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RESEARCH

Absorption, Steady-State Fluorescence and Solvent Effect Studies of Fluorescent Haloarchaeal Bacterioruberin

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Abstract

Fluorescence characterization of halophilic archaeal C50 carotenoid–bacterioruberin extracts was investigated using UV/Vis and steady-state fluorescence spectrophotometry in solvents with different polarity. Different extracts showed maximum absorption and fluorescence wavelengths between 369–536 nm and 540–569 nm. Stokes' shifts varied between 50–79 nm depending on the solvent. In particular, water extract showed significant Stokes' shifts with the increase in polarity index; however, fluorescence wavelength (band position) and shape were found to be independent of polarity. According to the obtained results, it is thought that bacterioruberin will be a new alternative material with increasing applications in optics, biosensor/chemosensor, biotechnology, analytical chemistry and nanotechnology due to its fluorescence properties.

Keywords Carotenoid extracts · Bacterioruberin · Absorption · Emission · Solvent effect · Photophysical properties

Introduction

Carotenoids are natural pigments produced by plants, fungi, algae, bacteria, and archaea that are essential for several biological functions, such as photoprotection and antioxidation [1, 2]. Bacterioruberin is a lipophilic, pink-red pigment mainly found in halophilic archaea and infrequently in halophilic bacteria, which are microorganism groups that survive in extremely saline environments [3]. Halophilic archaea produce bacterioruberin for their ability to survive under extreme conditions, such as high salinity, UV radiation, low water activity, and maintaining membrane stability [4]. Although there are several studies on the biological functions of bacterioruberin in halophiles [5–8], there are no sufficient studies on its fluorescence properties. Understanding the fluorescence properties of bacterioruberin, is crucial for biosensor/chemosensory, biotechnology, analytical chemistry, and materials science applications. Fluorescence properties are also of great importance in materials science, nanotechnology, sensors, and optical systems, and therefore attract the attention of researchers among the topics to be investigated [9–12].

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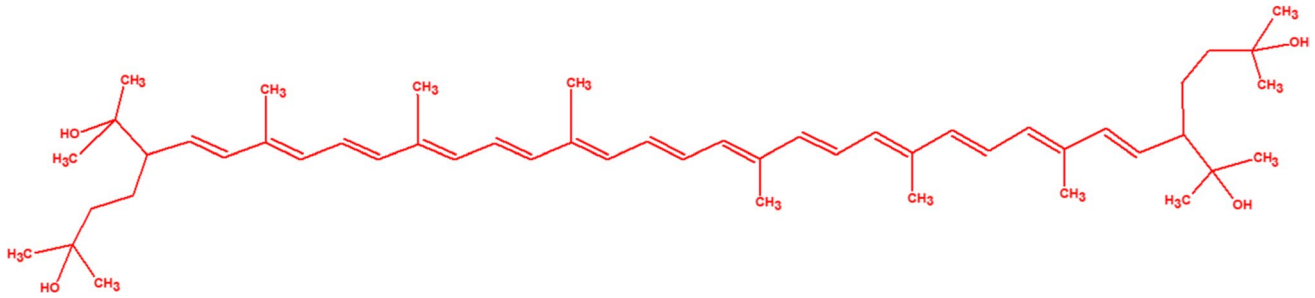
There are many environmental or structural parameters that affect fluorescence [13, 14]. Molecular structure is the most important of these [14, 15]. Fluorescent structures usually contain conjugated double bonds [16]. Molecules containing two or more conjugated double bonds (–C = C, C = C–, etc.) have greater electron mobility [16, 17]. Scheme 1 shows the molecular structure of the carotenoid showing conjugation in its structure. Carotenoids have a linear conjugated structure called polyenes [18]. This feature of carotenoids makes them important in applications such as light harvesting and photoprotection in photosynthetic organisms [19, 20]. The simple structure of linear polyenes makes them quite suitable as test compounds for spectroscopic studies. The conjugation in their structure (–C = C–C = C-) contributes to the excited state energy and thus to the fluorescence properties [16, 21]. Another effective parameter is the solvent polarity and local environment [15]. The solvent effect has been emphasized in the literature that the fluorescence emission wavelength affects it [15, 22]. In particular, the polarity index of the solvent is one of the issues that should be taken into consideration. Therefore, the study of the solvent effect on the absorption and fluorescence emission properties plays an important role [23–25].

There are several reports in the literature on different applications for carotenoids and similar structures. D´ıaz et al. (2008) in their study mentioned that the spectral and photophysical properties of berberine were studied in



Scheme 1 General chemical structure of carotenoid (The structure was drawn using ChemSketch)

different solvents using UV/Vis absorption-fluorescence spectroscopy. They found that the absorption and emission maxima were between 421–431 nm and 514–555 nm. It was found that berberine had the largest shift and the largest fluorescence emission wavelength in water. This is consistent with our study [23].

Andersson et al. (2001) investigated the photophysical characterization of natural *cis*-Carotenoids in their study. They focused attention on the excited states of two carotenoids, phytoene and phytofluene, with three and five conjugated double bonds both with 15-*cis*-conformations. Additionally, they investigated the dependence of the photophysical properties on temperature and viscosity. They found that the transition dipole moment of absorption and emission are parallel in phytoene and nonparallel in phytofluene [26].

