FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 9, May, 2026, pp 339 – 352
DOI: https://doi.org/10.33003/fjs-2026-1009-5362

Extraction, Characterization, and Comparative Evaluation of Natural Colourants from Carrot (*Daucus Carota*) and Spinach (*Spinacia Oleracea*) for Potential Applications in Food, Cosmetic, and Textile Industries

***[1]Albashir Yasir, [2]Hauwa Yahaya Umar and [1]Mahmud Khalifa Shuaibu**

[1]Department of Industrial Chemistry, Federal University Dutsinma. Nigeria.
[2]Federal College of Education (T) Gombe, Gombe State Nigeria.

*Corresponding authors' email: ayasir@fudutsinma.edu.ng

Received: 12 May 2026
Accepted: 25 June 2026
Published: 02 July 2026

ABSTRACT

Natural colourants are increasingly being investigated as sustainable alternatives to synthetic dyes for applications in food, cosmetics, pharmaceuticals, and textiles. This study comparatively extracted and evaluated pigments from carrot (*Daucus carota*) and spinach (*Spinacia oleracea*) to assess their industrial potential. Carotenoid-rich pigments from carrot were obtained using an acetone–ethanol system followed by petroleum ether partitioning, while chlorophyll-rich pigments from spinach were extracted with ethanol under light-protected conditions. Carrot extract exhibited higher extraction yield (8.42 ± 0.11%) and pigment concentration (118.6 ± 3.4 mg/g extract) than spinach extract (5.66 ± 0.09% and 87.4 ± 2.7 mg/g extract, respectively). UV–Visible spectroscopy confirmed characteristic absorption maxima of carotenoids (425, 450, and 474 nm) and chlorophylls (430, 645, and 663 nm). Carrot pigments showed greater pH, thermal, and photostability and stronger antioxidant activity (IC_{50} = 54.8 µg/mL) than spinach pigments (IC_{50} = 69.2 µg/mL). In textile dyeing, carrot extracts produced higher colour strength and superior fastness properties on cotton, silk, and wool. They also exhibited better colour retention and consumer acceptance in model food and cosmetic formulations. Overall performance scores were 89.6% for carrot and 69.8% for spinach, indicating that carrot-derived carotenoid pigments possess greater potential for broad industrial applications, while spinach-derived chlorophyll pigments remain valuable where natural green coloration is desired.

Keywords: Natural Colourants, Carotenoids; Chlorophyll, Carrot, Spinach, Antioxidant Activity, Textile Dyeing, Food Colourants

INTRODUCTION

Colour is one of the most important quality attributes influencing consumer perception, acceptability, and market value of food, cosmetic, pharmaceutical, and textile products. In food systems, colour often serves as an immediate indicator of freshness, flavour expectation, and overall product quality, while in cosmetics and textiles it strongly affects visual appeal and consumer preference. For decades, synthetic colourants have been widely used because of their low cost, high tinting strength, and excellent processing stability. However, growing concerns regarding their potential toxicological effects, environmental persistence, and consumer rejection of artificial additives have intensified the search for safer and more sustainable alternatives. Natural colourants derived from plants, microorganisms, and other biological sources have therefore attracted increasing attention because they are generally biodegradable, renewable, and often associated with additional bioactive properties such as antioxidant activity and nutritional value (Clydesdale, 1993; Delgado-Vargas & Paredes-López, 2003; Stringheta *et al.*, 2012). Among natural pigments, carotenoids and chlorophylls are two of the most commercially relevant classes because of their abundance in edible plant materials and their dual functional roles as colourants and bioactive compounds. Carotenoids are lipid-soluble tetraterpenoid pigments responsible for yellow, orange, and red colours in many fruits and vegetables. Beyond their colouring function, carotenoids such as β-carotene are valued for their provitamin A activity, antioxidant properties, and possible health-promoting effects, making them attractive for food, nutraceutical, pharmaceutical, and cosmetic formulations (Britton *et al.*, 2008; Khoo *et al.*, 2011; Rodriguez-Amaya, 2019). Chlorophylls, by contrast, are magnesium-containing porphyrin pigments that impart green colour to leafy vegetables and are important not only in photosynthesis but also as natural green colourants in food and personal-care products. Chlorophyll-containing extracts may also exhibit antioxidant and functional properties, although chlorophyll pigments are known to be sensitive to heat, light, oxygen, and acidic conditions, which can limit their industrial use (Humphrey, 1980; Heaton & Marangoni, 1996; Lichtenthaler, 1987).

Carrot (*Daucus carota*) and spinach (*Spinacia oleracea*) are particularly attractive candidates for comparative evaluation because they are inexpensive, widely available, food-grade plant materials representing two chemically distinct pigment systems. Carrot is rich in carotenoids, especially β-carotene, which contributes its characteristic orange colour and has established applications as a natural food colourant and nutritionally valuable ingredient. Spinach, on the other hand, is a well-known source of chlorophyll pigments and offers a natural green colour that is difficult to obtain from many other edible plant sources. The contrasting chemistry of carotenoids and chlorophylls suggests that these pigments may behave differently during extraction, storage, processing, and end-use application. In particular, differences in polarity, oxidative susceptibility, pH sensitivity, and thermal stability are likely to affect their suitability for specific industrial uses (Gross, 1991; Mortensen, 2006; Singh & Pandey, 2018). A major challenge in the industrial use of natural colourants is that

pigment performance depends on more than colour alone. A colourant intended for commercial application must combine adequate extraction yield, high pigment concentration, desirable spectral properties, stability under processing and storage conditions, compatibility with different substrates or formulations, and, where possible, beneficial functional attributes such as antioxidant activity. For example, pH stability is critical in beverages and fermented foods, thermal stability is essential during pasteurization, cooking, textile dyeing, and cosmetic processing, and light stability strongly influences shelf life in packaged products. Likewise, textile applications require acceptable colour strength and fastness properties, whereas food and cosmetic applications demand not only visual appeal but also storage stability and consumer acceptance. As a result, the industrial selection of a natural pigment source should be based on a broad comparative assessment rather than on extraction efficiency alone (Francis, 1995; Wrolstad *et al.*, 2005; Tiwari *et al.*, 2013). Although carrot carotenoids and spinach chlorophylls have each been studied individually, there is still limited integrated comparative information on their relative suitability across multiple application sectors, particularly in a framework that simultaneously considers extraction behaviour, physicochemical stability, antioxidant potential, textile dyeing performance, and performance in model food and cosmetic systems. Such a comparative approach is valuable because it addresses the practical industrial question of not only whether a pigment can be extracted, but also which pigment source performs better, under what conditions, and for which application domain**.** A systematic side-by-side evaluation of carrot and spinach pigments therefore provides a more useful basis for selecting a natural colourant for real product development and industrial formulation.

Accordingly, the present study aimed to extract carotenoid-rich pigments from carrot and chlorophyll-rich pigments from spinach, characterize the extracts spectrophotometrically, and comparatively evaluate their suitability for food, pharmaceutical, cosmetic, and textile applications. Specific attention was given to extraction yield, pigment concentration, UV–Visible absorption characteristics, pH stability, thermal stability, light stability, antioxidant activity, textile dyeing performance, and behaviour in model food and cosmetic formulations. By integrating these parameters, the study sought to identify the more versatile natural colourant source for broad industrial use while also clarifying the niche advantages of each pigment system.

MATERIALS AND METHODS

Materials

Fresh carrot roots (*Daucus carota*) and fresh spinach leaves (*Spinacia oleracea*) were used as plant sources of natural pigments. Analytical-grade ethanol (95%), acetone, petroleum ether, methanol, distilled water, hydrochloric acid, sodium hydroxide, 2,2-diphenyl-1-picrylhydrazyl (DPPH), Trolox standard, and buffer solutions (pH 2, 4, 6, 7, 8, 10, and 12) were employed during extraction and characterization. Bleached cotton, silk, and wool fabrics were used for textile dyeing experiments. Instrumentation included a UV–Visible spectrophotometer, rotary evaporator, analytical balance, pH meter, water bath, magnetic stirrer, centrifuge, and colour measurement equipment.

