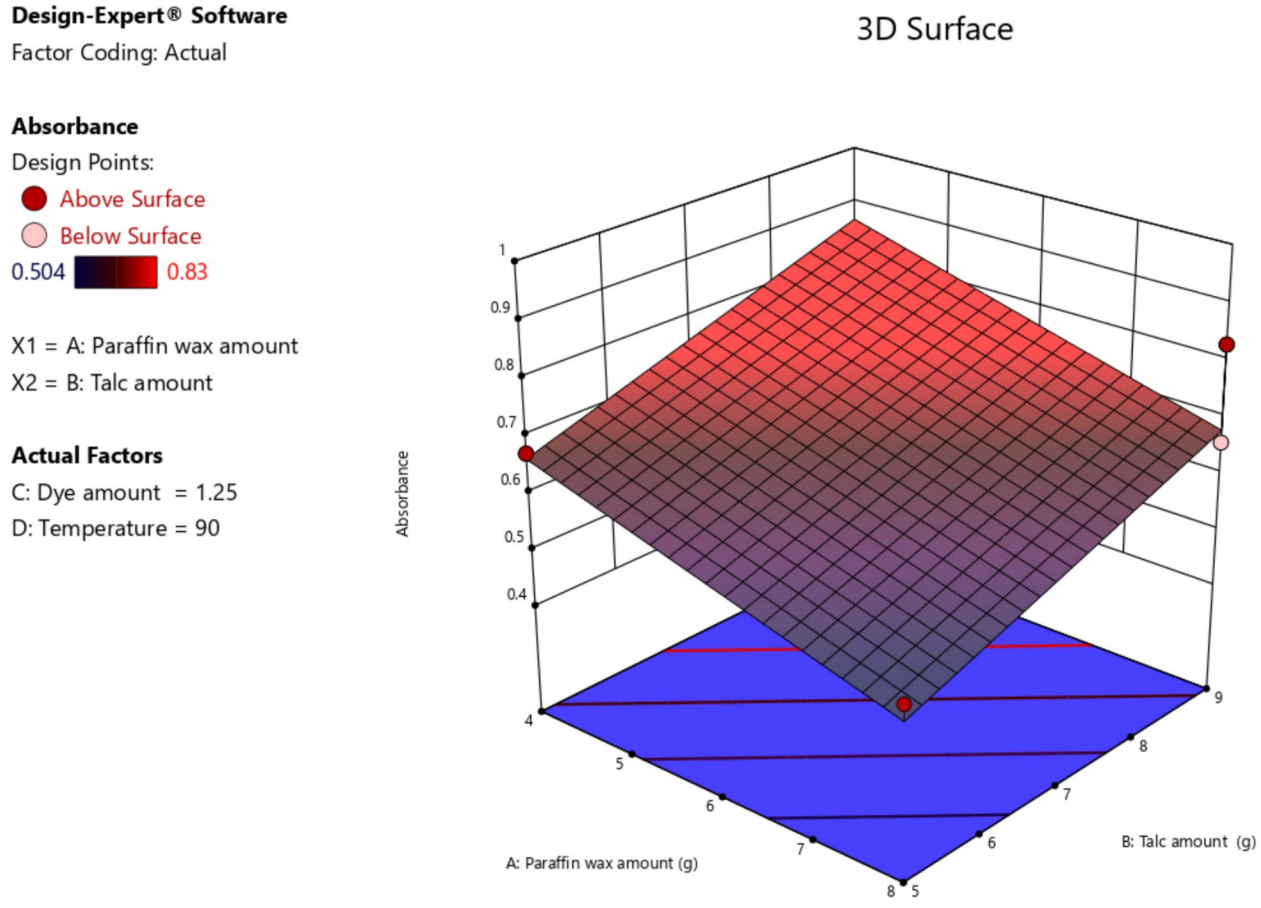


Fig. 8 Talc and paraffin wax amounts interaction effect on crayon's absorbance

performing similarly to commercial crayons under different environmental exposures.

