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The Optical Properties of Natural Capsanthin Dye Solutions and Their Application as Antibacterial

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ABSTRACT: In the present work, the linear optical properties of Capsanthin (paprika) dye were studied by preparing liquid samples (solutions of natural Capsanthin dyes dissolved in distilled water) at different concentrations (0.01, 0.03, and 0.05 mM). The absorbance spectra of the solutions were calculated using a UV-Vis spectrophotometer. The results of the linear optical properties of the dye solutions showed that increasing the concentration of Capsanthin dye leads to an increase in absorbance values and a decrease in transmittance values, which is consistent with the Beer-Lambert law. They also showed that increasing the concentration leads to an increase in the calculated linear optical parameters.

1. INTRODUCTION

Natural dyes have several advantages compared to rare earth metal compounds. They can be obtained through simple processes [1,2]. have a high absorption coefficient, are harmless and environmentally friendly as they do not leave harmful residues, are easily biodegradable, and are widely found in the environment [3,4]. For example, paprika dye, obtained from the pepper genus, is widely used as a food coloring [5]. The color reflection of paprika dye and the percentage of red or yellow Dye were measured immediately after drying for three months, and the results showed better color reflection [6]. The dye is classified as an E160C food additive. [7]. Natural dyes exhibit both linear and nonlinear optical properties, making them promising materials for various photonic and optoelectronic applications.

The absorption of the natural dye Capsanthin in solutions depends on intermolecular electronic transitions, which are often of the $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ types. These transitions occur when the molecule is exposed to a photon energy corresponding to the difference between the energy levels, allowing the electron to move from the ground state to the excited state. This phenomenon is analyzed by UV-Vis spectroscopy, where absorption peaks appear at characteristic wavelengths that indicate the type of electronic transition. These peaks can therefore be used to determine the optical efficiency of the dye and its suitability for applications such as organic solar cells or smart membranes [8].

2. THEORETICAL PART

Optical properties can be widely utilized in devices such as solar cells, as well as in medical and technological applications. [9]. If I_0 is the intensity of the incident light and I is the intensity of the transmitted light:

$$I = I_0 e^{-\alpha d} \dots \dots \dots (1)$$

Where α is the absorption coefficient and d is the path length of the absorbing species.

The absorption coefficient α can be calculated from the absorption data as [10,11].

$$\alpha = 2.303 \frac{A}{d} \dots\dots\dots (2)$$

The Beer-Lambert law has implicit assumptions that must be met experimentally for it to apply otherwise there is a possibility of deviations from the law to be observed [12].

The reflectance (R) has been determined from values of transmission (T), and absorbance (A), using the relationship [13]:

$$A + R + T = 1 \dots\dots\dots (3)$$

The refractive index was calculated by dividing the speed of light in a vacuum by its speed in the material. [14]:

$$n = \frac{c}{V} \dots\dots\dots (4)$$

where (c) is the velocity of the light in vacuum and (v) is the velocity of the light in specimen.

$$n^* = n - ik \dots\dots\dots (5)$$

where: n^* is complex refractive index, n is real part of refractive index and k is imaginary part of refractive index (extinction coefficient). The relation between absorption coefficient and the molar absorptivity or extinction coefficient (k) is

$$k = \frac{\alpha \lambda}{4\pi} \dots\dots\dots (6)$$

The real part of refractive index (n) can be determined by:

$$n = \frac{1 + \sqrt{R}}{1 - \sqrt{R}} \dots\dots\dots (7)$$

Where R is the reflectance to estimate the nature of absorption [15].

3. EXPERIMENTAL PART

3.1 Material Used

3.1.1 Natural Capsanthin dye

The red pigment in paprika originates from capsanthin, a xanthophyll-type carotenoid [16]. Capsanthin is a carotenoid found in sweet red peppers, New Mexico chili peppers, and capsicum peppers, and is one of the components of paprika. [17] Capsanthin is also one of the most potent antioxidants because it contains a conjugated double bond and a cyclopentane molecule. [18,19]. Figure (1) shows the natural Capsanthin dye powder and their chemical structure.

