A Study On the Optoelectronic Parameters of Natural Dyes Extracted from Beetroot, Cabbage, Walnut, and Henna for Potential Applications in Organic Electronics

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Abstract
In this work, the optoelectronic parameters of natural dyes extracted from beetroot, red cabbage, walnut leaves, and henna were comprehensively investigated, namely the optical energy gap ($E_g$), extinction coefficient ($k$), refractive index ($n$), dielectric constant ($\varepsilon_\infty$), and optical conductivity ($\sigma_r$). Results showed a high refractive index, dielectric constant and optical conductivity ($n = 6.08$, $\varepsilon_\infty = 37.18$ and $\sigma_r = 13.92 \times 10^{-3} S/cm$) for the dye extracted from red cabbage, while minimum values of $n = 1.19$, $\varepsilon_\infty = 1.5$ and $\sigma_r = 0.039 \times 10^{-3} S/cm$ were obtained for the henna dye. The transition type of the optical absorption of the dyes was found to be a direct allowed transition, which is taken place between the bonding and antibonding molecular energy levels. The reported results herein are essential in revealing the viability of these natural dyes for potential applications in organic electronics, including organic photovoltaics, photodiodes, and sensors.

Keywords Optoelectronic parameters · Natural dyes · Beetroot · Cabbage · Walnut · Henna

Introduction

Nowadays, the use of organic dyes has become the focus of interest in both academia and industry owing to the unique features offered by these materials such as flexibility, optoelectronic tuneability, and cost-effectiveness [1–3]. Furthermore, they provide a higher absorption coefficient and stronger exciton generation compared with those of the inorganic materials [4, 5]. Commercial dyes have been used in various applications; however, they are suffering from the high cost, supply shortage, heavy metal toxicity and complex synthesizing problems that ultimately limit their broad applications. Alternately, it is possible to overcome these issues with the usage of natural dyes [5, 6].

Natural dyes are organic compounds capable of well absorbing the light, thereby maintaining their intrinsic color due to the presence of chromophore in them [7]. Betalains are vacuolar nitrogenous plant pigments with a core structure known as betalamic acid [8]. The best-known sources of betalains are beetroot and cacti [9]. Anthocyanins were also found in a large group of plants containing red-blue pigments, which are water soluble and pH sensitive [10]. Red cabbage is one of the main sources of anthocyanins and glycoside moieties of anthocyanidins that are derived from flavylum [11]. In addition to the different natural pigments, brown dye and red–orange dye were found in juglone (black walnuts) and lawson (henna plant), respectively [12, 13]. A review of literature showed that organic dyes were successfully utilized in the photovoltaic devices [14–20]. Additionally, organic dyes can be interestingly used in the coloration technology and organic electronics. However, before the viability of these materials is fully explored for different applications, a broad investigation on their optoelectronic parameters is required to be performed. Therefore, in the current research work, some natural dyes are extracted by a green chemistry approach and their optoelectronic parameters are comprehensively investigated. The dyes are extracted from beetroot, red cabbage, walnut leaf, and henna. This study performs a broad investigation to determine the
most important parameters of the dyes, namely the optical energy gap, refractive index, dielectric constant, and optical conductivity. The reported results herein are specifically important to explore the viability of these natural dyes for potential applications in organic electronics.

Materials and Methods

The beetroot, red cabbage and henna were purchased from the local markets, while walnut leaves were collected from a local farm. The raw materials were cut into small pieces and crushed by a grinder followed by a drying process to produce a very fine powder of the materials. In the extraction process, there are some factors affecting the concentration of the extracted dye from the natural product such as the extraction method, material source, and solvent type. It was found from literature that the polar solvents showed a good success in the extraction process due to the better solubility of the dyes in polar solvents compared to that of the nonpolar solvents. Moreover, the polarity of the solvent influences the absorption spectra of the natural dyes, thereby defining the amount/concentration of the dye pigment. Therefore, in this work, ethanol, distilled water, and a combination of ethanol-HCl were used. Table 1 shows the designation of the extracted dyes and the used solvents for this purpose. Initially, 100 ml distilled water was put into separate beakers, and boiled on a hotplate for two minutes. Later, the beakers were transferred, and 50 g of each sample was poured into the boiled waters separately. The prepared solutions of sample B1 and C1 were left for two hours followed by their filtration and storage in the refrigerator for 24 h. In another approach, 100 ml of ethanol was mixed with HCl (0.1) with the ratio of 99:1, then 50 g of samples B2 and C2 was put into the beakers and left for two hours. Afterwards, filtration process was performed, and the extracted solutions were stored in the refrigerator for 24 h. On the other hand, 200 g of the mashed B3 and C3 samples were separately put into a beaker containing distilled water as a solvent. Then, the beaker was transferred into a hot bath and agitated at 60 °C for six hours. After filtration process, the prepared solutions were put into the oven at 50 °C until they became a paste. Later, 0.1 g of the paste was diluted using 10 ml of distilled water. Finally, a Soxhlet extractor was used for the extraction of dyes with ethanol solvent. The same procedure of preparation, filtration and extraction were performed for the other samples. To extract the dye from walnut leaf, 150 g of its powder was immersed in 500 ml of ethanol and left for 24 h in a hot bath at 60 °C. The photo of the extracted dyes is given in the supplementary files (online resource 1).