Preparation of Plant Samples

Fresh carrot roots and spinach leaves were procured from a local market and transported to the laboratory for processing. Carrots were washed thoroughly with distilled water to remove adhering soil and foreign materials, peeled, sliced into thin pieces (approximately 2–3 mm), and dried in a hot-air oven at 45 °C for 24 h to constant weight. The dried carrot slices were ground to a fine powder and stored in amber containers until extraction. Spinach leaves were washed, sorted to remove stems and damaged portions, shade-dried for 48 h, and then further dried in a hot-air oven at 40 °C for 6 h. The dried leaves were pulverized and stored in airtight amber bottles protected from light.

Extraction of Carotenoid Pigments from Carrot

Carotenoid pigments were extracted from carrot powder by solvent extraction. Briefly, 50 g of dried carrot powder was transferred into a 500 mL conical flask and mixed with 250 mL of acetone–ethanol (80:20, v/v). The suspension was stirred continuously for 3 h at room temperature using a magnetic stirrer. The extract was filtered through Whatman No. 1 filter paper, and the residue was re-extracted twice under the same conditions to maximize pigment recovery. The combined filtrates were transferred to a separatory funnel and mixed with an equal volume of petroleum ether. Distilled water was added gradually to facilitate phase separation. The upper petroleum ether layer containing carotenoid pigments was collected, dried over anhydrous sodium sulfate, and concentrated under reduced pressure using a rotary evaporator at 40 °C. The resulting carotenoid-rich extract was stored in amber glass bottles at 4 °C until further analysis.

Extraction of Chlorophyll Pigments from Spinach

Chlorophyll pigments were extracted from spinach powder using ethanol as extraction solvent. Fifty grams of spinach powder was transferred into a conical flask containing 250 mL of ethanol. Extraction was conducted under dark conditions to minimize chlorophyll degradation, and the mixture was stirred continuously for 4 h at room temperature. The resulting extract was centrifuged at 5000 rpm for 10 min and filtered through Whatman No. 1 filter paper. The solvent was removed under reduced pressure using a rotary evaporator, and the concentrated chlorophyll-rich extract was stored in amber bottles at 4 °C prior to characterization and application studies.

Determination of Extraction Yield and Pigment Concentration

Extraction Yield

Extraction yield was determined gravimetrically after complete solvent removal. The dried extracts obtained from carrot and spinach were weighed using an analytical balance, and the extraction yield was calculated according to the following equation (Harborne's Phytochemical Methods; Handbook of Natural Colorants):

$$\text{Extraction Yield (\%)} = \frac{\text{Weight of Extract Obtained}}{\text{Weight of Raw Material Used}} \times 100 \quad (1)$$

Carotenoid Concentration

For carotenoid analysis, 10 mg of carrot extract was dissolved in 100 mL of petroleum ether and the absorbance was measured at 450 nm using a UV–Visible spectrophotometer. Carotenoid concentration in the extract solution was estimated according to (Harborne's Phytochemical Methods):

$$\text{Carotenoid Concentration} = \frac{A_{450} \times \text{V} \times 10^4}{2592 \times \text{W}} \quad (2)$$

Where A_{450} is the absorbance at 450 nm, V is the extraction volume (mL), and W is the sample weight (g).

Chlorophyll Concentration

Chlorophyll content in spinach extract was determined spectrophotometrically by recording absorbance at 663 and 645 nm. Chlorophyll a, chlorophyll b, and total chlorophyll were calculated using the following expressions (Harborne's Phytochemical Methods) :

$$\text{Chlorophyll a} = 12.7(A_{663}) - 2.69(A_{645}) \quad (3)$$

$$\text{Chlorophyll b} = 22.9(A_{645}) - 4.68(A_{663}) \quad (4)$$

$$\text{Total Chlorophyll} = \text{Chlorophyll a} + \text{Chlorophyll b} \quad (5)$$

where A_{663} and A_{645} are the absorbance values measured at 663 and 645 nm, respectively. For comparative reporting in this study, pigment contents were expressed on an extract basis (mg/g extract).

UV–Visible Spectroscopic Characterization

The spectral characteristics of the extracted pigments were examined using a UV–Visible spectrophotometer. Appropriate dilutions of the carrot and spinach extracts were prepared using their respective extraction solvents, and absorbance spectra were recorded using 1 cm quartz cuvettes over the wavelength range of 200–800 nm. The corresponding solvent was used as the blank for baseline correction. Particular attention was given to the characteristic absorption maxima of carotenoids (approximately 425–475 nm) and chlorophyll pigments (approximately 430, 645, and 663 nm), and the wavelength of maximum absorbance (λmax) was recorded for subsequent stability analyses (Lichtenthaler, 1987; Rodriguez-Amaya, 2001).

Stability Studies

pH Stability

The pH stability of the extracted pigments was evaluated using buffer solutions adjusted to pH 2, 4, 6, 7, 8, 10, and 12. Aliquots (5 mL) of each extract were mixed with 45 mL of the corresponding buffer solution and allowed to equilibrate for 30 min at room temperature. Absorbance was then measured at the respective (λmax) value. Colour retention was calculated accordint to equation (6), (Giusti & Wrolstad, 2001; Castañeda-Ovando et al., 2009):

$$\text{Colour Retention (\%)} = \frac{A_t}{A_0} \times 100 \quad (6)$$

where A_t is the absorbance after treatment and A_0 is the initial absorbance before treatment.

Thermal Stability

Aliquots of the extracts were heated at 40, 60, and 80 °C for 30 min. After cooling to room temperature, absorbance values were measured and colour retention was calculated using Equation (6).

Light Stability

Samples were exposed to ultraviolet light under controlled laboratory conditions, and absorbance measurements were recorded after 24, 48, and 72 h of exposure to evaluate pigment degradation. Colour retention was calculated relative to the initial absorbance.

Determination of Antioxidant Activity

Antioxidant activity was assessed using the DPPH radical scavenging assay. Different concentrations of each extract (20, 40, 60, 80, and 100 µg/mL) were prepared. One millilitre of each extract solution was mixed with 3 mL of freshly prepared 0.1 mM DPPH solution and incubated in the dark for 30 min at room temperature. Absorbance was measured at 517 nm. The percentage scavenging activity was calculated according to equation (7), (Harborne's Phytochemical Methods):

$$\text{Scavenging Activity (\%)} = \frac{A_c - A_s}{A_c} \times 100 \quad (7)$$

where A_c is the absorbance of the control and A_s is the absorbance of the sample. The IC_{50} value, defined as the concentration required to inhibit 50% of DPPH radicals, was estimated from the inhibition curve.

Evaluation of Textile Dyeing Performance

Bleached cotton, silk, and wool fabrics were selected as textile substrates. Fabric samples (10 cm × 10 cm; approximately 5 g) were mordanted in 10% alum solution at 80 °C for 45 min, rinsed thoroughly with distilled water, and air-dried. Dye baths containing the extracted pigments were prepared at 10% on weight of fabric (owf) using a liquor ratio of 1:20. Fabrics were immersed in the dye baths, the temperature was gradually increased to 80 °C, and dyeing was continued for 60 min with occasional agitation. After dyeing, the samples were cooled, rinsed, and air-dried. Colour strength was determined using a reflectance spectrophotometer, and Kubelka–Munk colour strength was calculated according to equation (8), (Kubelka & Munk, 1931; Broadbent, 2001):

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (8)$$

Were K is the absorption coefficient, S is the scattering coefficient and R is the reflectance of dye fabrics

Wash fastness and light fastness were evaluated according to relevant ISO 105 standard procedures.