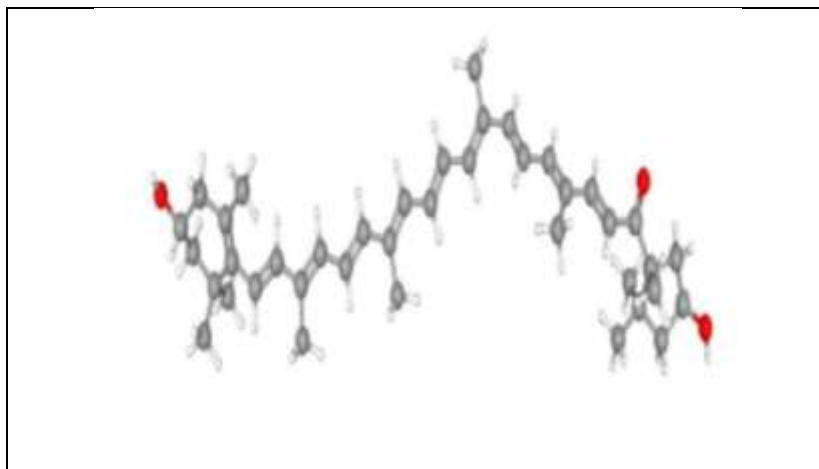


Figure (1): Chemical structure of natural Capsanthin.

Table (1) Properties of Natural Capsanthin dye [19] .

Property	Description
Dye Name	Capsanthin
Appearance	Deep red solid
Solubility and Solvent	Water
Chemical formula	C ₄₀ H ₅₆ O ₃
Molecular Weight	584.885 g/mol

3.1.2 Preparation of Natural Capsanthin dye solutions

Natural Capsanthin dye was prepared at a specific weight to obtain a 1 mM according to the weight equation:

$$M = C \times V \times M_w / 1000 \dots\dots\dots(8)$$

Where:

M: The weight of the dye required to achieve the desired concentration in grams

C: The concentration to be prepared in mol/L

V: The volume of solvent required to be added to the material in cubic centimeters

M_w: The molecular weight of the dye used in grams/mol.

To prepare dyes solutions at different concentrations (0.01, 0.03 and 0.05) mM, specific volume of the same solvent is added to a specific volume of that concentration (the higher concentration). The following relationship, called the dilution relationship, is used:

$$C_1 V_1 = C_2 V_2 \dots\dots\dots(9)$$

Where

C₁: The first (higher) concentration.

C₂: The second (lighter) concentration.

V1: The required volume of the first concentration.

V2: The volume required to add to the first concentration to obtain the second concentration.

Three concentrations were obtained for natural Capsanthin dye. Figure (2) shown the solutions of natural Capsanthin dye at different concentrations .



Figure (2) The solutions samples of natural Capsanthin dyes of at different concentrations

4. RESULTS AND DISCUSSION AND CONCLUSIONS

4.1. The absorbance and transmittance spectra of natural Capsanthin dye solutions.

Figure (3) shows the absorbance spectra of natural Capsanthin dye solutions that dissolved in distilled water at different concentrations (0.01,0.03,0.05) mM, which were measured using UV-VIS Spectrophotometers. It is noted from the figure that increasing the dyes concentrations leads to an increase in the absorbance values for dye solutions, this is consistent with the beer-Lambert law, this was overall obtained to the increasing number of molecules per volume unit at high concentrations.

Figure (4) shows the transmittance spectra of natural Capsanthin dye solutions at different concentrations. It is noted from the figure that increasing the dye concentrations leads to an decreases in the transmittance values for dye solutions. this is due to the increase in absorbance values.

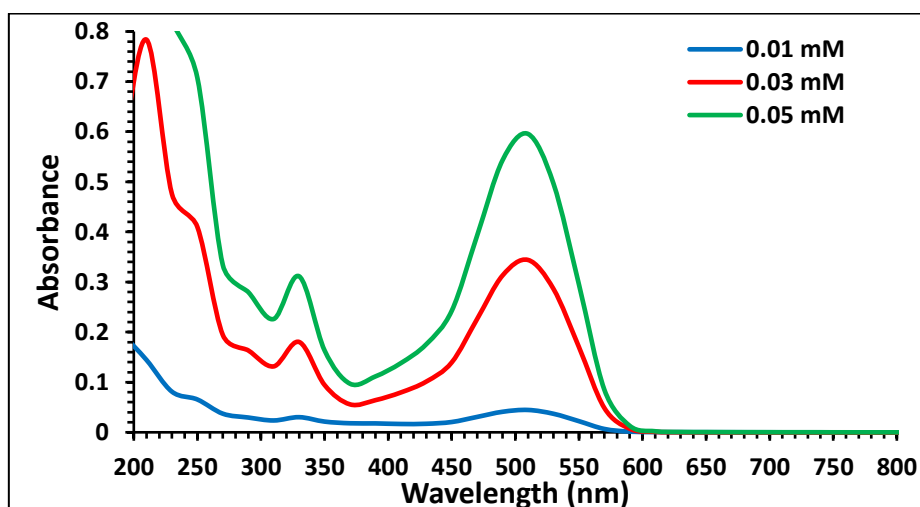


Figure (3): The absorbance spectra as function of wavelength for natural Capsanthin dye solutions at different concentrations