Optimization of crayon production

The absorbance of the formulated crayons was significantly influenced by talc, natural dye, paraffin wax content, and processing temperature as shown in Table 1. Higher absorbance values were typically observed at intermediate to high talc content (7–9 g) and elevated dye concentrations (1.25–2 g), particularly at higher temperatures (90–100 °C). For instance, a formulation containing 7 g of talc, 2 g of dye, 4 g of paraffin wax, processed at 90 °C, yielded one of the highest recorded absorbances (0.816). Lower talc content (5 g) or lower processing temperatures (80 °C) resulted in decreased absorbance, highlighting the importance of both filler and thermal energy in promoting light absorption. These trends can be explained by the physicochemical interactions within the wax–dye–talc matrix. Talc provides a high surface area and structural framework that facilitates adsorption and uniform dispersion of the dye, thereby enhancing optical density. In contrast, paraffin wax is largely inert and hydrophobic; increasing its content can encapsulate dye particles, limiting light interaction and decreasing absorbance. Temperature affects the viscosity of the wax matrix, promoting better mixing and even distribution of dye molecules within the talc scaffold. The combined effects of talc, dye, wax, and temperature therefore determine the crayon's color intensity, illustrating the need for optimized formulations that balance optical performance with structural integrity (Table 2).

Statistical analysis: analysis of variance for the linear model

The analysis of variance (ANOVA) performed using Design Expert software highlights the statistical significance of the model and its factors. The model's F-value of 33.2 indicates that the model is highly significant, with only a 0.01% probability that such a large F-value could arise from random noise. Terms with p-values below 0.05 are considered statistically significant; in this analysis, factors A, B, and C were identified as significant contributors, while terms with p-values above 0.10 were deemed insignificant. The predicted R^2 value of 0.7709 is in close agreement with the adjusted R^2 of 0.6235, differing by less than 0.2, which confirms the model's strong predictive capability. Moreover, the Adequate Precision

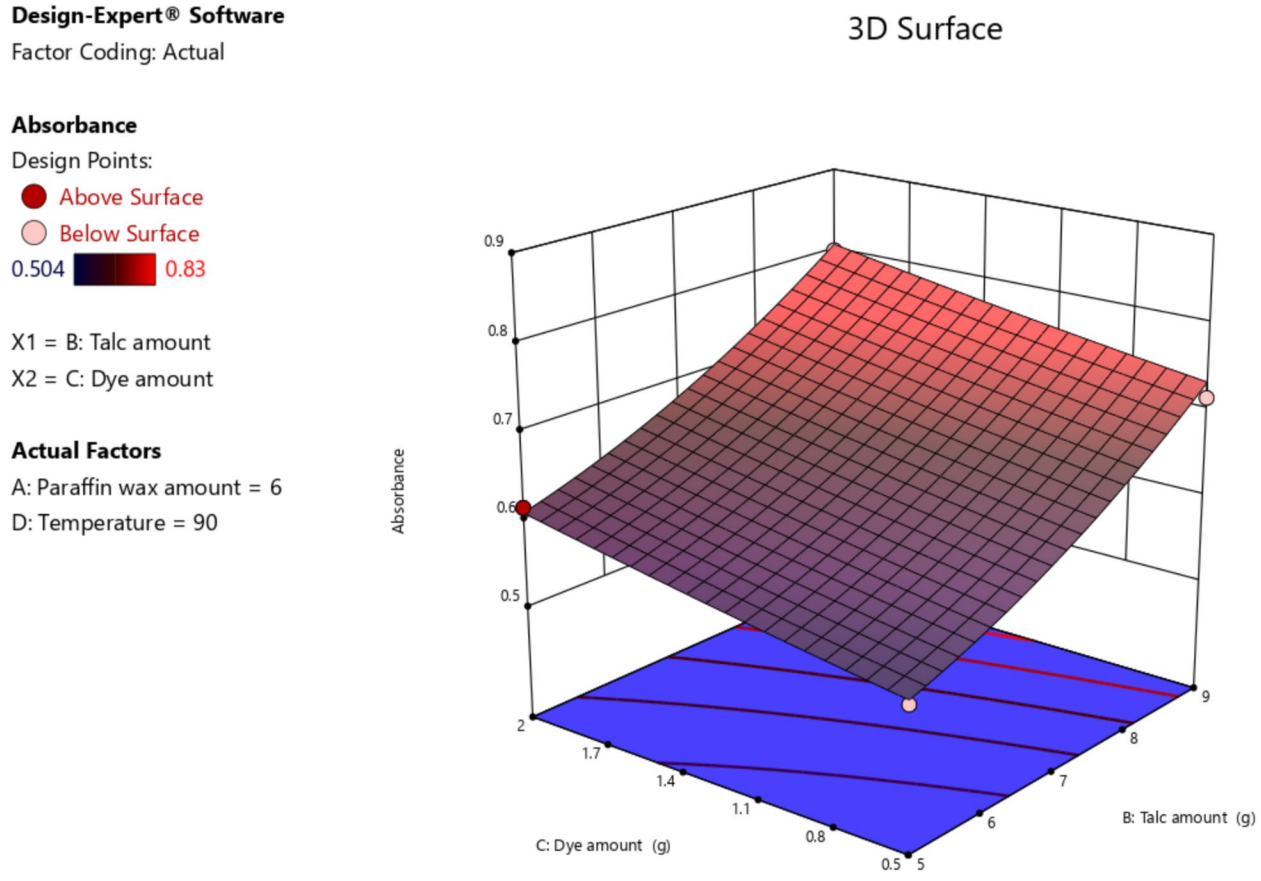


Fig. 9 Interaction effect of dye amount and talc amount on formulated crayon's absorbance