Evaluation of Food and Cosmetic Applications

Model beverage and yogurt systems were prepared to evaluate the suitability of the extracts as food colourants. For beverage application, the extracts were added at 0.1% (w/v) to a standard sugar solution, and the coloured beverages were stored at 4 °C and 25 °C for 30 days. Colour intensity and stability were monitored during storage. For yogurt application, the extracts were incorporated at 0.2% (w/w), and colour retention, visual appearance, and consumer acceptability were evaluated during storage.

For cosmetic application, model lip balm and cream formulations were prepared. Pigment extracts were incorporated at 1% into a lip balm formulation consisting of beeswax, coconut oil, and shea butter, and the resulting products were assessed for colour uniformity, stability, and appearance. Cream formulations containing 1% extract were stored at 25 °C and 40 °C for 60 days and evaluated for colour stability, phase separation, and overall appearance.

Statistical Analysis

All experiments were conducted in triplicate and results were expressed as mean ± standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA), and differences were considered statistically significant at ($p < 0.05$).

Comparative Performance Scoring

To compare the overall industrial suitability of the two colourants, a weighted scoring approach was used. Extraction yield, pigment concentration, stability, antioxidant activity, textile dyeing performance, food application, and cosmetic application were each assigned a weighting factor according to their industrial relevance. Normalized performance scores were multiplied by the corresponding weights and summed to

generate the overall comparative performance score for each pigment source.

RESULTS AND DISCUSSION

Extraction Yield and Pigment Concentration

The extraction yield and pigment concentration of the carrot- and spinach-derived colourants are presented in Tables 1 and 2. All analyses were conducted in triplicate (n = 3), and results are expressed as mean ± standard deviation.

Carrot produced a significantly higher extraction yield (8.42 ± 0.11%) than spinach (5.66 ± 0.09%). The greater extraction yield obtained from carrot may be attributed to its relatively high carotenoid content and to the effectiveness of the acetone–ethanol extraction system in solubilising lipophilic pigments. By contrast, the lower yield recorded for spinach suggests either lower overall pigment recovery under the extraction conditions used or greater susceptibility of chlorophyll-containing material to degradation and handling losses during processing.

The extraction yield obtained for carrot in the present study is comparable to values reported for carotenoid-rich vegetable matrices extracted using organic solvent systems. Rodriguez-Amaya (2001) reported that extraction efficiency of carotenoids is strongly influenced by solvent polarity and the structural association of pigments within plant tissues. Similarly, Britton *et al.,* (2008) observed that mixtures of polar and non-polar solvents often enhance carotenoid recovery by improving pigment solubilisation and diffusion from plant cells. The lower extraction yield observed for spinach agrees with the findings of Lichtenthaler (1987), who reported that chlorophyll extraction efficiency may be affected by pigment instability, enzymatic degradation, and interactions with cellular components during processing.

A similar trend was observed for pigment concentration. Carrot extract contained a higher total carotenoid concentration (118.6 ± 3.4 mg/g extract) than the total chlorophyll concentration measured in spinach extract (87.4 ± 2.7 mg/g extract). These findings indicate that, under the extraction conditions employed, carrot represented a richer and more productive source of recoverable colourant than spinach.

The carotenoid concentration recorded for carrot is consistent with previous reports identifying carrot roots as one of the most abundant dietary sources of β-carotene and related carotenoids (Khoo *et al.,* 2011; Rodriguez-Amaya, 2019). Likewise, the chlorophyll concentration obtained for spinach agrees with the observations of Gross (1991) and Heaton and Marangoni (1996), who reported that spinach contains substantial chlorophyll levels but that pigment recovery may be influenced by extraction conditions and post-harvest degradation processes. Differences between the present results and values reported in the literature may be attributed to variations in cultivar, maturity stage, environmental growing conditions, extraction methodology, and analytical procedures.

From an industrial standpoint, a higher extraction yield and pigment concentration are advantageous because they improve raw material utilisation efficiency and may reduce the cost associated with producing a given quantity of natural colourant. The results therefore suggest that carrot possesses considerable potential as a commercially viable source of natural colourants, while spinach remains an important source of chlorophyll-based green pigments for food, textile, and pharmaceutical applications..

Table 1: Extraction Yield of Carrot and Spinach Colourants

Sample	Replicate 1 (%)	Replicate 2 (%)	Replicate 3 (%)	Mean ± SD (%)
Carrot	8.31	8.52	8.44	8.42 ± 0.11
Spinach	5.76	5.58	5.64	5.66 ± 0.09

Table 2: Pigment Concentration of Carrot and Spinach Extracts

Sample	Pigment Type	Pigment Concentration (mg/g extract)
Carrot	Total carotenoids	118.6 ± 3.4
Spinach	Total chlorophyll	87.4 ± 2.7

UV–Visible Spectroscopic Characteristics

The UV–Visible spectra of the extracted pigments confirmed the successful isolation of carotenoid-rich and chlorophyll-rich fractions from carrot and spinach, respectively. Carrot extract exhibited characteristic carotenoid absorption maxima at 425, 450, and 474 nm, with the strongest absorption observed at 450 nm. These absorption bands are characteristic of carotenoid molecules containing extended conjugated polyene chains, which facilitate $\pi \rightarrow \pi^*$ electronic transitions responsible for their intense yellow–orange coloration (Britton *et al.,* 2008; Rodriguez-Amaya, 2019).

The absorption maxima obtained for carrot are in close agreement with previous studies, which reported that β-carotene and related carotenoids typically exhibit three well-defined absorption peaks within the wavelength range of approximately 420–480 nm, depending on solvent composition and pigment composition (Britton *et al.,* 2008; Rodriguez-Amaya, 2001). The close correspondence between the present results and published values indicates that the extraction procedure effectively preserved the structural integrity of the carotenoid chromophores.

Spinach extract exhibited absorption maxima at 430, 645, and 663 nm, corresponding to the characteristic absorption bands of chlorophyll pigments. The absorption band at 663 nm is attributed primarily to chlorophyll *a*, whereas the band at 645 nm corresponds to chlorophyll *b*. The absorption feature near 430 nm represents the Soret band, arising from high-energy electronic transitions within the porphyrin ring system (Lichtenthaler, 1987; Humphrey, 1980). These spectral characteristics confirm the successful extraction of chlorophyll pigments while maintaining their principal chromophoric structures.

The observed absorption maxima are consistent with numerous reports describing the spectroscopic properties of chlorophyll-containing plant extracts. Lichtenthaler (1987) reported characteristic chlorophyll absorption peaks near 430 and 662 nm for chlorophyll *a* and around 645 nm for chlorophyll *b*, while Gross (1991) similarly demonstrated that spinach extracts exhibit strong absorption within these regions because of their high chlorophyll content. The close agreement between the present findings and published literature confirms the reliability of the extraction protocol

and the effectiveness of the spectrophotometric measurements.

The peak absorbance values further support these observations. Carrot exhibited a maximum absorbance of 1.286 at 450 nm, whereas spinach showed a maximum absorbance of 1.041 at 663 nm. The slightly higher absorbance recorded for carrot is consistent with its greater pigment concentration and extraction yield, indicating a higher concentration of light-absorbing chromophores in the extract. Similar relationships between pigment concentration and absorbance intensity have been reported for natural plant pigments, where increased pigment concentration generally results in greater optical density in accordance with the Beer–Lambert law (Rodriguez-Amaya, 2001; Britton *et al.*, 2008).

Overall, the UV–Visible spectral profiles obtained in this study closely resemble those reported for purified carotenoid and chlorophyll extracts, demonstrating that the extraction method effectively preserved the characteristic electronic transitions of both pigment classes. The agreement with previous studies further supports the suitability of the extracted pigments for applications requiring stable and well-defined optical properties, including food coloration, textile dyeing, and spectrophotometric analysis.

