Performance of dye-sensitized solar cells extracted dye from wood apple leaves

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Abstract
In this work, wood apple leaves dye has been extracted, characterized, and examined as a potential photosensitizer for dye-sensitized solar cells (DSSCs). The dye was extracted in an ethanolic medium from the fresh wood apple leaves and characterized using thin-layer chromatography (TLC), ultraviolet-visible (UV-Vis), and Fourier transform infrared (FTIR) spectroscopy. The current density-voltage (J–V) characteristics measurements were performed on the two assembled DSSCs for 1–22 days using fresh and seven days old extracted dye. The characterization results revealed that the extracted dye mainly contains the compound of carotenoids (neoxanthin), chlorophyll a, chlorophyll b, and their derivative (pheophytin) with various functional groups. The J–V characteristics of DSSCs indicate that an open-circuit voltage and short circuit current density radically decrease with increasing time, thus degrading the efficiency of cells. A degraded DSSCs suffered from high defect recombination may be induced by Mg ions migrating from chlorophyll dye into DSSC. Therefore, the extracted dye may be used for energy harvesting from the wood apple leaves.

1. Introduction
Dye-sensitized solar cell (DSSC) is evolving as one of the most promising photovoltaic technologies due to their low cost, environmentally friendly, and simple fabrication compared to typical silicon-based solar cells [1]. The performance of cells depends on the quality of materials used as semiconductor electrodes and photosensitizers or dyes [2]. Natural dyes are organic and in plant organisms along with leaves, flowers, fruit, and vegetable. However, microorganisms include fungi, algae, bacteria, and a few animal structures. Synthetic pigments (organic) are produced within the laboratory, while inorganic may be discovered in nature or reproduced through synthesis. Thus, plants are considered leading manufacturers of herbal (natural) pigments [3].

To investigate the influence of the utilization of organic dyes on the photovoltaic performance of low-cost DSSCs, carminic acid (CA) obtained from cochineal insect was employed as a photosensitizer and achieved 1.0% efficiency in preparing the film by spin coating of TiO₂ paste from P25 with pre- and post-treatment using titanium tetra isopropoxide [4]. The CA, papaya peel, and microalga Scenedesmus obliquus extract were tested as sensitizers and achieved efficiency of 0.228%, 0.093%, and 0.064%, respectively. However, the maximum efficiency of 0.36% was recorded for DSSC sensitized with the combination of the three pigments [5]. The efficiencies of extracted dyes from black mulberry (1.30%) and madder roots (1.27%) were found to be much higher than that of synthetic organic dye [eosin-y, C₂₀H₈Br₄O₅] (1.07%), preparing the film by spin coating of TiO₂ paste using titanium (IV) isopropoxide [6]. Novel natural dyes extracted from St. Lucie cherry, yellow jasmine, and madder berries are reported to act as sensitizers for the first time using photoanodes composed of three TiO₂ layers prepared through the spin-coating method [7].

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There are several natural pigments, which are from plant extract and grouped into chlorophyll, carotenoids, flavonoids, and betalain in the majority and have been verified as sensitizers in DSSCs. These natural dyes and their organic derivatives become a perfect candidate for green solar cells because of eco-friendly, economical, renewable, and widely available [1]. Among the utilized of these natural dyes in DSSCs, chlorophylls have been examined extensively due to the porphyrin ring. These are comparable to synthetic organic metal-porphyrin dyes with an efficiency of ~7.1% [8]. Recently, a new generation DSSCs was developed using a combination of donor-p-acceptor porphyrin dyes attaining an efficiency of 13% [9]. However, these natural dyes can be degraded easily at high temperatures and show low efficiency compared to synthetic dyes [1, 2]. Researchers have confirmed that chlorophyll is a complex pigment. It can be used for DSSCs as a dye or photosensitizer due to its substantial radiation absorption property in the visible wavelength range. Its molecules can quickly be excited by sunlight exposure, boosting cell performance. However, this pigment is unstable and decays quickly with heat and light exposure in acidic and alkaline conditions [1, 2]. This pigment can be decomposed by losing Mg\(^{2+}\) ions from the porphyrin ring and producing pheophytins. These pheophytins are chemically stable with heavy-metal ions such as Cu\(^{2+}\) and Zn\(^{2+}\) that Mg\(^{2+}\) ions may replace in chlorophylls [10].