Chen et al. (2018) investigated the effects of carotenoids on the absorption and fluorescence properties and fluorescence quenching of Chlorophyll a. Fluorescence and absorption characteristics of Chlorophyll a were modulated by the carotenoids with different numbers of conjugated carbon–carbon double bonds in solutions. They emphasized that the absorption of Chlorophyll a and carotenoids are linearly dependent on intrinsic factors, conjugate length and functional groups, and on the polarizability of the solvent. As a result of in their study, the absorption bands of the Chlorophyll a and carotenoids showed a red shift when the solvent polarizability increased [27].

Bruna et al. (2019) reported the biological synthesis of CdS fluorescent nanoparticles by polyextremophilic halophilic bacteria isolated from Atacama Salt Flat (Chile), Uyuni Salt Flat (Bolivia) and Dead Sea (Israel). Absorbance, emission-excitation spectra of QDs produced by *Halobacillus* sp. DS2 in 1–3 h were recorded, as well as the emission wavelength. *Halobacillus* sp. DS2 after 1–3 h was found emission wavelengths between 420–500 and 440–530 nm, respectively. They also studied the effect of different NaCl concentrations on the fluorescence emission intensity [28].

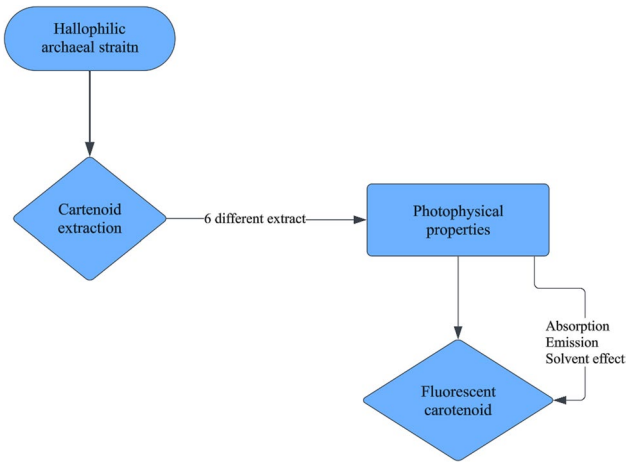
Jaebeom Lee et al. (2019) studied metal-enhanced fluorescence properties of carotenoids in thin polymer films. Their paper investigated the fluorescence enhancements of both carotenoids (, all-trans-β-carotene and 8′-apo-β-carotene-8′-al) in the silver substrate by time-resolved fluorescence measurements. The absorption and steady-state emission spectra of carotene in thin polystyrene and polyethylene glycol films and the spectroscopic properties of carotenoids in polymer films were given. The absorption bands of carotene appeared at 471 and 498 nm in a polystyrene film and at 452, 475, and 514 nm in a polyethylene glycol film. The emission spectra of carotene were centered at 568 and 585 nm in the polystyrene and polyethylene glycol films. The emission bands of carotene in solutions were observed in a similar wavelength range of 524–571 nm [29].

In this study, we focus on the photophysical properties of a C50 carotenoid bacterioruberin extracted from a halophilic archaeon *Halorubrum ezzemoulense* TC23 isolated from Ayvalık Saltern, Turkey. Firstly, carotenoid was extracted in solvents of different polarity. Extracted carotenoids were characterized by UV–Vis and fluorescence spectrophotometry. In this context, absorption and steady-state fluorescence of carotenoid extracts were recorded. UV_{max}, $emission_{max,}$ and Stokes' shifts were determined to investigate photophysical properties. Additionally, images of extracts were presented in daylight and UV regions in each solvent. Furthermore, the relationship between fluorescence characterization of carotenoid extracts with solvents of different polarities was studied in detail.

Experimental

Chemicals

Dimethyl sulfoxide, Dimethylformamide, Methanol, Acetone, Isopropyl alcohol, L-glutamic acid, trisodium citrate, $MgSO_4 7H_2O$, $MnCl_2\ 4H_2O$, and $FeCl_2 4H_2O$ were obtained from Sigma-Aldrich (St. Louis, USA). Casamino acids, KCl, NaCl, yeast extract were obtained from Merck (Darmstadt, Germany). Deionized water was used in the study (Human power II) (Scheme 2).



Scheme 2. The workflow of the experimental study

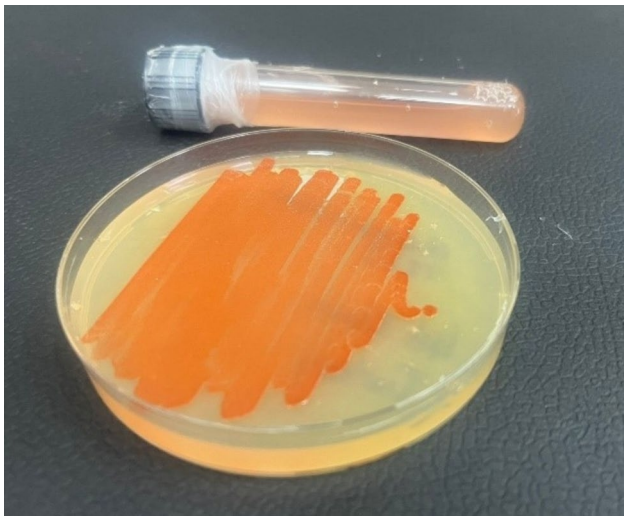


Fig. 1 *Halorubrum ezzemoulense* TC23 on agar plate (bottom) and broth medium (up)