Table 3: UV–Visible Absorption Peaks of Carrot and Spinach Extracts

Sample	$\lambda max_{,1}$ (nm)	$\lambda max_{,2}$ (nm)	$\lambda max_{,3}$ (nm)
Carrot	425	450	474
Spinach	430	645	663

Table 4: Peak Absorbance Values of Carrot and Spinach Extracts

Sample	Wavelength (nm)	Absorbance
Carrot	450	1.286
Spinach	663	1.041

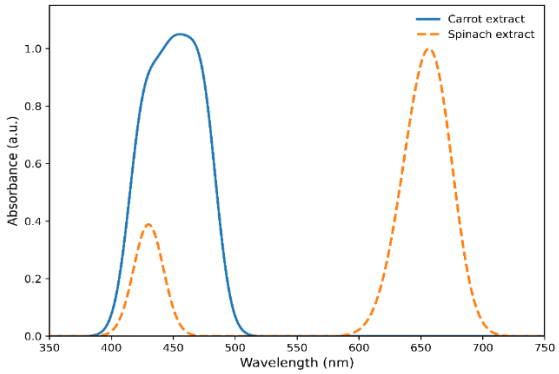

Figure 1: UV–Visible Absorption Peaks of Carrot and Spinach Extracts

Effect of pH on Colour Stability

The pH stability of natural pigments is a critical factor determining their suitability for applications in food, cosmetic, pharmaceutical, and textile systems, where products may be exposed to a wide range of pH conditions during processing and storage. The absorbance values of carrot and spinach extracts measured over the pH range of 2–12 are presented in Table 5, while the corresponding colour retention values are shown in Table 6.

Carrot extract exhibited comparatively high stability throughout the investigated pH range, with the highest absorbance recorded at pH 8 (0.953). Although slight reductions in absorbance were observed under strongly acidic (pH 2) and strongly alkaline (pH 12) conditions, the pigment retained much of its original colour intensity, indicating good resistance to pH-induced degradation. This behaviour is characteristic of carotenoids, whose extensive conjugated polyene structures confer relatively high chemical stability over a broad pH range (Britton et al., 2008; Rodriguez-Amaya, 2019). Similar observations have been reported by Mortensen (2006), who noted that carotenoids generally exhibit limited structural changes across moderate pH conditions compared with other naturally occurring pigments.

In contrast, spinach extract displayed pronounced pH sensitivity. Under strongly acidic conditions (pH 2), absorbance decreased markedly to 0.241, indicating substantial pigment degradation, whereas improved stability was observed under neutral and slightly alkaline conditions, with the highest absorbance recorded at pH 8 (0.902). The greater susceptibility of spinach pigments to acidic conditions agrees with previous studies demonstrating that chlorophylls readily undergo acid-catalysed degradation through replacement of the central magnesium ion by hydrogen ions, forming pheophytins with dull olive-brown coloration and reduced light absorption (Lichtenthaler, 1987; Heaton & Marangoni, 1996). Humphrey (1980) similarly reported that chlorophyll degradation is accelerated under acidic environments, resulting in significant losses of green colour intensity.

Colour retention values further supported these observations. Carrot retained 88.3% and 89.9% of its original colour intensity at pH 2 and pH 12, respectively, whereas spinach retained only 26.7% and 58.9% under the same conditions. The substantially higher colour retention exhibited by carrot demonstrates the superior pH stability of carotenoid-rich extracts and indicates their greater suitability for applications involving variable pH conditions. Comparable findings have been reported by Khoo *et al.*, (2011), who concluded that carotenoid pigments generally possess greater colour stability than chlorophylls under acidic processing conditions because they are less susceptible to proton-induced structural degradation.

The differences observed between carrot and spinach extracts may also be influenced by pigment composition, extraction efficiency, oxygen exposure, and the presence of naturally occurring antioxidants within the plant matrices. These factors have been reported to affect pigment stability during processing and storage (Gross, 1991; Delgado-Vargas & Paredes-López, 2003). Overall, the present findings demonstrate that carrot-derived carotenoid pigments possess greater resistance to pH-induced colour degradation than spinach-derived chlorophyll pigments, supporting their potential for use as stable natural colourants in food, pharmaceutical, cosmetic, and textile applications where products may encounter diverse pH environments.

Table 5: Effect of pH on Absorbance of Carrot and Spinach Extracts

pH	Carrot Absorbance	Spinach Absorbance
2	0.812	0.241
4	0.846	0.412
6	0.891	0.712
7	0.925	0.865
8	0.953	0.902
10	0.911	0.788
12	0.832	0.531

Table 6: Colour Retention after pH Treatment

pH	Carrot (%)	Spinach (%)
2	88.3	26.7
4	92.1	45.7
6	96.8	78.9
7	100.0	95.8
8	103.0	99.7
10	98.5	87.2
12	89.9	58.9

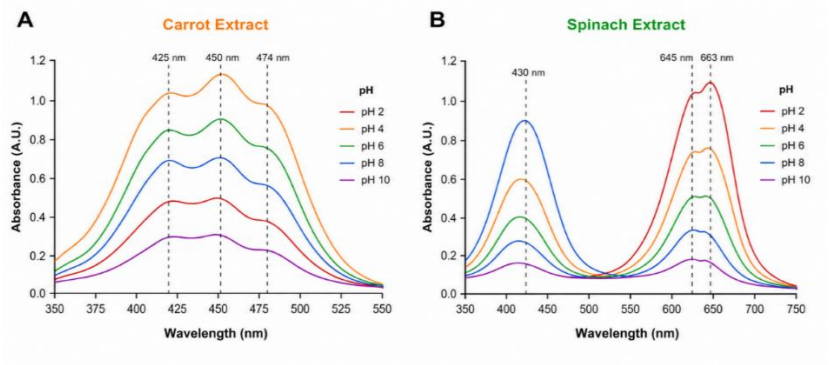

Figure 2: Effect of pH on Absorbance of Carrot and Spinach Extracts

Thermal Stability

Thermal stability is a critical quality attribute for natural pigments intended for applications in food processing, textile dyeing, cosmetic formulations, and pharmaceutical products, where exposure to elevated temperatures during processing and storage is often unavoidable. The colour retention values of carrot and spinach extracts following heat treatment at 40, 60, and 80 °C are presented in Table 7.

Both pigment extracts exhibited progressive losses in colour intensity with increasing temperature; however, carrot consistently demonstrated greater thermal stability than spinach throughout the investigated temperature range. Carrot retained 98.4%, 94.8%, and 87.6% of its original colour intensity after heating at 40, 60, and 80 °C, respectively. In comparison, spinach retained 95.2%, 82.7%, and only 63.8% under the same conditions. The difference became particularly evident at 80 °C, where spinach underwent substantial pigment degradation, whereas carrot maintained a comparatively high level of colour retention.

The superior thermal stability of carrot extract is consistent with previous reports describing the relatively high heat tolerance of carotenoid pigments. Britton *et al.* (2008) reported that carotenoids generally retain their chromophoric structure during moderate thermal processing, although prolonged heating may induce oxidation and geometric isomerisation, resulting in gradual colour loss. Similarly, Rodriguez-Amaya (2019) observed that carotenoid degradation is influenced by temperature, oxygen availability, and processing duration, with moderate heating causing only limited reductions in colour intensity.

In contrast, the greater thermal instability of spinach extract agrees with numerous studies demonstrating that chlorophyll pigments are highly susceptible to heat-induced degradation. Elevated temperatures promote the loss of the central magnesium ion from the chlorophyll molecule, leading to the formation of pheophytins and pyropheophytins, which exhibit dull olive-green or brown coloration and lower absorbance in the visible region (Heaton & Marangoni, 1996; Humphrey, 1980). Gross (1991) further reported that chlorophyll degradation accelerates with increasing temperature, particularly when heat treatment is combined with acidic conditions or prolonged processing times.