Researchers have expanded energy conversion efficiency with derivatives of chlorophyll pigment due to its carboxylic group [1, 2, 11]. It has been known that the anchoring groups play a critical role in the binding with semiconductor metal and affect electron injection rates and stability of the adsorbed dye. Therefore, this influences the photovoltaic performance and stability of DSSC [12–14]. The carboxylic groups (COOH) are the most used anchor groups because of their stability and ease of synthesis [12]. Simultaneously, it is widely obtained from natural resources and proved to make the capping ligands for encapsulation and stabilization of TiO\(_2\) nanoparticles [15]. Therefore, looking for more organic/natural resources that can provide more power to utilize as a photosensitizer in energy harvesting technology is required [16]. The most crucial factor of the DSSC performance is reduced due to the degradation of dye with minimal effect on liquid electrolyte leakage, dye desorption, solvent volatilization, weak interaction between TiO\(_2\) and dye molecules, etc [17–20].

The DSSC performance was significantly affected by the concentration of the pigments present in extracted dye. Therefore, it is essential to track the changes in the pigment concentration of the extracted dye over time. The change of pigment concentration or degradation mechanism of the extracted dye is related to the blue or red shift of the absorption maximum as well as the change in absorption intensity and pH value of the extracted dye solution [21]. The chlorophyll degradation mechanisms might occur through the formation of chlorophyllide or pheophytins or both ways if the extract was not exposed to light, heat, and oxygen. In the degradation processes of leaves extract, the main reason for a change in structure from native chlorophyll to pheophytin is that core magnesium ion has lost been in the chlorophyll structure [22].

Bael (Aegle marmelos) is a well-known wood apple that is local, easily, and abundantly available in India. Aegeline (antioxidant alkaloid amide) and 1,3-dimethylamylamine are the dominant ingredients of A. marmelos leaves [23]. Especially, the present study encourages the exploration of novel alternative plants.

This paper presented the dye extracted from wood apple fresh green leaves and characterization by chromatography, ultraviolet-visible, and Fourier transforms infrared spectroscopy at room temperature. As a novelty in the present study, the stability of wood apple leaves considered natural sensitizers in DSSCs were reported for the first time. Moreover, functional groups of related to DSSCs were first identified using FTIR spectroscopy. Here we also report the electrical parameters of DSSCs by using the photovoltaic performances of the extracted dye.

2. Experimental

2.1. Dye extraction
As shown in figure 1(a), fresh leaves of wood apple were collected and cleaned with normal water and then left to dry under the air of an electric fan. After that, these leaves were grinded using the electrical grinder. Then the leaves powder was immersed in a beaker with ethanol addition for 60 min and grinded through Agate mortar and pestle. The resultant solution was filtered through the Whatman filter paper and kept in the dark under laboratory conditions, as shown in figure 1(b).

2.2. Counter electrode
A homogeneous paste is prepared for the counter electrode by dispersion of 0.55 g of graphite fine powder in 3.0 ml ethanol and then stirred for 45 min on the magnetic stirrer at room temperature. After that, this paste was deposited on the well-clean fluorine-doped tin oxide (FTO) glass substrate with dimensions of 25 mm × 25 mm × 2.2 mm, as shown in figure 1(c).
2.3. Photoelectrode
A paste was prepared from the commercially available titanium dioxide powder using 0.5 g by adding a 1.0 ml mixture of deionized water, chloroform, and ethanol (1.0: 6.5: 3.5 ratios) for the photoelectrode. This paste was grinded in Agate mortar and pestle for 10 min by adding a 3.0 ml ethylene glycol and stirred in a beaker on a magnetic stirrer for 2 h for a homogeneous paste at room temperature. Then this TiO₂ paste was deposited on the cleaned FTO glass substrate (figure 1(d)) by the doctor blade method and left to dry at room temperature. After that, this substrate was baked for 10 min at 460 °C and then cooled to 100 °C in a muffle furnace. Finally, it is immersed in the extracted dye for 24 h and then washed gently with deionized water, as shown in figure 1(e).