Halophilic Archaeal Strain and Culture Conditions

Halorubrum ezzemoulense TC23, a halophilic archaeon isolated from Ayvalık Saltern, was used as the source of bacterioruberin (NCBI BioProject Number: PRJNA1092433). The strain was inoculated into a 50 mL of MAM JCM 168 medium contained casamino acids (5 g/L), L-glutamic acid (1 g/L) and yeast extract (5 g/L), trisodium citrate (3 g/L), $MgSO_4 7H_2O$ (29.5 g/L), KCl (2 g/L), NaCl (150 g/L), $FeCl_2 4H_2O$ (0.036 g/L), and $MnCl_2\ 4H_2O$ (0.36 mg/L). The culture was incubated at 39 °C for 7 days [30].

Carotenoid Extraction

Halophilic archaeal carotenoids were extracted using six different solvents; Water, Dimethyl sulfoxide, Dimethylformamide, Methanol, Acetone and Isopropyl alcohol. To this end, the culture cultivated in broth medium for 7 days was divided into tubes and centrifuged at 9,000 rpm for 20 min. The pellets were treated with 3 mL of solvents followed by vortex and sonication for 60 min. Following the process of re-centrifugation, the C50 carotenoid–bacterioruberin containing supernatants were moved to a fresh tube, and the extracts were kept away from light [31]. The extracts were analyzed using a UV–VIS Spectrophotometer (Epoch 2, BioTek Instruments, Inc., USA) within the wavelength range of 300–600 nm. Figure 1 shows images of *Halorubrum ezzemoulense* TC23 on agar plate (bottom) and broth medium (up) (Fig. 2).

Photophysical Characterization

Photophysical characterization of the carotenoid extracts was determined using ultraviolet–visible (UV–Vis, Shimadzu, Pharmaspec) and steady-state fluorescence spectrophotometers. Absorption measurements were performed at 300–700 nm range and room temperature. Steady-state fluorescence excitation and emission measurements were performed using a fluorescence spectrophotometer (Horiba Fluoromax-4). The excitation and emission slit spacing was 1 nm and the integration (measurement) time was 0.1 s. We investigated the effects of solvent polarity on the absorption and fluorescence properties of carotenoid extracts. Absorption and emission spectra of carotenoid extracts in solvents with different polarities were measured. In this context; Water, Dimethyl sulfoxide, Dimethylformamide, Methanol, Acetone and Isopropyl alcohol were used. The change in photophysical properties according to polarity indexes was examined in detail. The workflow of the experimental study is shown step by step in Scheme 2.

Results and Discussion

Photophysical Properties

Bacterioruberin is a highly lipophilic compound, yet, the inclusion of four terminal hydrophilic groups provides a little solubility in water [5]. Even though the bacterioruberin solubility in the obtained extract was poor, the observation of a strong fluorescence effect constitutes one of the unique aspects of the study.

The photophysical studies of halophilic archaeal C50 carotenoid bacterioruberin extracts which obtained from different polarity indexes were performed using absorption and fluorescence techniques. The polarizability of solvents decreases in the following order: Water > DMSO > DMF > Methanol = Acetone > IPA [33].

The polarizability of the solvent causes the excited state structure of the carotenoid to change. It is thought that