Optical absorption spectra of the extracted dyes were measured by using a double beam UV–Vis spectrophotometer (Perkin Elmer, Lambda 25) at room temperature. To perform this, the extracted dyes were put into the cuvette and their absorbance was recorded in the wavelength range from 200 to 1100 nm. The absorption response of the samples was utilized to determine the optical band gap, optical transition types, optical dispersion parameters, optical dielectric constant, loss factor, and optical conductivity.

Results and Discussion

Figure 1(a-d) shows the absorption coefficient of the dyes in the wavelength range from 200 to 1100 nm, which was calculated from the absorbance data using [21]:

\[
\alpha = \frac{2.303A}{t}
\]  

Where \( t \) is the width of the cuvette (1 cm) and \( A \) is the recorded absorbance. For the beetroot dye, the absorption spectrum indicated the presence of betalain chromophore [10] as multiple absorption peaks were found around 475, 525 and 575 nm due to the presence of mixed pigments. These pigments are attributed to yellow betaxanthins (indicaxanthin), red–purple betacyanin (betanin) and betanidin, respectively [22]. It was reported that the betalain dyes can be affected by temperature and pH [23–25]. Figure 1(a) shows the absorption coefficient spectrum of the beetroot dye, which was extracted by different methods. Results showed that all the dyes are strongly absorbent in the ultraviolet region, which can be due to the presence of red-violate betalain group [24]. However, different absorption peaks were observed in the visible region. The sample B2 showed absorption peaks at 486 and 549 nm, suggesting that the extracts contain both betaxanthins and betanidin.

| Sample | Description |
|--------|-------------|
| B1     | 50 g Beetroot + 100 ml Distilled water |
| B2     | 50 g Beetroot + 100 ml Ethanol:HCl (0.1) (99:1) |
| B3     | 0.1 g Beetroot paste + 10 ml Distilled water (dilution) |
| B4     | 0.1 g Beetroot paste + 10 ml Ethanol (dilution) Soxhlet method |
| C1     | 50 g Cabbage + 100 ml Distilled water |
| C2     | 50 g Cabbage + 100 ml Ethanol:HCl (0.1) (99:1) |
| C3     | 0.1 g Cabbage paste + 10 ml Distilled water (dilution) |
| C4     | 0.1 g Cabbage paste + 10 ml Ethanol (dilution) Soxhlet method |
| C5     | 100 g Henna + 200 ml Ethanol |
| F      | Sample B1: Sample C1 (1:1) |
| W      | 150 g Walnut + 500 ml Ethanol |

Note: The samples B1 and C1 were left for two hours followed by their filtration and storage in the refrigerator for 24 h. The sample B3 and C3 were put into the beakers with 10 ml of distilled water. The sample C5 was prepared using 200 ml of ethanol. The extracted dyes were diluted using 10 ml of distilled water. The extraction process was performed in the presence of ethanol-HCl (0.1) (99:1) for a duration of two minutes. The absorbance was recorded in the wavelength range from 200 to 1100 nm.
while one peak for the B3 sample was observed in the visible region at 417 nm, which can be due to the presence of indicaxanthin. However, no absorption peaks were observed in the visible region of the samples B1 and B4. The absorption spectra of the dyes from red cabbage are shown in Fig. 1(b). One can notice that all the samples show a strong absorption in the UV region, which is well matched with the absorption characteristic of the anthocyanin dye. This strong absorption in the UV region is due to the conjugated aromatic phenolic double bonds in anthocyanin [26]. Samples C1 and C2 have almost the same absorption peak around 560 nm, indicating the presence of anthocyanidin [27]. The peaks between 360 and 470 nm are belong to a non-acylated pigment [28], which are observed in all the samples except C2. Figure 1(c) shows the absorption spectrum of the mixed dyes of B1 with C1 and B2 with C2 by 1:1 (V/V) ratio. Interestingly, both samples presented a broad absorption band extending over the UV and visible regions. Figure 1(d) shows the absorption coefficient for the extracted dyes of walnut leaf and henna. One can see that the dyes exhibited similar spectrum due to their comparable chemical structures. The broad absorption in the UV region is referred to the presence of intermolecular hydrogen bonds from benzoquinone and electron delocalization of benzoquinone in the quinone ring. In addition, the UV absorption points out to the existence of naphthoquinone in the form of hydrogen bonds with carbonyl [29]. However, the absorption in the visible region (blue and red light) are corresponding to the mixture of chlorophyll [30]. These peaks were also observed for both extracted dyes.
The measurement of the optical energy gap and the nature of electronic transitions in the organic dyes are crucial for optoelectronics applications. The absorption spectra can be used to determine the type of electronic transitions and optical bandgap. To various extends, Tauc’s equation was used by the researchers to deduce the optical band gap and the type of electronic transitions governing the absorption process. We have noticed that the use of Tauc’s equation to assign the nature of absorption transitions is highly efficient [31, 32] despite its seldom use by other researchers [33–38].