2.4. Electrolyte
A solution of 4.0 g potassium iodide and 50 ml acetonitrile was prepared by continuous stirring with the addition of 0.6 g iodine. Another homogeneous solution was prepared in 10 ml of deionized water by dissolving 2.0 g sodium nitrate through continuous stirring for 1 h. Both these solutions were mixed by stirring continuously for 2 h, which served as electrolytes for the cell.

2.5. Cell assembly
One drop of the electrolyte solution was initially dropped on the photoelectrode and counter electrode using a capillary for the cell assembly. Afterwards, these electrodes were placed in the sandwich configuration so that the conducting side faced each other. Then this configuration was fixed with the paper clip binder, as shown in figure 1(f). Two cells were assembled, one using freshly extracted dye (DSSC I) and the second seven days old extracted dye (DSSC II).

2.6. Characterization techniques
Room temperature thin layer chromatography (TLC) was performed on the extracted dye from the wood apple leaves by the conventional one-dimensional ascending method on the silica gel 60 F₂₅₄ aluminum sheet of 2.0 × 8.0 cm² as a polar stationary phase. The baseline was drawn by graphite pencil 2.0 cm away from one end on this sheet. Then, using a glass capillary, one tiny drop of the extracted dye was put on this baseline and dried at room temperature. This plate was immersed vertically in a 250 ml glass beaker with a solvent of deionized water, acetone, and petroleum ether in 2:1:9 ratios as a non-polar mobile phase for 15 min (figure 2). After the mobile phase and pigment run, the plate was taken from the beaker and left to dry for 10 min. The active compound bands of extracted dye were located and circled on the TLC plate upon eye visualization.
Shimadzu UV-Vis spectrophotometer (UV-1800) was used to record the absorption spectra of the extracted dye in the 400–700 nm wavelength range. The ALPHA II, Bruker, FTIR spectrometer with an ATR (Attenuated Total Reflection) sampling accessory was used to record the Fourier transforms infra-red spectra in the 4000 to 400 cm\(^{-1}\) wavenumber range.

Keithley 2450 source meter of Tektronix interfaced with a computer through window-based Kick Start software was used to record the current-voltage characteristics on the assembled dye in the presence of a 200 W tungsten bulb. FLUKE 941 light meter was used to measure the illuminance of the bulb at the point on cell location. Vernier Caliper was used to measure the assembled cell’s active area (1.14 \(\times\) 2.25 = 2.565 cm\(^2\)).

3. Results and discussion

The recorded photograph on the TLC plate for the wood apple leaves dye extract is shown in figure 3. Five prominent spots were observed on the photograph, which indicated the presence of carotenoids as neoxanthin and chlorophyll as chlorophyll a and chlorophyll b and its derivatives as pheophytin a and pheophytin b in the extract and agreed with the reported results [24, 25]. Similar spots were reported as carotenoids as well as chlorophyll and its derivatives for the extract from various medicinal plants leave [26, 27]. The ratio of the distance travelled by the spot to the distance travelled by the mobile phase is used to calculate the retention factors (\(R_f\)) values, as shown in figure 3. These \(R_f\) values agreed with the reported results for leaf extracts from...
Oryza saliva L. [27]. The calculated \( R_F \) value for a given compound is relatively unique as it depends on the chemical structure of each compound [28]. Neoxanthin has a conjugated double bond structure ‘polyene chain’ with oxygenated groups (C=O) [29]. Chlorophyll a and chlorophyll b have a complex system of alternating single and double conjugated bond structure, with CH3 and CHO on a single side chain of the cyclic tetrapyrrole of chlorophyll a and chlorophyll b, respectively [30]. Pheophytin a and b are dechelated central magnesium ions from chlorophyll a and b, respectively [22]. The compounds with functional groups such as hydroxy R-OH, carbonyl, or carboxyl R-COOH and amino groups R-NH are highly polar. In contrast, the compounds with a functional group such as R-CH3 are low polar [31]. Thus, the neoxanthin (low \( R_F = 0.30 \)) is strongly retained by the silica, and the chlorophyll b (\( R_F = 0.35 \)) is more lipophilic than chlorophyll a (\( R_F = 0.54 \)) and pheophytin a (\( R_F = 0.74 \)) and pheophytin b (\( R_F = 0.88 \)) in the wood apple leaves extract [28]. However, the calculated \( R_F \) values were affected by the solvent age, pigment solubility, spotted pigment amount on the TLC plate, chamber equilibration, and chamber lining with chromatographic paper [32]. From figure 3, the pigment compounds travel gradually from the pigment line toward the solvent line in the mobile phase system solvent. Thus, the dye can strongly bond with the adsorbent (e.g., TiO2) through its movements [33].