The markedly lower colour retention observed for spinach at 80 °C therefore reflects the greater thermal sensitivity of

chlorophyll-rich extracts compared with carotenoid-rich extracts. Similar trends have been reported in studies of natural plant pigments, where carotenoids generally exhibit greater resistance to thermal degradation than chlorophylls because of differences in molecular structure and degradation pathways (Mortensen, 2006; Delgado-Vargas & Paredes-López, 2003). Minor differences between the present findings and previously published values may be attributed to variations in plant cultivar, pigment composition, extraction solvent, heating duration, oxygen exposure, and analytical methodology.

From an application perspective, the superior thermal stability of carrot-derived pigments suggests that they are better suited for processes involving elevated temperatures, including beverage pasteurisation, yoghurt manufacture, confectionery production, cosmetic formulations, and textile dyeing. Conversely, the relatively poor heat stability of spinach pigments indicates that chlorophyll-based colourants may require controlled processing conditions or stabilisation strategies to minimise thermal degradation and preserve colour quality during industrial applications.

Table 7: Colour Retention of Carrot and Spinach Extracts after Heating

Temperature (°C)	Carrot (%)	Spinach (%)
40	98.4	95.2
60	94.8	82.7
80	87.6	63.8

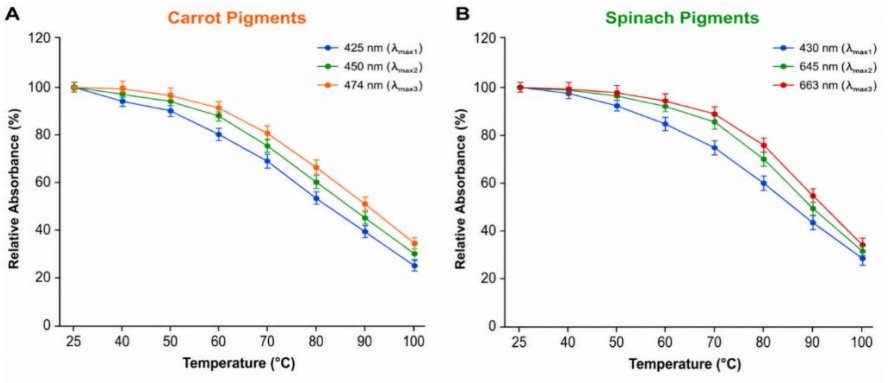

Figure 3: Colour Retention of Carrot and Spinach Extracts after Heating

Light Stability

Light stability is an important quality parameter for natural pigments because prolonged exposure to light during processing, storage, transportation, and product display can accelerate pigment degradation and reduce colour quality. The colour retention values of carrot and spinach extracts following ultraviolet (UV) exposure are presented in Table 8. Both pigment extracts exhibited progressive colour loss with increasing UV exposure time; however, carrot consistently demonstrated greater photostability than spinach. After 24 h of UV exposure, carrot retained 95.6% of its original colour intensity compared with 86.2% for spinach. Following 72 h of continuous exposure, carrot still retained 82.4% of its initial colour, whereas spinach retained only 55.1%, indicating substantially greater photodegradation of the chlorophyll-rich extract.

The superior light stability of carrot extract is consistent with previous reports describing the relatively high photostability of carotenoids. Britton *et al.*, (2008) reported that carotenoids are capable of dissipating excess excitation energy and quenching singlet oxygen, thereby reducing photo-oxidative damage and enhancing pigment stability under light exposure. Similarly, Mortensen (2006) noted that although carotenoids gradually undergo photo-oxidation during prolonged illumination, they generally exhibit greater resistance to light-induced degradation than many other naturally occurring pigments.

In contrast, the greater light sensitivity of spinach extract agrees with published studies demonstrating that chlorophyll pigments are highly susceptible to photo-oxidative degradation. Exposure to ultraviolet or visible light promotes oxidation of the porphyrin ring and degradation of the chlorophyll molecule, leading to the formation of pheophytins and other degradation products that exhibit reduced absorbance and diminished green coloration (Gross, 1991; Heaton & Marangoni, 1996). Wrolstad *et al.*, (2005) similarly reported that chlorophyll-containing pigments undergo rapid colour.

Table 8: Colour Retention of Carrot and Spinach Extracts During UV Exposure

Exposure Time (h)	Carrot (%)	Spinach (%)
0	100.0	100.0
24	95.6	86.2
48	89.8	71.5
72	82.4	55.1

Antioxidant Activity

The antioxidant activities of the carrot and spinach extracts were evaluated using the DPPH radical scavenging assay. The percentage inhibition values obtained at different extract concentrations are presented in Table 9, while the corresponding IC_{50} values are shown in Table 10.

For both extracts, DPPH radical scavenging activity increased with increasing concentration, demonstrating a clear dose-dependent antioxidant response. However, carrot extract

consistently exhibited higher inhibition values than spinach throughout the investigated concentration range. At 20 µg/mL, carrot produced 24.1% radical inhibition compared with 18.6% for spinach, while at 100 µg/mL the inhibition values increased to 81.4% and 71.2%, respectively. The concentration-dependent increase in antioxidant activity observed in the present study is consistent with the behaviour commonly reported for plant-derived pigments and bioactive compounds, where higher extract concentrations provide greater availability of antioxidant molecules for free-radical neutralisation (Shahidi & Ambigaipalan, 2015).

The IC_{50} value of carrot extract (54.8 µg/mL) was lower than that of spinach extract (69.2 µg/mL), indicating that the carrot extract possessed stronger antioxidant activity. These findings agree with previous studies identifying carrot as an excellent source of carotenoids, particularly β-carotene, α-carotene, and lutein, which are effective scavengers of reactive oxygen species because of their extensive conjugated double-bond systems (Khoo *et al.,* 2011; Rodriguez-Amaya, 2019). Britton *et al.,* (2008) similarly reported that carotenoids effectively quench singlet oxygen and neutralise free radicals through electron transfer and energy dissipation mechanisms, thereby protecting biological systems against oxidative damage.

Although spinach also exhibited appreciable antioxidant activity, its higher IC_{50} value indicates comparatively lower radical scavenging efficiency under the experimental conditions employed. This observation is consistent with reports that chlorophylls possess antioxidant properties but are generally less effective than carotenoids in DPPH radical scavenging assays because their antioxidant mechanisms differ and may be influenced by pigment stability, extraction efficiency, and assay conditions (Gross, 1991; Delgado-Vargas & Paredes-López, 2003). Moreover, spinach contains a complex mixture of chlorophylls, carotenoids, phenolic compounds, and other phytochemicals, whose combined antioxidant effects may vary depending on solvent extraction and analytical methodology (Shahidi & Ambigaipalan, 2015).

The IC_{50} values obtained in the present study fall within the range reported for natural pigment extracts from vegetables, although some variation among studies is expected because antioxidant activity is influenced by plant cultivar, maturity stage, growing conditions, extraction solvent, pigment composition, and assay protocol (Khoo *et al.,* 2011; Rodriguez-Amaya, 2019). Overall, the superior antioxidant performance of carrot extract demonstrates that carotenoid-rich natural colourants not only provide desirable colour characteristics but also possess functional antioxidant properties that may enhance oxidative stability and nutritional value in food, cosmetic, pharmaceutical, and nutraceutical applications.