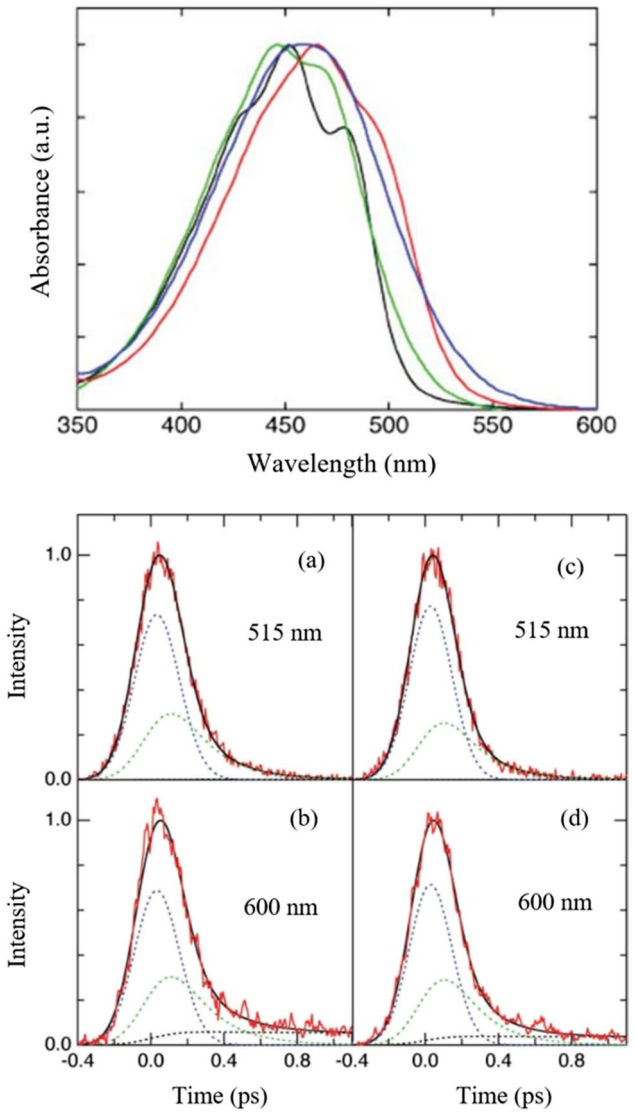


Fig. 2 Up-Absorption spectra in n-hexane (black), toluene (red), acetonitrile (green), and methanol (blue). Bottom-Fluorescence kinetics (**a**) at 515 nm in n-hexane, (**b**) at 600 nm in n-hexane, (**c**) at 515 nm in methanol, and (**d**) at 600 nm in methanol [32]

the conjugate length of the molecule slightly lengthens as the solvent polarizability increases. This situation shows the response of the electron structure to the solvent effect (Figs. 3 and 4).

The difference in absorption and emission maxima in different solvents is due to the fact that a molecule exhibits different optical properties depending on the solvent-molecule interactions in the solution [24]. The variety of these interactions has important effects on the energy, structure and dynamics of the molecule. The properties of the solvent, especially the polarity, viscosity, dielectric constant, proton donor–acceptor properties and molecular structure of the solvent, cause the observed shifts in the absorption and emission spectra [34, 35]. Polar solvents can change the electron distribution of the molecule by establishing strong interactions with polarized molecules. These changes affect the energy levels of the molecule and thus cause changes in the locations of the absorption and emission maxima. Highly polar solvents (e.g. water, methanol) usually stabilize the charge distribution of the molecule, which generally leads to lower energy levels being more accessible [36]. As a result, absorption and emission at longer wavelengths can be observed. Low polarity solvents provide a less polarized environment, which can cause the molecule to shift less in energy levels, and absorption and emission are observed at shorter wavelengths [37].

Absorption, Steady-State Fluorescence and Solvent Effect Studies

The absorption and emission spectra of all fluorescent bacterioruberin extracts are given in Fig. 3. Maximum absorption–emission and Stokes' shift were recorded in solvents of different polarity. The obtained data are presented in Table 1. The different extracts exhibited maximum absorption and fluorescence emission wavelengths between 369–536 nm and 540–569 nm. Stokes shifts were found between 50–79 nm (Fig. 5 and Table 1). The difference in the polarity index of the extracts showed shifts in absorption and fluorescence emission. Absorption maximum wavelengths are similar. The excitation wavelength was taken as the basis of the maximum wavelengths in the absorption spectra of carotenoids (based on the literature). Therefore, the excitation wavelength was used as the basis for the maximum wavelengths with the exception of DMSO.

DMSO, although a highly polar solvent, is known for its lower dielectric constant (≈47) and special solvation properties, unlike water and other polar solvents. The highly polarized structure of DMSO can affect the electron density and energy levels of the molecule in solution, leading to shifts in absorption and emission wavelengths. In measurements made with DMSO, the transmission of the exciting light or the interaction of the molecule with its excited state are different.

Stokes shift is the difference between the absorption and emission maxima of a molecule and is a result of interactions between the molecule and the solvent in solution [38]. The presence of less polar solvents causes a fluorescence change by shifting the fluorescence peak [39]. The difference in Stokes shift between water and IPA is due to the different polarity indexes and chemical properties of the solvents. Water, with its higher polarity, hydrogen bonding and higher dielectric constant, produces a greater solvation effect, while IPA exhibits a smaller Stokes shift due to its lower polarity and weaker hydrogen bonds. The water extract exhibits a large emission wavelength (569 nm) and