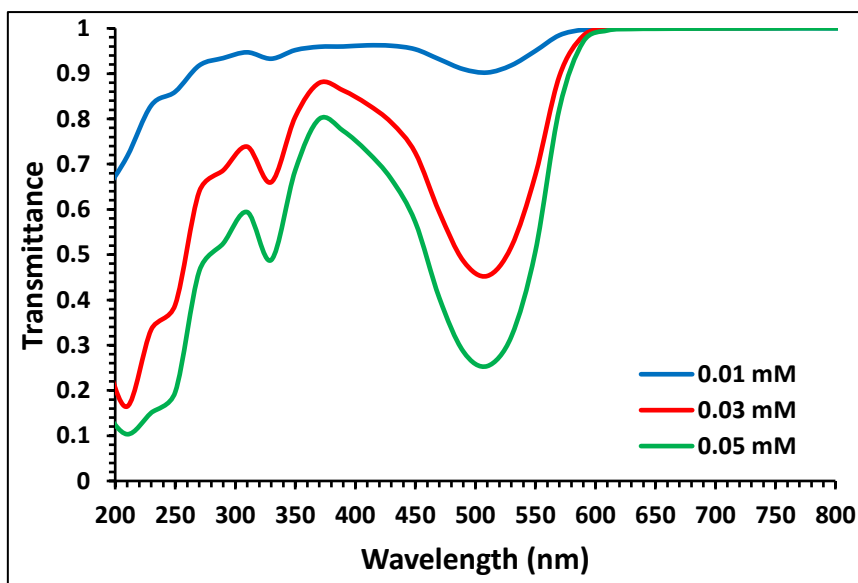


Figure (4): The transmittance spectra as function of wavelength for natural Capsanthin dye solutions at different concentrations.

4.1. The Optical Parameters of Capsanthin natural dye solutions

By using the absorbance and transmittance values of Capsanthin natural dye solutions the most important optical parameters. Figures (5-7) shows the linear absorption coefficient, refractive index and extinction coefficient curves of Capsanthin natural dye solutions as function of wavelength for natural Capsanthin dye solutions at different concentrations. It is noted from these figures the increase in absorbance with increasing concentration leads to an increase of all optical parameters, as shown in Table (4), this Table shows the most important optical parameters at the wavelength (510) nm.

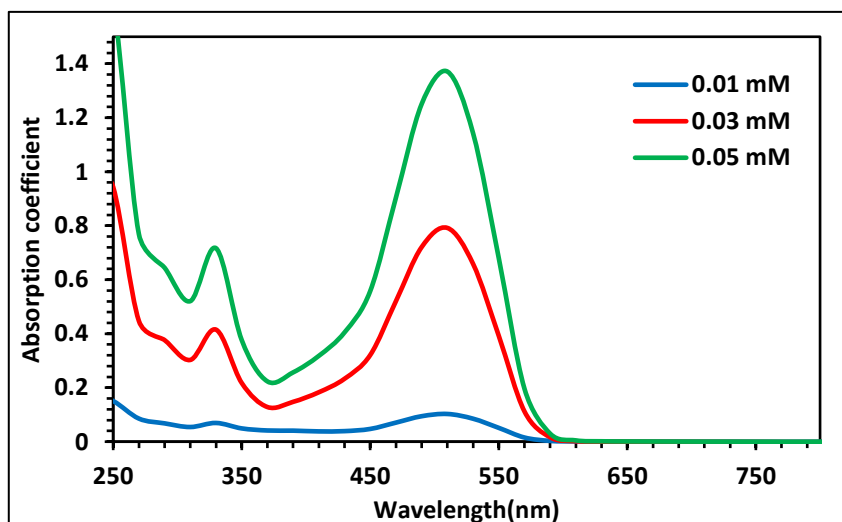


Figure (5): The Absorption coefficient spectra as function of wavelength for natural Capsanthin dye solutions at different concentrations