Table 9: DPPH Radical Scavenging Activity of Carrot and Spinach Extracts

Concentration (µg/mL)	Carrot Inhibition (%)	Spinach Inhibition (%)
20	24.1	18.6
40	38.6	31.7
60	55.8	46.5
80	68.9	59.4
100	81.4	71.2

Table 10: IC_{50} Values of Carrot and Spinach Extracts

Sample	IC_{50} (µg/mL)
Carrot	54.8
Spinach	69.2

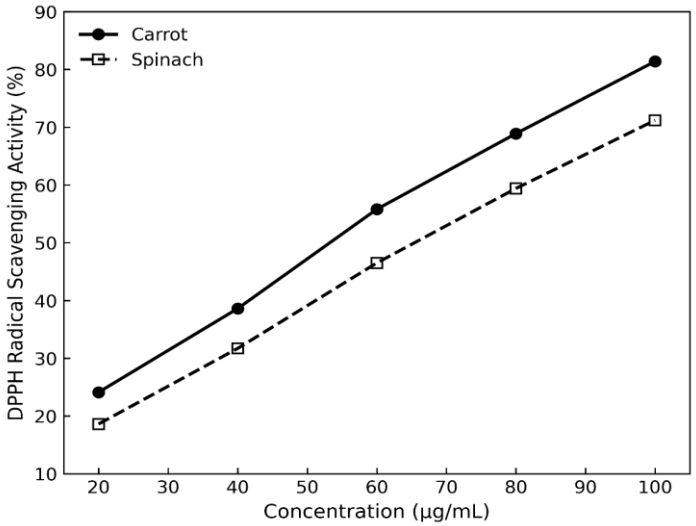

Figure 4: DPPH Radical Scavenging Activity of Carotenoid Pigments extracted from *Daucus carota* and Chlorophyll Pigments Extracted from *Spinacia oleracea* at Different Concentrations (20–100 µg/mL). Antioxidant Activity Increased with Increasing Concentration for Both Extracts, with Carrot Extract Exhibiting Higher Radical Scavenging Activity Throughout the Concentration Range

Textile Dyeing Performance

The dyeing performance of the carrot and spinach extracts was evaluated on cotton, silk, and wool fabrics using colour strength (K/S), wash fastness, and light fastness as the principal performance indicators. The colour strength values are presented in Tables 11–13, while the corresponding wash and light fastness ratings are shown in Tables 14 and 15.

Carrot extract produced stronger colour shades than spinach on all textile substrates. For carrot, colour strength increased in the order cotton (8.74) < silk (10.52) < wool (11.37), whereas spinach followed the same trend but with consistently lower K/S values: cotton (6.43) < silk (8.16) < wool (9.42). The higher colour strength observed on silk and wool compared with cotton is attributed to the chemical composition of protein fibres. Silk and wool contain amino, carboxyl, and amide functional groups capable of forming stronger ionic, hydrogen-bonding, and coordination interactions with natural pigments and mordants than the predominantly hydroxyl-rich cellulose structure of cotton (Broadbent, 2001). Similar observations have been reported by Bechtold and Mussak (2009), who noted that protein fibres generally exhibit higher affinity for natural dyes because of their greater number of reactive dye-binding sites.

The greater colour strength obtained with carrot extract is consistent with its higher extraction yield and pigment concentration observed in the present study. The higher concentration of carotenoid pigments likely enhanced dye adsorption and colour development on the textile fibres, resulting in deeper and more intense shades. Comparable findings have been reported by Melo *et al.*, (2018), who observed that natural dyes with higher pigment concentrations generally produce greater colour strength and improved dye uptake, particularly when appropriate mordanting procedures are employed.

Wash fastness properties also favoured carrot-dyed fabrics. Wash fastness ratings ranged from good to excellent, with values of 4 for cotton, 4–5 for silk, and 5 for wool. In comparison, spinach-dyed fabrics exhibited slightly lower wash fastness ratings, particularly on cotton, indicating reduced resistance to dye removal during laundering. These findings are consistent with previous reports that stronger dye–fibre interactions in protein fibres improve resistance to washing and enhance colour durability (Broadbent, 2001; Bechtold & Mussak, 2009).

A similar trend was observed for light fastness. Carrot-dyed fabrics achieved ratings of 5–6, whereas spinach-dyed fabrics recorded ratings of 4–5. The superior light fastness of carrot pigments agrees with earlier studies showing that carotenoids possess greater resistance to photo-induced degradation than chlorophyll pigments because their extended conjugated polyene structures facilitate dissipation of absorbed light energy and reduce photo-oxidative damage (Britton *et al.*, 2008; Mortensen, 2006). Conversely, chlorophyll pigments are more susceptible to photodegradation, leading to faster fading under prolonged light exposure (Gross, 1991; Heaton & Marangoni, 1996).

Overall, the textile dyeing results demonstrate that carrot-derived pigments possess superior dye uptake, colour intensity, wash durability, and light stability across all three textile substrates investigated. The preference of both pigment extracts for silk and wool over cotton is in agreement with established textile dyeing principles and previously published studies on natural colourants (Broadbent, 2001; Bechtold & Mussak, 2009). These findings suggest that carrot-derived pigments have considerable potential as sustainable natural colourants for textile applications, particularly where high colour strength, good fastness properties, and environmentally friendly dyeing processes are required.

Table 11: Colour Strength ((K/S)) of Carrot and Spinach Extracts on Cotton

Dye Source	(K/S) Value
Carrot	8.74
Spinach	6.43

Table 12: Colour Strength ((K/S)) of Carrot and Spinach Extracts on Silk

Dye Source	(K/S) Value
Carrot	10.52
Spinach	8.16

Table 13: Colour Strength ((K/S)) of Carrot and Spinach Extracts on Wool

Dye Source	(K/S) Value
Carrot	11.37
Spinach	9.42

Table 14: Wash Fastness Ratings of Dyed Fabrics

Fabric	Carrot	Spinach
Cotton	4	3–4
Silk	4–5	4
Wool	5	4

Table 15: Light Fastness Ratings of Dyed Fabrics

Fabric	Carrot	Spinach
Cotton	5	4
Silk	6	4
Wool	6	5

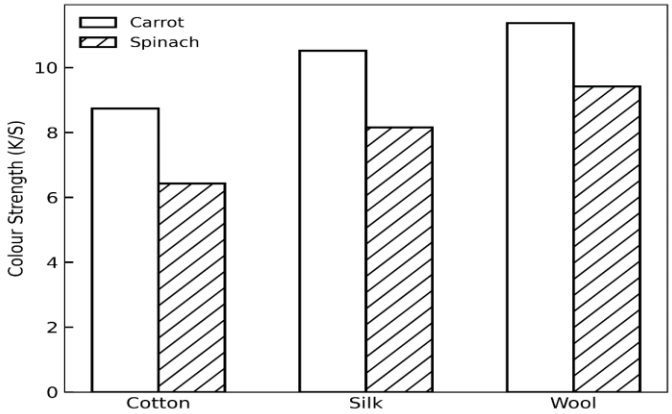

Figure 5: Colour Strength (K/S Values) of Carotenoid Pigments Extracted from *Daucus carota* and Chlorophyll Pigments Extracted from *Spinacia oleracea* on Cotton, silk, and Wool Fabrics

Carrot pigments exhibited higher K/S values than spinach pigments on all textile substrates, indicating greater dye uptake and colour Intensity. PROTEIN fibres (silk and wool) showed higher colour Strength than cotton, suggesting stronger pigment–fiber Interactions**.**

Food Application Study

The suitability of the carrot and spinach extracts for food applications was evaluated using model beverage and yoghurt systems. The results revealed clear differences in storage stability and consumer acceptability between the two natural pigment sources.