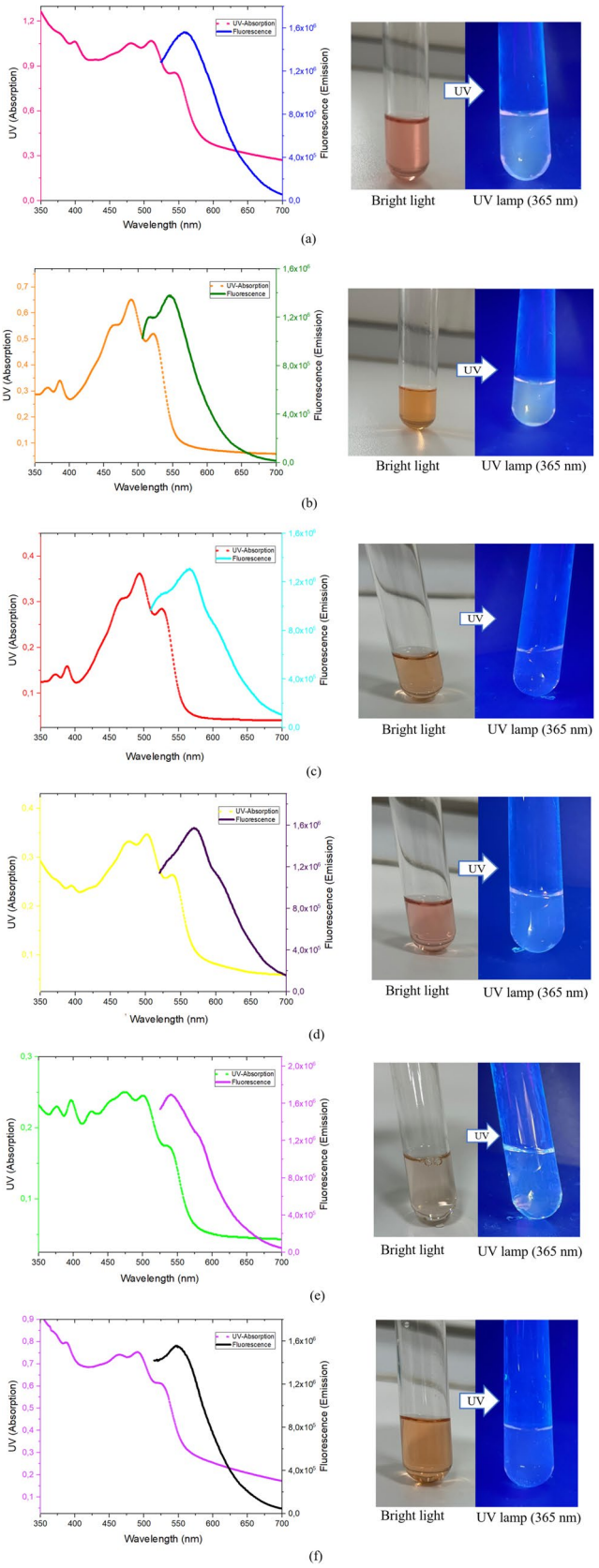


Fig. 3 UV absorption-steady-state fluorescence spectra in different solvents and the image of carotenoid in bright light (left) and UV lamp-365 nm (right) in different solvents **a**) DMSO **b**) Methanol **c**) IPA **d**) Water **e**) DMF f) Acetone

the largest shift (79 nm) is observed in water. Water is a very polar molecule and has the ability to form hydrogen bonds. Another interesting result is that the fluorescence emission wavelength of the less polarized extract (IPA) is observed to shift to longer wavelengths compared to other solvents (except water). As a result of, it was found that the fluorescence wavelength (band position) and shape are independent of polarity (Fig. 5).

Another noteworthy point is that the dielectric constants of methanol and acetone are similar and their polarity indexes are equal (5.1). This shows that their polarity properties are similar. This similarity causes the substances dissolved in these solvents to show similar peaks in their absorption and emission spectra. Polar solvents affect the absorption and emission of light at certain wavelengths by affecting the solvent-molecule interactions, which are affected by the polarity of the solvent. Therefore, when their polarities are similar, the absorption and emission properties in such solvents are expected to be similar. The results of our study support this theory as stated. The UV_{max} value of methanol and acetone was determined to be 490 nm; and the $emission_{max}$ value was determined to be 545, 546 nm, respectively. For a clearer understanding of the extracts in solvents with different polarities, normalized UV absorption and emission spectra on the same graph are shown in Fig. 4.

In addition to these results, the color change of all different solvent extracts under bright light and UV lamp was shown. It was observed that the extracts, which were light pink, yellow, orange, and transparent in bright light, emitted slightly bright blue under the UV lamp at room temperature.

Lun-Yi Zang et al. (1997) investigated absorbance changes of carotenoids in different solvents. Four carotenoids, namely lutein, zeaxanthin, lycopene, and b-carotene, were compared in terms of absorbance characteristics in hexane and methanol, respectively. At similar concentrations, carotenoids have been found to have highly variable optical properties in different solvents [40].

Harry A. Frank et al. (2000) reported the effect of the solvent environment on the spectroscopic properties of carotenoids. Carotenoids in several different solvents have been studied using steady-state absorption and fast-transient optical spectroscopic techniques. The effect of solvent environment on the spectroscopic properties of the lowest excited singlet states, especially of carbonyl-containing carotenoids, was clearly demonstrated in this study [41].

Seiji Akimoto et al. (2008) investigated one of the ketocarotenoids, siphonaxanthin, solvent effects on excitation