The Tauc’s equation can be represented as follows [39]:

$$ a h v = a_o (h v - E_g)^s $$

where $a_o$ is an energy-independent constant, $E_g$ is the energy gap, and the value of $s$ determines the type and nature of the optical transition [40]. The exponent value $s = \frac{1}{2}$ for the direct allowed transition, $\frac{3}{2}$ for the direct forbidden transitions, respectively, while it is about 2 for the indirect allowed transitions, and 3 for the indirect forbidden transitions, respectively. One can identify the type of the transition before estimating the energy gap, that is by taking the natural logarithm and derivation of Eq. 2 to yield:

$$ \frac{d\ln(ahv)}{dhv} = \frac{s}{h v - E_g} $$

The plot of $\frac{d\ln(ahv)}{dhv}$ versus $hv$ for all the samples and the approximate value of $hv = E_g$ taken at the peak of the curves are shown in the supplementary files (online resource 2). It can be seen that the denominator of the right-hand side of Eq. 3 approaches zero when the photon energy is approximately equal to the energy gap. Therefore, the approximate value of $E_g$ was utilized for plotting $\ln(ahv)$ versus $\ln(hv - E_g)$ and the values of $s$ were determined from the slope of the curves. It was found that $s = \frac{1}{2}$, which indicated

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![Fig. 2](image_url) Plot of $(ahv)^2$ versus $E$ for the dyes extracted from (a) beetroot, (b) red cabbage, (c) mixture of beetroot and red cabbage, and (d) walnut leaves and henna
the presence of a direct allowed transition between the inter-
molecular energy bands. Consequently, the precise value of 
the energy gap was determined from the Tauc’s equation, 
that is by plotting $(ahv)^2$ versus $(hv)$ and taking the extrapolation of the linear portion at $(ahv)^2 = 0$. The energy gap 
location of the samples is depicted in Fig. 2 (a-d) and the determined values of $E_g$ are shown in Table 2. Results 
showed that the energy gap of the dyes extracted from beet-
root and red cabbage are different because they are pH and 
temperature sensitive. Noticeably, the dyes extracted from 
henna and walnut possessed a very close value of the energy 
gap due to their symmetrical structure.

Following the absorption coefficient of the samples, the refractive index and extinction coefficient are other two optical parameters describe the materials performance. Refrac-
tive index tells us how the optical radiation propagates through a medium and it shows to what extent the speed of light is slowing down inside the medium compared to the speed of light in vacuum. The refractive index is a complex variable, and its imaginary part represents the extinction coefficient, which describes the amount of energy loss in the medium. Both refractive index ($n$) and extinction coefficient ($k$) were calculated from the absorbance data using the following equations [21]:

$$n = \frac{-2(R + 1) \pm \sqrt{4k^2R^2 + 16R - 4k^2}}{2(R - 1)}$$  \hspace{1cm} (4)

$$k = \frac{a\lambda}{4\pi}$$  \hspace{1cm} (5)