value of 8.993, which measures the signal-to-noise ratio, exceeds the minimum desirable threshold of 4, indicating an adequate signal and confirming the model's suitability for exploring the design space. The Lack of Fit F-value of 0.06 implies the Lack of Fit is not significant relative to the pure error. There is a 99.95% chance that a Lack of Fit F-value this large could occur due to noise. The resulting linear regression model, derived from coded factors, effectively describes the relationship between absorbance and the independent variables involved in the extraction process, as detailed in Eq. 3. A quadratic model was tested to capture possible curvature in the response surface, but analysis showed that a linear model adequately described the relationship between variables and crayon color absorbance, so the linear model was used for optimization

$$\begin{aligned}\text{Color absorbance } &= 0.6715 + +0.1020\ \text{A} + +0.0371\ \text{B} \\ &\quad - -0.0938\ \text{C} + +0.0067\ \text{D}\end{aligned} \tag{3}$$

The regression equation, expressed in terms of coded factors, enables prediction of absorbance based on factor levels, where high and low levels are represented by + 1 and −1, respectively. This coding facilitates the comparison of factor influences through their coefficients. The model identified that the absorbance of color was significantly affected by individual factors talc (A), dye (B), paraffin wax (C), temperature (D), and their interaction terms (AB, AC, AD, BC, BD, and CD). Specifically, absorbance increased with higher levels of talc, dye, and temperature, indicating positive linear effects, while it decreased with increasing paraffin wax content. Among the interactions, talc-dye (AB) and talc-temperature (AD) interactions positively influenced absorbance, whereas talc-paraffin wax (AC), dye-paraffin wax (BC), and paraffin wax-temperature (CD) interactions exerted negative effects on the absorbance response.

Interaction effects of process variables

Effect of interaction of talc and paraffin wax on the absorbance of color

The interaction between talc and paraffin wax (Fig. 8) showed that increasing talc content while reducing paraffin wax enhanced color absorbance, with the maximum observed at 9 g talc and 4 g paraffin wax (0.83) and the minimum at 5 g talc and 8 g wax (0.504). Mechanistically, talc acts as a high-surface-area scaffold**,** facilitating adsorption and uniform dispersion of the dye, which