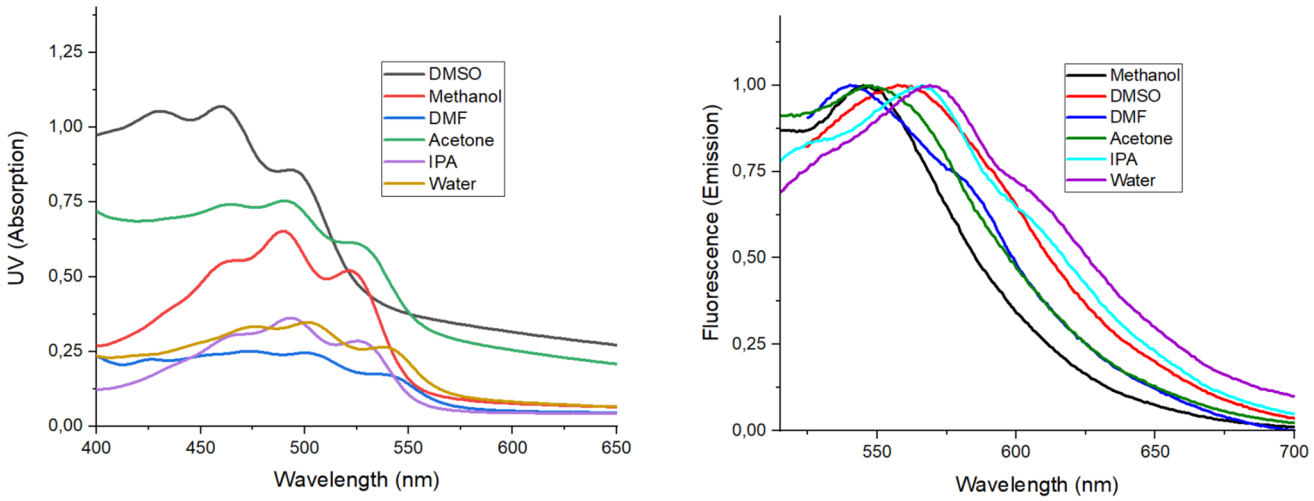


Fig. 4 UV absorption-normalized steady-state fluorescence spectra (Absorbance and emission are normalized to the maximum point.)

Table 1 Photophysical parameters for different polarity extract

Carotenoid extracts	Polarity index	Absorption (λ_{abs}, nm)	Excitation (λ_{exc}, nm)	Emission (λ_{ems}, nm)	Stokes' shift (λ_{stk}, nm)
Water	10.2	394, 476 502, 536	490	569	79
DMSO	7.2	369, 386, 463, 490, 521	508	560	52
DMF	6.4	376, 397, 426, 474, 571, 536	490	540	50
Methanol	5.1	369, 386, 463, 490, 521	490	545	55
Acetone	5.1	387, 465, 491, 524	490	546	56
IPA	3.9	372, 388 467, 493, 526	490	566	76

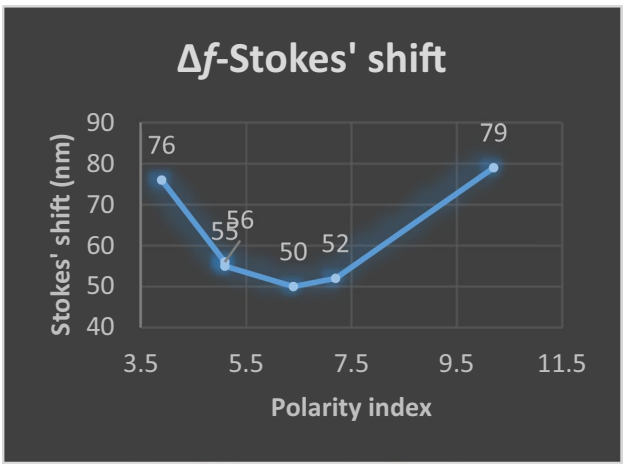


Fig. 5 Plot of the solvent polarity index vs Stokes' shift

relaxation dynamics using steady-state absorption and time-resolved fluorescence spectroscopy. They measured the absorption and fluorescence of siphonaxanthin in n-hexane, toluene, acetonitrile, and methanol. They noted the changes caused by the solvent. They emphasized that the absorption spectrum in methanol showed an increase in intensity in the long wavelength region, indicating the ability of siphonaxanthin to absorb green light. The absorbance and fluorescence data obtained in their study are presented in Fig. 2 [32].

Conclusion

In this work, we present the photophysical properties of a C50 carotenoid-bacterioruberin extracted in solvents of different polarities. In this context, the absorbance and steady-state fluorescence of the carotenoid-bacterioruberin extracts were measured and UV_{max}, $emission_{max}$, and Stokes' shifts were recorded. The highest Stokes' shift (79 nm) and fluorescence wavelength (569 nm) were found in water and the lowest in DMF (40–540 nm). It was observed that the fluorescence emission wavelength of the less polarized extract (IPA) was the second longest wavelength after water and had a Stokes shift. As a result, it was found that the fluorescence wavelength (band position) and shape were independent of polarity.

In conclusion, it was determined that the unique Haloarchaeal C50 carotenoid-bacterioruberin could be a valuable candidate for many fields such as optics, biosensors, biotechnology and nanotechnology due to its fluorescence properties (Stokes' shift and brightness under UV). The strong fluorescence effect of the water extract is especially important for green chemistry in terms of preventing the use of harmful solvents in industrial processes.

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Author Contributions **Merve Zurnacı:** Investigation, fluorescence characterization, absorption-emission measurements, writing–original draft, review & editing. **Fevziye Işıl Kesbiç:** Investigation, archaeal isolation, carotenoid extraction, writing–original draft, review & editing.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval Not applicable**.**

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflicts of Interest The authors declare no competing interests.