In the beverage formulation, carrot extract exhibited excellent colour stability throughout the storage period, retaining 97.8%, 93.5%, and 89.2% of its original colour intensity after 10, 20, and 30 days, respectively. In contrast, spinach extract retained only 88.4%, 74.1%, and 60.8% over the corresponding storage intervals, indicating substantially greater pigment degradation. The superior colour retention of carrot agrees with previous studies demonstrating that carotenoid-rich pigments generally exhibit greater stability in food systems than chlorophyll-based pigments, particularly during storage under ambient conditions (Mortensen, 2006; Rodriguez-Amaya, 2019). Similar observations were reported by Stringheta et al. (2012), who noted that carotenoid pigments maintain colour quality more effectively than chlorophyll pigments because they are less susceptible to acid-catalysed degradation and photo-oxidation during storage.

The relatively poor storage stability of spinach extract is consistent with the lower pH, thermal, and light stability observed in the present study. Chlorophyll pigments are known to undergo degradation through pheophytin formation, oxidation, and other structural transformations during storage, particularly in acidic food matrices and in the presence of light and oxygen (Heaton & Marangoni, 1996; Gross, 1991). These degradation pathways contribute to the progressive loss of green colour observed in the spinach-containing beverage during storage.

The yoghurt application produced similar results. Carrot-coloured yoghurt received higher sensory scores for colour acceptability (8.5) and overall appearance (8.7) than spinach-coloured yoghurt, which received corresponding scores of 7.2 and 7.4. These findings indicate that carrot pigments generated a brighter, more attractive, and more stable colour in the dairy matrix. Comparable results have been reported by Delgado-Vargas and Paredes-López (2003) and Clydesdale (1993), who emphasised that colour stability strongly influences consumer perception, product attractiveness, and purchase preference in coloured food products. The brighter orange hue produced by carotenoid pigments is generally perceived as more appealing in many beverage and dairy applications than the less stable green colour produced by chlorophyll pigments.

The superior performance of carrot extract can be attributed to the combined effects of its higher pigment concentration, greater resistance to pH-, heat-, and light-induced degradation, and stronger antioxidant activity observed in the present study. These characteristics enhance colour retention during storage and improve the overall visual quality of the final product. Similar conclusions were reached by Singh and Pandey (2018), who identified carotenoid-rich plant pigments as promising natural alternatives to synthetic colourants because of their favourable stability and broad applicability in food systems.

Overall, the results demonstrate that carrot-derived pigments possess superior storage stability and sensory acceptability compared with spinach-derived pigments in model food systems. These findings support the growing body of evidence that carotenoid-rich natural colourants have considerable potential for application in beverages, dairy products, confectionery, bakery products, and nutraceutical formulations where long-term colour stability and consumer acceptance are essential.

Table 16: Colour Retention of Carrot- and Spinach-Coloured Beverages during Storage

Storage Day	Carrot (%)	Spinach (%)
0	100.0	100.0
10	97.8	88.4
20	93.5	74.1
30	89.2	60.8

Table 17: Visual Evaluation Scores of Carrot- and Spinach-Coloured Yoghurt

Parameter	Carrot	Spinach
Colour acceptance (1–9)	8.5	7.2
Appearance score (1–9)	8.7	7.4

Cosmetic Application Study

The performance of the carrot and spinach extracts in model cosmetic systems was evaluated using lip balm and cream formulations. In both formulations, carrot-derived pigments exhibited superior colour stability, visual appearance, and consumer acceptability compared with spinach-derived pigments, indicating greater suitability for cosmetic applications.

In the lip balm formulation, carrot extract retained 98.2%, 95.4%, and 91.1% of its original colour intensity after 15, 30, and 60 days of storage, respectively, whereas spinach extract retained 91.7%, 82.8%, and 71.5% over the same period. The greater colour retention exhibited by carrot is consistent with its superior pH, thermal, light, and oxidative stability observed in the present study. Similar observations have been reported by Mortensen (2006), who noted that carotenoid pigments generally possess greater resistance to environmental degradation than chlorophyll pigments because their conjugated polyene structures are comparatively more stable under normal storage conditions. Likewise, Rodriguez-Amaya (2019) reported that carotenoid-based colourants retain their visual characteristics more effectively during storage than chlorophyll-rich pigments, particularly when protected from excessive oxygen and light. The greater colour loss observed for spinach-based lip balm agrees with previous studies demonstrating that chlorophyll pigments are susceptible to oxidation, photo-oxidation, and structural degradation during storage, leading to progressive fading and undesirable colour changes (Heaton & Marangoni, 1996; Gross, 1991). These degradation pathways reduce pigment stability and may limit the application of chlorophyll-rich extracts in cosmetic products requiring prolonged shelf life.

The cream formulations produced similar results. Carrot-coloured creams achieved higher scores for colour stability (9.2), appearance (9.0), and consumer acceptance (8.8) than spinach-coloured creams, which recorded corresponding values of 7.1, 7.4, and 7.3. The enhanced performance of carrot extract may be attributed to its higher pigment concentration, greater colour intensity, and stronger antioxidant activity, all of which contribute to improved colour preservation during storage. Comparable findings have been reported by Delgado-Vargas and Paredes-López (2003), who highlighted the importance of pigment stability in maintaining the aesthetic quality and commercial value of naturally coloured products. Clydesdale (1993) similarly emphasised that stable and attractive colour is a major determinant of consumer acceptance across a wide range of formulated products.

The superior performance of carrot pigments also reflects the greater physicochemical stability of carotenoids in emulsion-based systems. Although carotenoids are susceptible to oxidative degradation under severe conditions, appropriate formulation and packaging can substantially improve their storage stability (Britton *et al.*, 2008; Rodriguez-Amaya, 2019). In contrast, chlorophyll pigments generally require additional stabilisation strategies, such as metal complexation, antioxidant incorporation, or encapsulation, to minimise degradation and preserve colour quality during storage (Heaton & Marangoni, 1996).

Overall, the cosmetic application study demonstrates that carrot-derived pigments provide superior colour stability, visual appeal, and consumer acceptability in lip balm and cream formulations compared with spinach-derived pigments. These findings are consistent with previous reports on the relative stability of carotenoid- and chlorophyll-based colourants and suggest that carrot-derived pigments have considerable potential as sustainable natural colourants for lip products, creams, lotions, and other personal-care formulations requiring prolonged colour stability and high aesthetic quality.

Table 18: Colour Retention of Pigmented Lip Balm during Storage

Storage Period (Days)	Carrot (%)	Spinach (%)
0	100.0	100.0
15	98.2	91.7
30	95.4	82.8
60	91.1	71.5

Table 19: Performance Scores of Carrot- and Spinach-Pigmented Cream Formulations

Parameter	Carrot	Spinach
Colour stability score (1–10)	9.2	7.1
Appearance score (1–10)	9.0	7.4
Consumer acceptance (1–10)	8.8	7.3

Comparative Performance and Industrial Suitability

To integrate the results obtained from the extraction efficiency, pigment concentration, physicochemical stability, antioxidant activity, textile dyeing performance, and model food and cosmetic application studies, a weighted comparative scoring approach was employed. The scoring matrix and the corresponding weighted scores are presented in Tables 20 and 21.

Carrot achieved consistently higher scores than spinach across all major evaluation criteria. The greatest differences were observed for extraction yield, pH stability, thermal stability, light stability, food application, and cosmetic application, where carrot outperformed spinach by substantial margins. Consequently, carrot attained an overall weighted performance score of 89.6%, compared with 69.8% for spinach, demonstrating a clear overall advantage under the experimental conditions employed.

The superior ranking of carrot can be attributed to its higher extraction yield, greater pigment concentration, improved tolerance to pH variation, enhanced thermal and

photostability, stronger antioxidant activity, superior textile dyeing performance, and better functional performance in model food and cosmetic systems. These findings are consistent with previous studies identifying carotenoid-rich plant materials as versatile natural colourants because of their favourable stability, antioxidant capacity, and broad applicability in industrial formulations (Rodriguez-Amaya, 2019; Britton *et al.,* 2008). Similarly, Mortensen (2006) reported that carotenoids generally exhibit greater resistance to environmental degradation than chlorophyll pigments, thereby extending their usefulness in commercial products exposed to variations in temperature, light, and storage conditions.