where $R$ is the reflectance and $\alpha$ is the absorption coefficient, which were calculated using $R = 1 - T - A$, where $A$ is absorbance and $T$ is transmittance ($T = 10^{-\alpha}$ and $\alpha = \frac{2.303A}{l}$), where $l$ is the cuvette width. The refractive index of the dyes as a function of wavelength is shown in Fig. 3 (a-d). For each dye, the variation of the refractive index with wavelength is related to the polarization of the molecules. This is governed by the molecular interaction with electromagnetic wave, where the wide dispersion regions describe the polar nature of the samples [33]. At the high wavelength, the refractive index produced a plateau region, in which the extrapolation of the curve to the y-axis gives the static value of the refractive index, as shown in Table 2. It was observed from Table 2 that the value of $n$ is changed with the method of extraction and used solvent. With distilled water as the solvent, the red cabbage and beetroot dyes ($B_3$ and $C_3$) experienced a high value of refractive index, whereas for the $B_2$ and $C_2$ samples, in which ethanol was used, the value of $n$ was lowest. Moreover, with different extraction methods in which similar solvent was used, the value of $n$ showed a drastic change for both beetroot and red cabbage dyes. For instance, $B_3$ and $C_3$ presented the highest value of $n$ compared with those of the $B_1$ and $C_1$ dyes. Nevertheless, the henna extracted dye showed the lowest refractive index. Furthermore, Fig. 3 (e–h) shows the extinction coefficient ($k$)

| Sample | $n_\infty$ | $\varepsilon_\infty$ | $\sigma_\infty \times 10^{-3}$ | $E_g$ (eV) | Assigned pigment | Molecular formula | Pigment Nomenclatures |
|--------|-----------|---------------------|-----------------------------|----------|-----------------|-------------------|---------------------|
| B1     | 1.95      | 3.87                | 0.53                        | 2.75     | Betaxanthins    | $C_{18}H_{18}N_2O_6^{-2}$ | 2-(2S,4E)-4-{2-[4-hydroxy-3-methoxyphenyl]ethylimino}ethylidene-2,3-dihydro-1H-pyridine-2,6-dicarboxylate |
| B2     | 1.65      | 2.73                | 0.311                       | 3.72     |                  |                   |                     |
| B3     | 4.24      | 18.02               | 6.1                         | 2.36     |                  |                   |                     |
| B4     | 3.36      | 11.52               | 3.5                         | 3.18     | Betacyanin      | $C_{24}H_{26}N_2O_{13}$ | $(2S)-4-[(2S)-2,6-dicarboxy-2,3-dihydro-1H-pyridin-4-ylidene]ethylidene]-6-hydroxy-5-[(2S,3R,4S,5R,6R)-3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxy-2,3-dihydropicolin-1-ium-2-carboxylate |
|        |           |                     |                             |          | Betanidin       | $C_{18}H_{16}N_2O_8$ | $(2S)-4-[(2S)-2,6-dihydroxy-2,3-dihydro-1H-indol-1-yl[viny])]-2,3-dihydro-2,6-pyridinedicarboxylic acid |
| C1     | 1.54      | 2.42                | 0.224                       | 3.18     | Anthocyanin     | $C_{15}H_11O_6^+$ | 2-phenylchromenium |
| C2     | 1.77      | 3.21                | 0.448                       | 2.99     | Anthocyanidin   | $C_{13}H_11O_2^+$ | 3-hydroxy-2-phenylchromenium |
| C3     | 6.08      | 37.18               | 13.92                       | 2.25     |                 |                   |                     |
| C4     | 5.41      | 29.07               | 10.63                       | 2.67     |                 |                   |                     |
| E      | 2.25      | 5                   | 1.05                        | 2.96     |                 |                   |                     |
| F      | 1.4       | 2.01                | 0.128                       | 3.02     |                 |                   |                     |
| W      | 1.9       | 3.65                | 0.57                        | 1.776    | Juglone         | $C_{10}H_6O_5$ | 5-Hydroxynaphthalene-1,4-dione |
| H      | 1.19      | 1.5                 | 0.039                       | 1.775    | Lawsons         | $C_{10}H_6O_4$ | 4-Hydroxynaphthalene-1,2-dione |

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Table 2 The measured optoelectronic parameters of the extracted dyes
as a function of wavelength for all the dyes. Based on Eq. 5, it can be seen that the variation in \(k\) is almost similar to the corresponding absorption coefficient, as shown in Fig. 1(a-d). The changes in \(k\) represent the loss in the incident electromagnetic wave because of scattering and absorption per unit thickness of the medium [33]. For most of the studied dyes, the maximum values of \(k\) were observed to be in the UV region.

Figure 4 shows the variation in the optical dielectric constant in the wavelength range from UV to IR. The response of electrons in the material upon the incident of light can be interpreted by the optical dielectric constant \(\varepsilon\), which is a frequency dependent parameter. Since the dielectric constant is a complex variable, it has real and imaginary parts and can be mathematically represented by [34]:

\[
\varepsilon = \varepsilon_1 + i\varepsilon_2
\]

where \(\varepsilon_1\) represents the real part and \(\varepsilon_2\) represents the imaginary part of the dielectric constant. The real dielectric constant is further represented by Eq. 7, which is a measure of to what extent the material can be polarized due to the influence of the electromagnetic wave, while the imaginary part shows the optical loss, and it is described by Eq. 8.