References

1. Sikorski ZE (2002) Food components and their role in food quality. Chemical and functional properties of food components, p 367. https://doi.org/10.1201/9781420031805-1
2. Huang J, Hu Z, Li G et al (2022) Make your packaging colorful and multifunctional: The molecular interaction and properties characterization of natural colorant-based films and their applications in food industry. Trends Food Sci Technol 124:259–277. https://doi.org/10.1016/j.tifs.2022.04.028
3. Kesbiç FI, Gültepe N (2023) Bioactive components, sun protective properties, and total phenolic contents of halobacterial extracts. Biochem Syst Ecol 108:104647. https://doi.org/10.1016/j.bse.2023.104647
4. Feshangsaz N, Semsarha F, Tackallou SH et al (2020) Survival of the halophilic archaeon halovarius luteus after desiccation, simulated martian UV radiation and vacuum in comparison to bacillus atrophaeus. Origins Life Evol Biospheres 50:157–173. https://doi.org/10.1007/s11084-020-09597-7
5. Caimi AT, Yasynska O, Rivas Rojas PC et al (2022) Improved stability and biological activity of bacterioruberin in nanovesicles. J Drug Del Sci Technol 77:103896. https://doi.org/10.1016/j.jddst.2022.103896
6. Giani M, Pire C, Martínez-Espinosa RM (2024) Bacterioruberin: biosynthesis, antioxidant activity, and therapeutic applications in cancer and immune pathologies. Mar Drugs 22:167. https://doi.org/10.3390/md22040167
7. Manjula D, Jeevitha P, Ramya I et al (2018) Biotechnological applications of halophilic pigments – an overview. Int J Curr Microbiol Applied Sci 7:4392–4398. https://doi.org/10.20546/ijcmas.2018.707.512
8. Kesbiç FI, Metin H, Fazio F et al (2023) Effects of bacterioruberin-rich haloarchaeal carotenoid extract on the thermal and oxidative stabilities of fish oil. Molecules 28:8023. https://doi.org/10.3390/molecules28248023
9. Zurnacı M, Şener İ, Gür M, Şener N (2023) Organic fluorescent compounds based on phenanthroimidazole: A review of highlight studies. Luminescence 38:1690–1701. https://doi.org/10.1002/bio.4565
10. Sharma C, Verma M, Abidi SMS et al (2023) Functional fluorescent nanomaterials for the detection, diagnosis and control of bacterial infection and biofilm formation: Insight towards mechanistic aspects and advanced applications. Colloids Surf, B 232:113583. https://doi.org/10.1016/j.colsurfb.2023.113583
11. Manandhar E, Day BO, Sampson KM et al (2024) A 1,8-naphthalimide-based tripodal fluorescent chemosensor to selectively detect copper Ions. J Fluoresc. https://doi.org/10.1007/s10895-024-03867-7
12. Zurnacı M, Ünal F, Demir S et al (2021) Synthesis of a new 1,3,4-thiadiazole-substituted phenanthroimidazole derivative, its growth on glass/ITO as a thin film and analysis of some surface and optoelectronic properties. New J Chem. https://doi.org/10.1039/D1NJ04375G
13. Zurnacı M, Şener İ, Gür M, Şener N (2022) Study on Photophysical Properties of Novel Fluorescent Phenanthroimidazole-Thiadiazole Hybrid Derivatives. J Fluoresc 32:1155–1169. https://doi.org/10.1007/s10895-022-02916-3
14. Zacharioudaki D-E, Fitilis I, Kotti M (2022) Review of Fluorescence Spectroscopy in Environmental Quality Applications. Molecules 27:4801. https://doi.org/10.3390/molecules27154801
15. Lakowicz JR (1999) Introduction to fluorescence. In: Principles of fluorescence spectroscopy. Springer, Boston, MA. https://doi.org/10.1007/978-1-4757-3061-6_1
16. Williams RT, Bridges JW (1964) Fluorescence of solutions: A review. J Clin Pathol 17:371–394. https://doi.org/10.1136/jcp.17.4.371
17. Koda T, Kajikawa K (2005) Polymers and organic compounds, optical properties of, encyclopedia of condensed matter physics. Elsevier, pp 362–375. https://doi.org/10.1016/B0-12-369401-9/00599-4
18. Britton G (1995) Structure and properties of carotenoids in relation to function. FASEB J 9:1551–1558. https://doi.org/10.1096/fasebj.9.15.8529834
19. Henríquez V, Escobar C, Galarza J, Gimpel J (2016) Carotenoids in microalgae. In: Stange, C. (eds) Carotenoids in nature. Subcell Biochem vol 79. Springer, Cham. https://doi.org/10.1007/978-3-319-39126-7_8
20. Zulfiqar S, Sharif S, Saeed M, Tahir A (2021) Role of Carotenoids in Photosynthesis. Carotenoids: Structure and Function in the Human Body. Springer International Publishing, Cham, pp 147–187
21. Hudson BS, Kohler BE (1973) Polyene spectroscopy: The lowest energy excited singlet state of diphenyloctatetraene and other linear polyenes. J Chem Phys 59:4984–5002. https://doi.org/10.1063/1.1680717
22. Abdel-Halim ST (2011) Effect of solvent on absorption and fluorescence spectra of a typical fluorinated azo dye for its acidic and basic structures. Spectrochim Acta Part A Mol Biomol Spectrosc 82:253–259. https://doi.org/10.1016/j.saa.2011.07.045
23. Díaz MS, Freile ML, Gutiérrez MI (2009) Solvent effect on the UV/Vis absorption and fluorescence spectroscopic properties of