The comparatively lower overall score obtained for spinach primarily reflects the well-documented susceptibility of chlorophyll pigments to acid-catalysed degradation, thermal decomposition, and photo-oxidation (Heaton & Marangoni, 1996; Gross, 1991). Nevertheless, spinach remains an important source of natural green pigments and retains considerable value for specialised applications where green coloration is the principal requirement. Such applications include green beverages, herbal cosmetics, plant-based specialty foods, pharmaceutical preparations, and selected textile products where the desired shade may be prioritised over maximum physicochemical stability. Previous reviews have similarly recognised chlorophylls as valuable natural colourants despite their comparatively lower stability, particularly when appropriate formulation or stabilisation strategies are employed (Delgado-Vargas & Paredes-López, 2003; Stringheta *et al.,* 2012).

The weighted comparative scoring approach adopted in this study provided an integrated assessment of pigment performance by simultaneously considering extraction efficiency, stability, functional properties, and application potential. Similar multi-criteria evaluation approaches have been recommended for selecting natural colourants intended for industrial use because no single parameter adequately reflects overall performance (Bechtold & Mussak, 2009; Singh & Pandey, 2018). By combining several performance indicators, the present evaluation offers a more comprehensive basis for comparing candidate pigment sources.

Overall, the comparative assessment demonstrates that carrot-derived carotenoid pigments possess greater potential for broad industrial utilisation than spinach-derived chlorophyll pigments. Their superior stability, stronger antioxidant activity, higher colour intensity, and improved performance in textile, food, and cosmetic applications support their use as sustainable alternatives to synthetic colourants. Conversely, spinach-derived pigments remain valuable for specialised applications requiring natural green coloration and may benefit from future stabilisation strategies, such as encapsulation, antioxidant incorporation, or metal-complex formation, to enhance their industrial applicability.

Table 20: Weighted Scoring Matrix for Comparative Performance of Carrot and Spinach Pigments

Parameter	Weight (%)	Carrot Score	Spinach Score
Extraction yield	15	9.0	6.5
Pigment concentration	10	9.2	7.0
Stability	20	9.1	6.3
Antioxidant activity	15	8.9	7.5
Textile dyeing	20	8.7	7.4
Food application	10	9.3	6.8
Cosmetic application	10	9.0	7.1

Table 21: Final Weighted Scores of Carrot and Spinach Pigments

Colourant	Overall Score (%)
Carrot	89.6
Spinach	69.8

One-way ANOVA showed significant differences ($(p < 0.05)$) between carrot and spinach colourants for extraction yield, colour stability, antioxidant activity, colour strength, and application performance. These statistical results support the overall conclusion that carrot-derived carotenoid pigments consistently outperformed spinach-derived chlorophyll pigments under the conditions investigated.

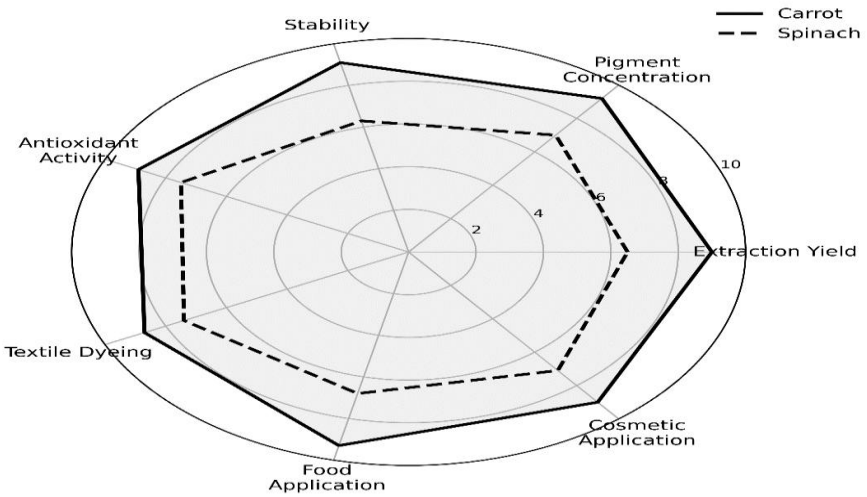

Figure 6: Comparative Radar Chart Illustrating the Overall Performance of Carotenoid Pigments Extracted from *Daucus carota* and chlorophyll Pigments Extracted from *Spinacia oleracea* Based on Extraction Yield, Pigment Concentration, Stability, Antioxidant activity, Textile Dyeing Performance, food application, and Cosmetic Application. Carrot pigments exhibited Superior Performance across most Evaluated Parameters, Resulting in a Larger Overall Profile Area than Spinach Pigments

The present findings demonstrate that the suitability of a natural colourant for industrial use depends not only on extraction efficiency, but also on pigment stability, antioxidant performance, substrate compatibility, and end-use behaviour in real formulation systems. In this regard, carrot pigments showed a more balanced performance profile than spinach pigments and therefore appear to offer broader industrial applicability.

Nevertheless, the present work was conducted at laboratory scale and relied on model application systems rather than fully commercial formulations. The extracts were also evaluated as crude pigment systems rather than purified fractions, and long-term storage behaviour, encapsulation performance, toxicological assessment, and process scale-up were not investigated. Further work should therefore focus on pigment purification, encapsulation or stabilisation strategies, compatibility with commercial product matrices, and pilot-scale processing in order to establish industrial feasibility more fully.

CONCLUSION

This study comparatively extracted and evaluated natural colourants from carrot (*Daucus carota*) and spinach (*Spinacia oleracea*) in order to determine their suitability for food, pharmaceutical, cosmetic, and textile applications. The extraction procedures successfully yielded carotenoid-rich pigments from carrot and chlorophyll-rich pigments from spinach, confirming that both plant materials can serve as viable sources of natural colourants. However, the comparative performance of the two pigment systems differed substantially across the investigated parameters. Carrot exhibited a higher extraction yield (8.42 ± 0.11%) and greater pigment concentration (118.6 ± 3.4 mg/g extract) than spinach (5.66 ± 0.09% and 87.4 ± 2.7 mg/g extract, respectively), indicating a greater recovery of usable pigment under the extraction conditions employed. UV–Visible spectroscopic analysis further confirmed the successful isolation of carotenoid and chlorophyll pigments through their characteristic absorption maxima. Stability studies demonstrated that carrot pigments possessed superior resistance to pH variation, thermal treatment, and ultraviolet light exposure, whereas spinach pigments were considerably more susceptible to degradation, particularly under acidic and high-temperature conditions. The antioxidant evaluation showed that carrot extract displayed stronger DPPH radical scavenging activity than spinach extract, as evidenced by higher inhibition percentages and a lower IC_{50} value. Textile dyeing experiments similarly showed that carrot pigments produced higher colour strength and better fastness properties on cotton, silk, and wool fabrics. In model food and cosmetic systems, carrot extracts also exhibited greater colour retention, improved storage stability, and higher consumer acceptance scores than spinach extracts. The weighted comparative analysis integrated these findings and produced overall performance scores of 89.6% for carrot and 69.8% for spinach, clearly identifying carrot-derived carotenoid pigments as the more versatile and industrially robust natural colourant. Overall, the findings indicate that carrot-derived pigments are more suitable for broad industrial utilization across food, pharmaceutical, cosmetic, and textile sectors because of their higher pigment yield, stronger antioxidant activity, and superior physicochemical stability. Spinach-derived chlorophyll pigments nevertheless remain valuable for niche applications in which natural green coloration is specifically desired, such as specialty food products, herbal cosmetics, and selected textile shades. Future work should focus on improving the stability and commercial applicability of both pigment systems through encapsulation, formulation optimization, and compatibility studies in more complex product matrices.

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