The optical loss takes place because of the time lag of \(\pi/2\) between the electric field of the incident photon and the component of electronic or atomic polarization in the optical frequency range [41].

\[
\varepsilon_1 = n^2 - k^2
\]

Fig. 3 Refractive index and extinction coefficient spectra for the dyes extracted from (a & e) beetroot, (b & f) red cabbage, (c & g) mixture of beetroot and red cabbage, and (d & h) walnuts leaves and henna
\[ \varepsilon_2 = 2nk \]  

\[ \tan \delta = \frac{\varepsilon_2}{\varepsilon_1} \]  

Noteworthy, the real part of the dielectric constant resembles the refractive index due to the small value of \( k \). However, the imaginary part is mainly dependent on the absorption coefficient (see Eqs. 7 and 8). The variation in the real dielectric constant for all the extracted dyes is shown in Fig. 4(a-d). It was seen that the peak observed in the UV region is belong to B2 sample, while other samples show their characteristic peaks at different wavelengths. It has been reported that the higher value of the real dielectric constant indicated the presence of interaction between the electrons and incident photons in the extracted dyes [35].

\[ \varepsilon_2 = 2nk \]  

\[ \tan \delta = \frac{\varepsilon_2}{\varepsilon_1} \]  

It is worth noting that the mixed dye of anthocyanin and betalin presented a broad peak in the wavelength range from 400 to 600 nm, as shown in Fig. 4(c). This is where the dyes from walnut leaves and henna showed a sharp peak between 500 and 700 nm. The values of the real dielectric constants which were determined from the intersection of the extrapolated plateau region to the y-axis are tabulated in Table 2. The dyes extracted from red cabbage, especially C3, presented the maximum value of \( \varepsilon_1 \), while the dyes extracted from henna has the lowest value of \( \varepsilon_1 \). One can notice that the value of \( \varepsilon_1 \) for the extracted dyes with water solvent is greater compared to those extracted with ethanol and HCl solvent. This might be due to the polar nature of water. In addition to the dielectric constant, Fig. 4(e–h) shows the imaginary dielectric constant of all the extracted dyes as a function of wavelength. It can be concluded that

Fig. 4 The spectra of the real and imaginary optical dielectric constant for the dyes extracted from (a & e) beetroot, (b & f) red cabbage, (c & g) mixture of beetroot and red cabbage, and (d & h) walnuts leaves and henna
the variation in the imaginary part of the dielectric constant is related to the absorption coefficient of the dyes and their mixtures, as shown in Fig. 4(g), with a broad peak across UV and visible region. Furthermore, the dissipation factor (tan δ) was calculated from Eq. 8, thereby dividing the imaginary part to the real part of the dielectric function [31]. The spectra of the dissipation factor for all the samples are shown in Fig. 5(a-d). It was seen that each single dye presented different characteristic peaks because of the effect of solvents and extraction methods. The anthocyanin dye, which was extracted from red cabbage with distilled water (C3), has a maximum peak value in the range of 400 to 500 nm compared to that of the betalain dye which was extracted from beetroot using the same solvent and extraction method. This is ascribed to the rate of absorption of anthocyanin, which is greater than that of the betalain dye, whereas their mixture showed a broad peak in the UV region. However, the dyes from walnut leaves and henna showed a broad peak expanded to 500 nm and a sharp peak nearby 700 nm.

To determine the electronic characteristics of a material, optical conductivity as a powerful tool can be used, which describes the response of electrons to the absorbed photons. Since the optical conductivity is a complex variable, it is derived from the optical dielectric constant [36]:

\[ \sigma^* = \sigma_r + i\sigma_i \]  

(10)

\[ \sigma_r = \omega\varepsilon_2\varepsilon_o \]  

(11)

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Fig. 5 The dielectric lost tangent (dissipation factor) spectra for the dyes extracted from (a) beetroot, (b) red cabbage, (c) mixture of beetroot and red cabbage, and (d) walnuts leaves and henna