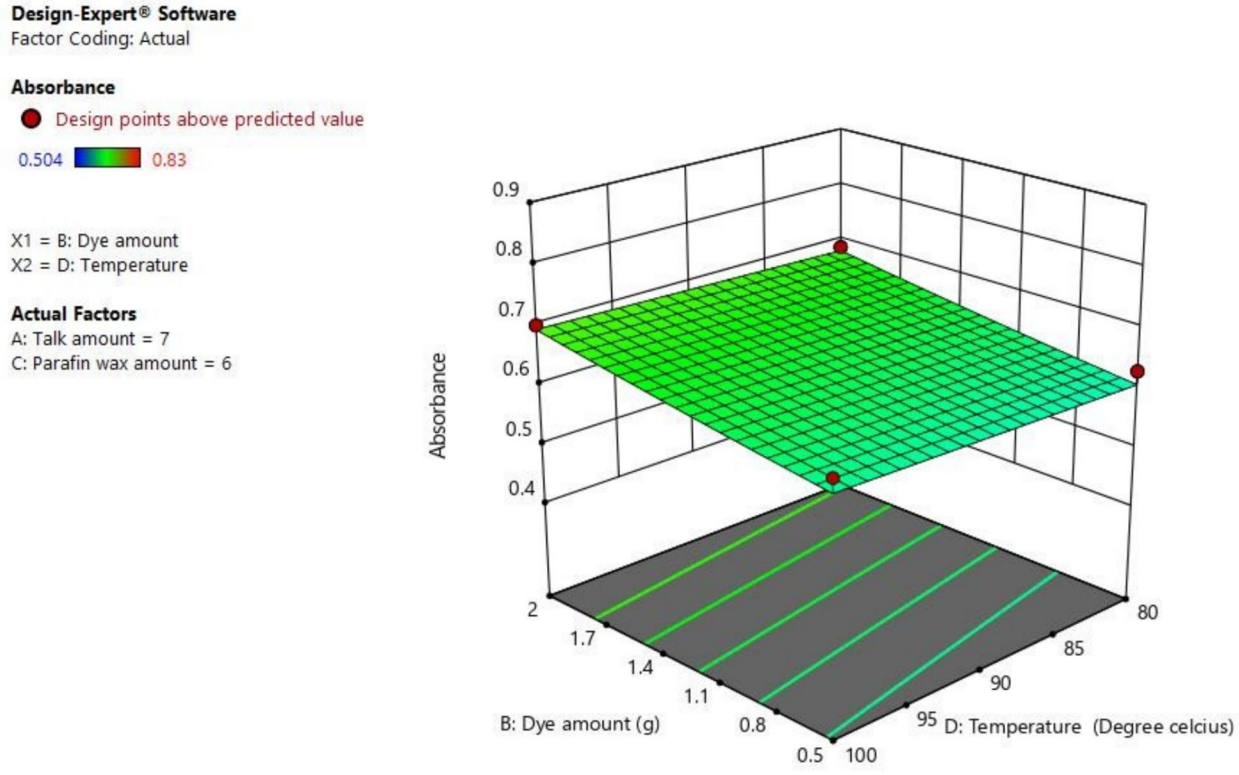


Fig. 10 Temperature and dye amount interaction effect on crayon's absorbance

increases the effective interaction of the pigment with light. In contrast, paraffin wax is hydrophobic and largely inert; higher wax content can encapsulate dye particles, hindering light interaction and reducing absorbance. Thus, optimal absorbance is achieved by balancing the structural support provided by wax with the dispersive and light-scattering role of talc.

Effect of interaction of talc and dye on the absorbance of color

The interaction of talc and dye (Fig. 9) revealed that increasing both components improved absorbance, with the highest value at 9 g talc and 2 g dye (0.8). Talc stabilizes dispersed dye molecules, preventing aggregation and facilitating uniform pigment distribution throughout the crayon matrix. Higher dye content necessitates more talc to ensure proper dispersion, enhancing the optical density and producing more vivid and visible colors. This synergistic effect demonstrates that the filler (talc) and pigment (dye) act together to maximize color intensity.

Effect of interaction of dye and temperature on the absorbance of color

The interaction between dye concentration and temperature indicated that higher dye levels combined with elevated temperatures (up to 100 °C) increased absorbance, achieving a maximum of 0.701. Mechanistically, higher temperatures reduce the viscosity of the wax matrix, allowing the dye to dissolve more effectively and disperse uniformly during mixing. This improved molecular mobility ensures that pigment molecules are well-distributed within the matrix, resulting in enhanced light absorption and more intense color (Fig. 10).

Effect of interaction of paraffin wax and temperature on the absorbance of color

Increasing temperature while decreasing paraffin wax content also enhanced absorbance, with the maximum observed at 100 °C and 4 g wax (0.785) and the minimum at 80 °C and 8 g wax (0.542) as shown in Fig. 11. Lower wax content at high temperatures allows the dye and talc to interact more freely, improving pigment dispersion and light absorption. Conversely, higher wax levels reduce the accessibility of dye particles and may slightly hinder color intensity. Additionally, at elevated temperatures, excessive wax can compromise crayon strength due to increased flammability, emphasizing the need to optimize both thermal and matrix conditions to balance optical performance and mechanical integrity.

Conclusion

In this study, an eco-friendly crayon was successfully formulated using natural dye extracted from Rumex abyssinicus. Optimization via the Box–Behnken design