berberine. Photochem Photobiol Sci 8:970–974. https://doi.org/10.1039/b822363g
24. Liu L, Sun Y, Wei S et al (2012) Solvent effect on the absorption and fluorescence of ergone: Determination of ground and excited state dipole moments. Spectrochim Acta Part A Mol Biomol Spectrosc 86:120–123. https://doi.org/10.1016/j.saa.2011.10.016
25. Groß P, Ihmels H (2024) Studies About the Effect of Halogenated Solvents on the Fluorescence Properties of 9-Aryl-Substituted Isoquinolinium Derivatives – A Case Study. J Fluoresc. https://doi.org/10.1007/s10895-024-03691-z
26. Andersson PO, Takaichi S, Cogdell RJ, Gillbro T (2007) Photophysical characterization of natural cis-carotenoids¶. Photochem Photobiol 74:549–557. https://doi.org/10.1562/0031-8655(2001)0740549PCONCC2.0.CO2
27. Chen C, Gong N, Qu F et al (2018) Effects of carotenoids on the absorption and fluorescence spectral properties and fluorescence quenching of Chlorophyll a. Spectrochim Acta Part A Mol Biomol Spectrosc 204:440–445. https://doi.org/10.1016/j.saa.2018.06.061
28. Bruna N, Collao B, Tello A et al (2019) Synthesis of salt-stable fluorescent nanoparticles (quantum dots) by polyextremophile halophilic bacteria. Sci Rep 9:1953. https://doi.org/10.1038/s41598-018-38330-8
29. Lee J, Song J, Lee D, Pang Y (2019) Metal-enhanced fluorescence and excited state dynamics of carotenoids in thin polymer films. Sci Rep 9:3551. https://doi.org/10.1038/s41598-019-40446-4
30. Enache M, Itoh T, Kamekura M et al (2008) Halophilic archaea isolated from man-made young (200 years) salt lakes in Slănic, Prahova, Romania. Open Life Sciences 3:388–395. https://doi.org/10.2478/s11535-008-0034-5
31. Kesbiç FI, Gültepe N (2022) C50 carotenoids extracted from Haloterrigena thermotolerans strain K15: antioxidant potential and identification. Folia Microbiol 67:71–79. https://doi.org/10.1007/s12223-021-00905-w
32. Akimoto S, Yokono M, Higuchi M et al (2008) Solvent effects on excitation relaxation dynamics of a keto-carotenoid, siphonaxanthin. Photochem Photobiol Sci 7:1206–1209. https://doi.org/10.1039/b802658k
33. Kleiman M, Ryu KA, Esser-Kahn AP (2016) Determination of factors influencing the wet etching of polydimethylsiloxane using tetra- n -butylammonium fluoride. Macromol Chem Phys 217:284–291. https://doi.org/10.1002/macp.201500225
34. Haidekker MA, Brady TP, Lichlyter D, Theodorakis EA (2005) Effects of solvent polarity and solvent viscosity on the fluorescent properties of molecular rotors and related probes. Bioorg Chem 33:415–425. https://doi.org/10.1016/j.bioorg.2005.07.005
35. Sıdır İ, Gülseven Sıdır Y, Berber H, Taşal E (2013) A study on solvatochromism of some monoazo dye derivatives. J Mol Liq 178:127–136. https://doi.org/10.1016/j.molliq.2012.11.011
36. Majid A, Kiran S, Sandhu Q et al (2022) The effects of polar solvents on structural, electronic, and optical properties of organic dyes. Int J Quantum Chem 122:e26876. https://doi.org/10.1002/qua.26876
37. Homocianu M (2024) Exploring solvatochromism: A comprehensive analysis of research data. Microchem J 198:110166. https://doi.org/10.1016/j.microc.2024.110166
38. Fleming KG (2010) Fluorescence theory. In: Encyclopedia of spectroscopy and spectrometry. Elsevier, pp 628–634. https://doi.org/10.1016/B978-0-12-374413-5.00357-2
39. Kamel B, Sayem El-Daher M, Bachir W et al (2022) Effect of solvents on the fluorescent spectroscopy of BODIPY-520 derivative. J Spectrosc 2022:1–6. https://doi.org/10.1155/2022/1172183
40. Zang LY, Sommerburg O, van Kuijk FJG (1997) Absorbance changes of carotenoids in different solvents. Free Radical Biol Med 23:1086–1089. https://doi.org/10.1016/S0891-5849(97)00138-X
41. Frank HA, Bautista JA, Josue J et al (2000) Effect of the solvent environment on the spectroscopic properties and dynamics of the lowest excited states of carotenoids. J Phys Chem B 104:4569–4577. https://doi.org/10.1021/jp000079u