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where \( \sigma_r \) and \( \sigma_i \) are the real and imaginary part of the complex optical conductivity, respectively, \( \omega \) is the angular frequency, and \( \varepsilon_\infty \) is the permittivity of free space. One can conclude from Eq. 10 that the real optical conductivity is related to the imaginary optical dielectric constant and hence it depends on the absorption coefficient. Thus, increasing the magnitude of the real optical conductivity is directly related to the transport response of electrons, which are excited by the absorbed photon energy [42]. In contrast, the imaginary optical conductivity is related to the real optical dielectric constant, representing the interaction between the electromagnetic wave and electrons in the form of polarization. The spectra of real and imaginary optical conductivity are shown in Fig. 6 and the measured values of real optical conductivity are listed in Table 2. It was concluded that anthocyanin dye (C3) has the maximum value of \( \sigma_r = 13.92 \times 10^{-3} \text{S/cm} \), while the extracted dye from henna has the lowest value of \( \sigma_r = 0.039 \times 10^{-3} \text{S/cm} \). In addition, it was seen from the spectra of the real conductivity that both betalain and anthocyanin dyes extracted by distilled water as a solvent (B3&C3) have a broad peak extended over the UV and visible regions. The dyes from henna and walnut leaves have a broad peak, starting from UV region to 500 nm in the visible region and a sharp peak at near IR region. Figure 6 (e–h) shows the imaginary spectra of the optical conductivity, resembling the real optical dielectric constant spectra.

![Graphs showing spectra of real and imaginary optical conductivity](image-url)

**Fig. 6** The spectra of real and Imaginary optical conductivity of the dyes extracted from (a & e) beetroot, (b & f) red cabbage, (c & g) mixture of beetroot and red cabbage, and (d & h) walnuts leaves and henna.
Noticeably, the combination of two dyes has led to broadening the photo-absorption in the UV region, indicating that molecular interactions between their moieties are mostly taken place in the high energy levels.

Conclusions

In conclusion, a broad investigation and measurement of the optoelectronic parameters of natural dyes extracted from beetroot, red cabbage, walnut leaves, and henna were successfully carried out. The absorption spectrum response of the dyes was used to determine the optical energy gap ($E_g$), extinction coefficient ($k$), refractive index ($n$), dielectric constant ($\varepsilon_r$), and optical conductivity ($\sigma$). The highest values of the refractive index, dielectric constant and optical conductivity were found to be for the dyes extracted from red cabbage ($n = 6.08$, $\varepsilon_r = 37.18$ and $\sigma = 13.92 \times 10^{-3}$ S/cm) while minimum values of $n = 1.19$, $\varepsilon_r = 1.5$ and $\sigma = 0.039 \times 10^{-3}$ S/cm were recorded for the henna dye. A direct allowed transition was confirmed for all the studied dyes. It was concluded that the optoelectronic parameters of some of the dyes are highly dependent on the nature of the solvents and the extraction method. The reported results herein are important to explore the viability of the studied dyes for potential applications in organic electronics, including organic photovoltaics, photodiodes, and sensors.

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Data Availability The data and material are available within the manuscript.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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References

1. Hemmatzadeh R, Mohammadi A (2013) Improving optical absorptivity of natural dyes for fabrication of efficient dye-sensitized solar cells. J Theor Appl Phys 7(1):57
2. Hemmatzadeh R, Jamalí A (2015) Enhancing the optical absorption of anthocyanins for dye-sensitized solar cells. J Renew Sustain Energy 7:013120. https://doi.org/10.1063/1.4907599
3. Grant TM, Gorisse T, Daulet O, Wantz G, Lessard BH (2017) Multifunctional ternary additive in bulk heterojunction OPV: increased device performance and stability. J Mater Chem A 5(4):1581–1587
4. Chen YC, Hsu CY, Lin RYY, Ho KC, Lin JT (2013) Materials for the active layer of organic photovoltaics: ternary solar cell approach. ChemSusChem 6(1):20–35
5. Güzel E, Arslan BS, Durmaz V, Cemur M, Tutar ÖF, San T, İşleyen M, Nebioglu M, Şisman I (2018) Photovoltaic performance and photo-stability of anthocyanins, isouquinoline alkaloids and betalains as natural sensitizers for DSSCs. Sol Energy 173:34–41. https://doi.org/10.1016/j.solener.2018.07.048
6. Najm AS, Mohamad AB (1838) Ludin NA (2017) The extraction and absorption study of natural dye from Areca catechu for dye sensitzed solar cell application. AIP Conf Proc 1:020019. https://doi.org/10.1063/1.4982191
7. Delgado-Vargas F, Jiménez AR, Paredes-López O (2000) Natural Pigments: Carotenoids, Anthocyanins, and Betalains—Characteristics, Biosynthesis, Processing, and Stability. Crit Rev Food Sci Nutr 40(3):173–289. https://doi.org/10.1080/10408690901189257
8. Khan MI, Giridhar P (2015) Plant betalains: Chemistry and biochemistry. Phytochemistry 117:267–295
9. Guerrero-Rubio MA, Escrivan J, García-Carmona F, Gandía-Herrero F (2020) Light Emission in Betalains: From Fluorescent Flowers to Biotechnological Applications. Trends Plant Sci 25(2):159–175
10. Calogero G, Yum J-H, Sinopoli A, Di Marco G, Grätzel M, Nazeeruddin MK (2012) Anthocyanins and betalains as light-harvesting pigments for dye-sensitized solar cells. Sol Energy 86(5):1563–1575. https://doi.org/10.1016/j.solener.2012.02.018
11. Kerio L, Wachira F, Wanyoko J, Rotich M (2012) Characterization of anthocyanins in Kenyan teas: Extraction and identification. Food Chem 131(1):31–38
12. Jahanban-Esfahlan A, Ostadrahimi A, Tabibiazar M, Amarowicz R (2019) A Comprehensive Review on the Chemical Constituents and Functional Uses of Walnut (Juglans spp.) Husk. Int J Mol Sci 20(16). https://doi.org/10.3390/ijms20163920
13. Henari Z, F (2021) Optical nonlinear properties and optical switching of Henna (Lawson) films. Int J Thin Film Sci Technol 1(2):5
14. Paudel P, Pandey A, Shrestha RR, Neupane A, Lamichhane P, Adhikari R, Gyawali R, Kafle BP (2018) Optical properties of natural dyes:
prospect of application in dye sensitized solar cells (DSCs) and organic light emitting diodes (OLEDs). Food Res 2:429–436. https://doi.org/10.26656/fr.2017.2(5).096.