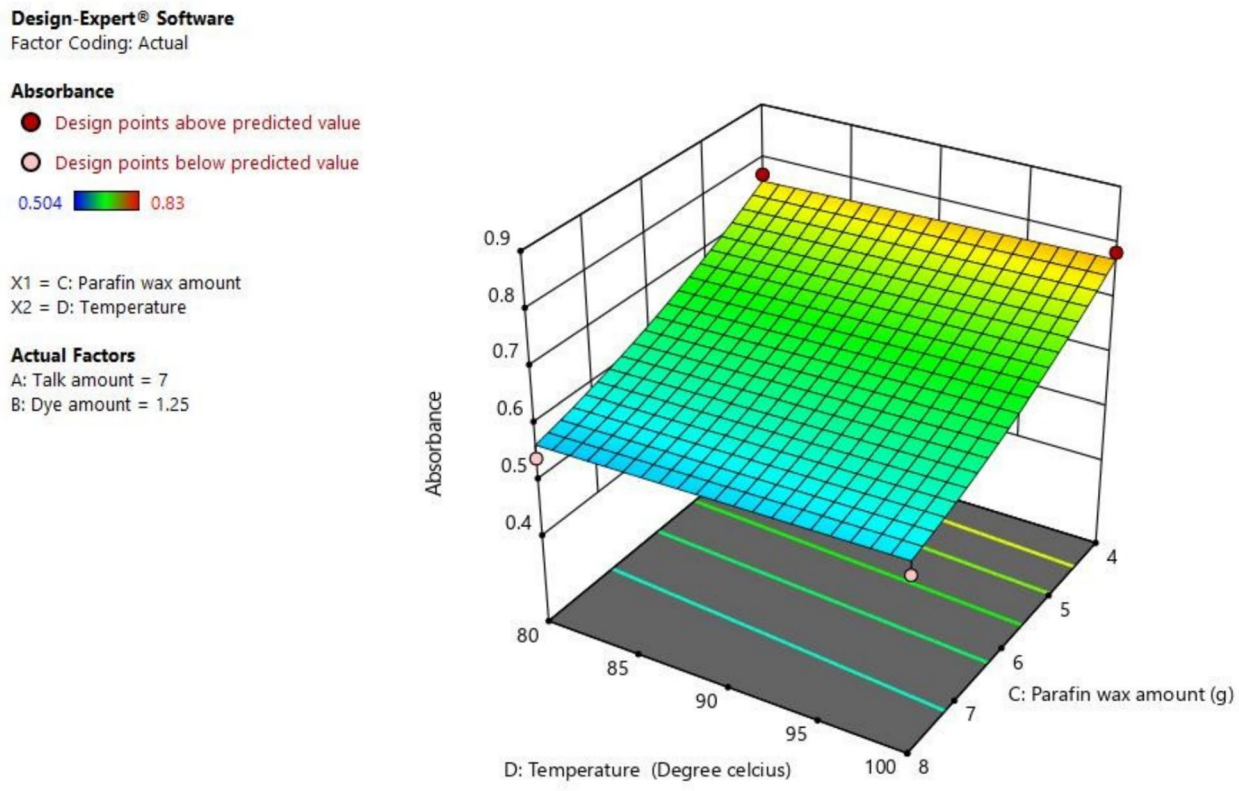


Fig. 11 3D representation of interaction effect of paraffin wax and temperature on crayon's absorbance

identified the final optimized formulation as 8 g of paraffin wax, 1 g of beeswax, 1.25 g of natural dye, and 9 g of talc, processed at 90 °C, producing a crayon with a maximum color absorbance of 0.830 at λmax = 298.7 nm. Characterization of the optimized crayon revealed a tensile strength of 1.48 N/mm^2 and elongation at break of 1.34%, which are comparable to the commercial crayon (1.53 N/mm^2, 1.40%). Thermal analysis indicated onset degradation at 205.8 °C, Tmax at 312.5 °C, and a residual char of 12.5%, while the commercial crayon exhibited onset at 206.1 °C, Tmax at 374.3 °C, and residual char of 19.3%. The optimized crayon also demonstrated strong UV–Visible absorption consistent with anthraquinone chromophores, excellent adhesion, color binding, and durability on paper under sunlight, ambient, and heat exposure. Statistical analysis confirmed that all process parameters significantly influenced crayon quality, with the predicted R^2 (0.7709) closely matching the adjusted R^2 (0.6235), indicating a reliable model fit. Generally, these results demonstrate that *Rumex abyssinicus* is a viable natural pigment source for producing high-quality, sustainable crayons. The optimized crayons exhibit mechanical, thermal, and optical properties comparable to commercial crayons while providing an environmentally friendly alternative to synthetic pigments, supporting the development of eco-friendly children's art materials. While this study establishes the feasibility of natural-dye crayons, further investigations are recommended to ensure their practical applicability and safety. Comprehensive safety and toxicity testing, including ingestion and dermal exposure studies, should be conducted to confirm suitability for children. Additionally, stability evaluations under diverse environmental conditions and accelerated aging tests are needed to assess long-term performance, durability, and shelf life. These studies will provide a more complete understanding of the crayons' usability, safety, and sustainability in real-world applications.

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Authors' contributions
Naol Bekele: conceptualization, format analysis, data curation, investigation, methodology, validation, writing original draft, writing review and editing, Mikiyas Abewaa Gnaro: data curation, methodology, writing original draft, writing review and editing, Ashagrie Mengistu Kebede: writing original draft, writing review and editing.

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Data availability
The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval and consent to participate
Not applicable.

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