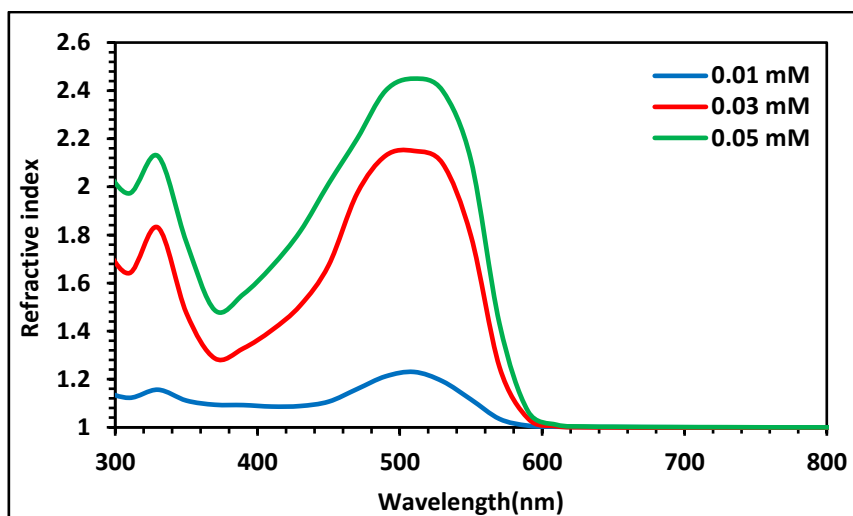


Figure (6): The Refractive index spectra as function of wavelength for natural Capsanthin dye solutions at different concentrations

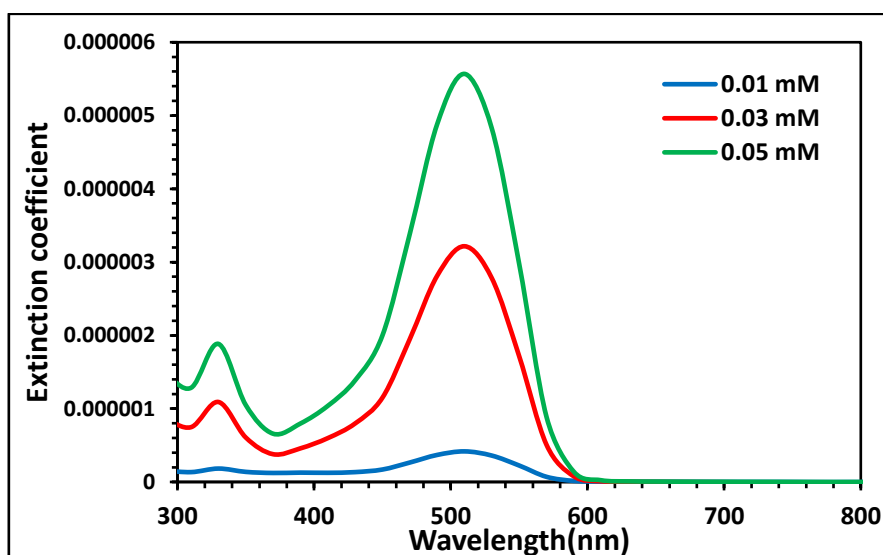


Figure (7): The Extinction coefficient function of wavelength for natural Capsanthin dye solutions at different concentrations.

Table (2) : The optical properties of natural Capsanthin dye solutions with different concentrations at wavelength (510 nm).

Dye Concentrations	A	T	α	k	n
0.01	0.05	0.90	0.1	4×10^{-7}	1.2
0.03	0.35	0.45	0.7	3×10^{-6}	2.1
0.05	0.61	0.25	1.3	5×10^{-6}	2.4

4.2 Antibacterial Activity of Natural Capsanthin Dye

Typical Gram-positive and Gram-negative bacteria were targeted with natural capesin stain solutions using the well diffusion method on agar. The bacteria used were *Staphylococcus aureus* (ATCC25922) and *Escherichia coli* (ATCC25923). Sterile

Mueller-Hinton agar plates were inoculated with bacterial suspensions modified according to the McFarland 0.5 standard. The 6 mm wells were filled with 100 μ L of capesin solutions at concentrations of 0.001, 0.003, and 0.005 mM. Ceroofloxacin (5 μ g/mol) was used as a positive control, and distilled water as a negative control. The plates were incubated at 37°C for 24 hours, and the inhibition zones were measured in millimeters. The results showed that capesin stain exhibited dose-dependent antibacterial activity against both Gram-positive and Gram-negative bacteria. Grams.