15. Dhafina WA, Daud MZ, Salleh H (2020) The sensitization effect of anthocyanin and chlorophyll dyes on optical and photovoltaic properties of zinc oxide based dye-sensitized solar cells. Optik 207:163808. https://doi.org/10.1016/j.ijylko.2019.163808.

16. Acedokun O, Sanusi YK, Awodugba AO (2018) Solvent dependent natural dye extraction and its sensitization effect for dye sensitized solar cells. Optik 174:497–507. https://doi.org/10.1016/j.ijylko.2018.06.064.

17. Calogero G, Di Marco G, Caramori S, Cazzanti S, Argazzi R, Bignozzi CA (2009) Natural dye sensitizers for photoelectrochemicals. Energy Environ Sci 2(11):1162–1172. https://doi.org/10.1039/B913248C.

18. Honda S, Nogami T, Oikita H, Benten H, Ito S (2009) The enhancement of the Light-Harvesting Efficiency in Polymer/Fullerene Bulk Heterojunction Solar Cells by Interfacial Dye Modification. ACS Appl Mater Interfaces 1(4):804–810. https://doi.org/10.1021/am80229p.

19. Honda S, Oikita H, Benten H, Ito S (2010) Multi-colored dye sensitization of polymer/fullerene bulk heterojunction solar cells. Chem Commun 46(55):6596–6598.

20. Zhang S, Shah MN, Liu F, Zhang Z, Hu Q, Russell TP, Shi M, Li C-Z, Chen H (2017) Efficient and 1,8-diiodo-octane-free ternary organic solar cells fabricated via nanoscale morphology tuning using small-molecule dye additive. Nano Res 10(11):3765–3774. https://doi.org/10.1007/s12274-017-1589-0.

21. Muhammad FF, Aziz SB, Hussein SA (2015) Effect of the dopant salt on the optical parameters of PVA: NaNO3 solid polymer electrolyte. J Mater Sci: Mater Electron 26(1):521–529.

22. Garcia-Salinas MJ, Ariza MJ (2019) Optimizing a Simple Natural Dye Production Method for Dye-Sensitized Solar Cells: Examples for Betalain (Bougainvillea and Beetroot Extracts) and Anthocyanin Dyes. Appl Sci 9(12):2515.

23. Sengupta D, Mondal B, Mukherjee K (2015) Visible light absorption and photo-sensitizing properties of spinach leaves and beetroot extracted natural dyes. Spectrochim Acta Part A Mol Biomol Spectrosc 148:85–92. https://doi.org/10.1016/j.saa.2015.03.120.

24. Isah KU, Ahmadu U, Idris A, Kimpa MI, Uno UE, Ndaimitto MM, Alu N (2014) Betalain pigments as natural photosensitizers for dye-sensitized solar cells: the effect of dye pH on the photovoltaic parameters. Mater Renew Sustain Energy 4(1):39. https://doi.org/10.1007/s40243-014-0039-0.

25. Hernandez-Martinez A, Estevez M, Vargas S, Rodriguez R (2013) Stabilized Conversion Efficiency and Dye-Sensitized Solar Cells from Beta vulgaris Pigment. Int J Mol Sci 14:4081–4093. https://doi.org/10.3390/ijms14024081.