Capsatin dye is one of the best dyes that shows antibacterial activity, as its effectiveness depends on the dosage applied against both Gram-positive and Gram-negative bacteria.. At the highest concentration (0.05 mM), inhibition zones reached 14 ± 0.5 mm for *S. aureus* and 11 ± 0.4 mm for *E. coli*, compared to ciprofloxacin (22–24 mm). The lower concentrations (0.01 and 0.03 mM) showed proportionally smaller inhibition zones as shown in the figure (8) .

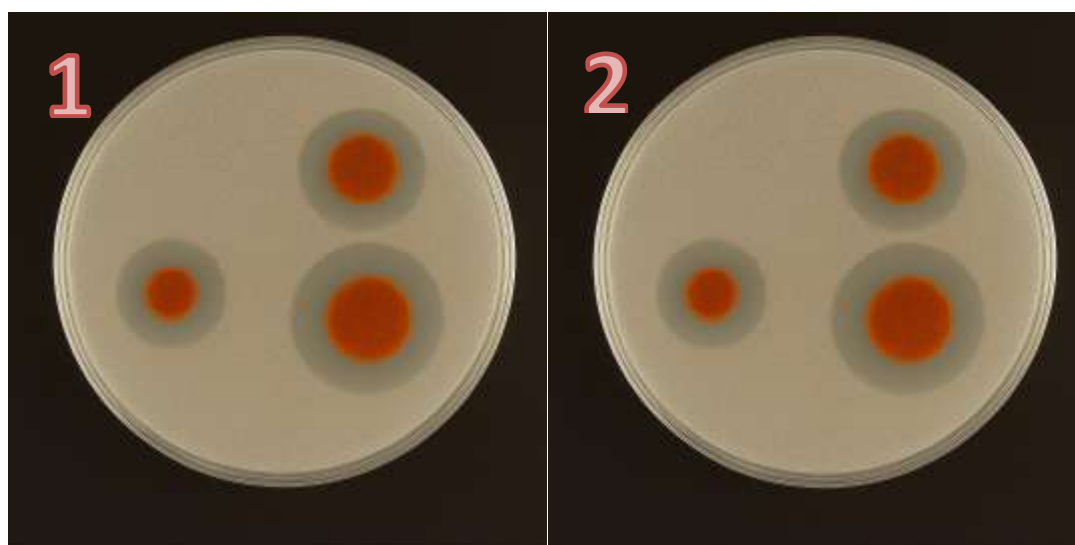


Figure (8) shows inhibition of both (1) gram-positive (2) gram-negative bacteria at different concentrations of red paprika dye is shown

Gram-positive bacteria have a thick layer of peptidoglycan, allowing for greater interaction with carotene, which is lipophilic and has a stronger effect against *Staphylococcus aureus*, depending on differences in cell wall structure., whereas Gram-negative bacteria have an additional outer membrane limiting penetration [1]. The antioxidant nature of Capsanthin, due to its conjugated double bonds and keto groups, likely contributes to membrane disruption and oxidative stress in bacterial cells [2]. These findings align with prior studies reporting antibacterial activity of carotenoids and paprika extracts against foodborne pathogens [3–5].

Importantly, the optical properties discussed earlier (high absorbance and refractive index) correlate with its bioactivity; the same conjugated π -electron system responsible for strong light absorption also enhances interaction with bacterial membranes and reactive oxygen species (ROS) generation, providing a dual functional advantage for biomedical and food preservation applications.

Table 3: Inhibition zones (mm) of Capsanthin dye against Gram-positive and Gram-negative bacteria at different concentrations.

Concentration (mM)	<i>S. aureus</i> (Gram +)	<i>E. coli</i> (Gram -)
0.01	8 ± 0.3	6 ± 0.2
0.03	11 ± 0.4	9 ± 0.3
0.05	14 ± 0.5	11 ± 0.4

5. CONCLUSIONS

The results demonstrated that natural capsanthin dye extracted from paprika exhibits distinctive linear optical properties that are clearly concentration-dependent. Increasing the dye concentration led to higher absorbance and lower transmittance values, consistent with the Beer–Lambert law. The calculated optical parameters, including absorption coefficient, refractive index, and extinction coefficient, all increased with concentration, highlighting the efficiency of capsanthin as an optically active material in the visible light range. Moreover, the study confirmed that capsanthin dye possesses concentration-dependent antibacterial activity, effectively inhibiting the growth of both Gram-positive and Gram-negative bacteria, with stronger effects observed against *Staphylococcus aureus*. These findings suggest that capsanthin has dual functionality—optical and biological—making it a promising candidate for applications in optical sensors, antimicrobial coatings, and food preservation. This underscores the value of utilizing natural materials for multifunctional technological and biomedical applications.

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