26. Woodall GS, Stewart GR (1998) Do anthocyanins play a role in UV protection of the red juvenile leaves of Syzygium? J Exp Bot 49(325):1447–1450. https://doi.org/10.1093/jxb/49.325.1447.

27. Zolkepli Z, Lim A, Ekanayake P, Tennakoon K (2015) Efficiency Enhancement of Cocktail Dye of Ixora coccinea and Tradescantia spathacea in DSSC. J Biophysics 2015:582091. https://doi.org/10.1155/2015/582091.

28. Ahmadani N, Robbins RJ, Collins TM, Giusti MM (2016) Molar absorptivity (ε) and spectral characteristics of cyanidin-based anthocyanins from red cabbage. Food Chem 197:900–906. https://doi.org/10.1016/j.foodchem.2015.11.032.

29. Qadariyah L, Azizah N, Syafiatullah A, Bhuma D, Mahfud M (2019) The Extraction of Natural Dyes from Henna Leaves (Lawsonia Inermis L.) by Ultrasound-assisted Method. IOP Conference Series: Materials Science and Engineering 543:012082. https://doi.org/10.1088/1757-899X/543/1/012082.

30. Saadaoui S, Youssef MAB, Karoui MB, Gharbi R, Smecca E, Strano V, Mirabella S, Alberti A, Puglisi RA (2017) Performance of natural-dye-sensitized solar cells by ZnO nanorod and nanowall enhanced photoelectrodes. Beilstein J Nanotechnol 8(1):287–295.

31. Muhammad FF, Sulaiman K (2011) Utilizing a simple and reliable method to investigate the optical functions of small molecular organic films – Alq3 and Gaq3 as examples. Measurement 44(8):1468–1474. https://doi.org/10.1016/j.measurement.2011.05.017.

32. Yukuphanoglu F, Hilmi E (2005) Refractive index dispersion and analysis of the optical constants of an ionomer thin film. Optica Applicata 35.

33. Aziz SB, Abdullah OG, Hussein AM, Abdulwahid RT, Rasheed MA, Ahmed HM, Abdalqadir SW, Mohammed AR (2017) Optical properties of pure and doped PVA: PEO based solid polymer blend electrolytes: two methods for band gap study. J Mater Sci: Mater Electron 28(10):7473–7479.

34. Amin PO, Kadhim AJ, Ameen MA, Abdulwahid RT (2018) Structural and optical properties of thermally annealed TiO2–SiO2 binary thin films synthesized by sol–gel method. J Mater Sci: Mater Electron 29(18):16010–16020. https://doi.org/10.1007/s10854-018-9688-6.

35. Soliman TS, Vshikov SA (2019) Effect of Fe nanoparticles on the structure and optical properties of polyvinyl alcohol nanocomposite films. J Non-Cryst Solids 519:119452. https://doi.org/10.1016/j.jnoncrysol.2019.05.028.

36. Sakr G, Yahia I, Fadel M, Fouad S, Romčević N (2010) Optical spectroscopy, optical conductivity, dielectric properties and new methods for determining the gap states of CuSe thin films. J Alloy Compd 507(2):557–562.

37. Sudhahar S, Krishna Kumar M, Silambaranasan A, Muralidharan R, Mohan Kumar R (2013) Studies on Structural, Spectral, and Optical Properties of Organic Nonlinear Optical Single Crystal: 2-Amino-4,6-dimethylpyrimidinium p-Hydroxybenzoate. J Mater Sci: Mater Electron 24(10):7473–7479.

38. Abomostafa HM (2021) Linear and nonlinear optical properties of innovative synthesis of nickel nanoparticles in polystyrene matrix as a new optical system. J Mol Struct 1225:129126. https://doi.org/10.1016/j.molstruc.2020.129126.

39. Tauc J (1968) Optical properties and electronic structure of amorphous Ge and Si. Mater Res Bull 3(1):37–46.

40. Davis E, Mott N (1970) Conduction in non-crystalline systems V. Conductivity, optical absorption and photoc conductivity in amorphous semiconductors. Philosophical Magazine 22 (179):0903–0922.

41. Sonal SA, Aggarwal S (2018) Optical investigation of soda lime glass with buried silver nanoparticles synthesised by ion implantation into Cryst Solids 485. https://doi.org/10.1016/j.jnoncrysol.2018.01.038.

42. Kemmler R, Huebner R, Löhle A, Neubauer D, Voloshenko I, Schopf L, Dressel M, Pronin A (2018) Free-carrier dynamics in Au2Pb probed by optical conductivity measurements J Phys: Condens Matter 30. https://doi.org/10.1088/1361-648X/aac7b1.

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