UV-Vis spectra of extracted dye from the leave of wood apple in the wavelength range of 400 to 700 nm for three concentrations (0.1, 0.2, and 0.3 g ml\(^{-1}\)) are shown in figure 4. Four broad absorption bands were observed in the range 450–475, 535–540, 609–616, and 650–675 nm for all concentrations. Among these two prominent absorption bands in the blue visible (450–475 nm) and red visible (650–675 nm) range indicate the presence of carotenoids (neoxanthin) or chlorophyll b and chlorophyll a, respectively [27, 34]. Another two absorption bands between the blue-red visible range of 535–540 nm and 609–616 nm represent the existence of pheophytin fraction in the ethanol extract and/or the presence of n–π* electronic transitions of the porphyrin ring, thus confirming the charge injection from the excited state of wood apple sensitizer into the conduction band of TiO2 [14, 35]. These observed band positions are consistent with reported carotenoid and chlorophyll pigment results obtained from Spinacia Oleracea leaves [36]. The broadening of the bands in the range 650–675 nm was observed for higher concentrations (0.3 g ml\(^{-1}\)). This broadening of the bands indicates the chlorophyll-chlorophyll interactions at higher concentrations. This interaction may be due to the aggregation of pheophytin or the existence of two pigments in the 650–675 nm range [37]. However, clear, sharp absorption peaks were observed for low concentrations (0.1 and 0.2 g ml\(^{-1}\)) in the spectra. The wood apple leaves extract stability at a concentration (0.3 g ml\(^{-1}\)) was studied for 22 days, as shown in figure 5. The dye absorbance in the 535–540 nm range increased up to 7 days. A small new electronic transition in the wavelength range 490–520 nm began after the seventh day of extractions. This increase in absorbance was ascribed to the formations of degradation products (pheophytin). However, absorbance in the range 609–616 nm decreased significantly, and bands slightly shifted toward a lower wavelength. This decay was ascribed to oxidized chlorophyll a transfer to b [38]. Also, the chlorophyll absorbance in 650–675 nm is slightly decreased. These features are known to accompany the formation of pheophytin. The results revealed that the extracted wood apple dye has a donor–π–acceptor structure.
The bandgaps ($E_g$) values of wood apple dye were determined by derivative spectroscopy of absorbance (A) as the function of photon energy ($h\nu$), (first-order dA/d$E$), for all concentrations as shown in figure 6 and for 0.3 g ml$^{-1}$ in figure 7 for 22 days. From figure 6 one optical transition occurred at $E_{g1}^{opt} = 1.85$ eV, and two fundamental transitions occurred at $E_{g1} = 2.03$ eV and $E_{g2} = 2.30$ eV for all concentrations. As the time increases from 1 to 22 days, the bandgap values of 0.3 g ml$^{-1}$ shift toward higher energy. This shift is
insignificant, as shown in figure 7. Earlier, a detailed discussion of the energy level diagram and electron transfer processes for wood apple leaves extract in DSSCs was reported [39].

FTIR spectroscopy was used to determine the leading functional groups and their importance regarding dye adsorption on the metal oxide layer, charge transfer properties, and cell efficiency. For this, the FTIR spectrum of wood apple leaves extract of 0.3 g ml⁻¹ concentration in the wavenumber range from 4000 to 600 cm⁻¹ is shown in figure 8. In the spectra, various functional groups were observed in the ethanol extraction. All the distinct and sharp absorption bands are pronounced with their wavenumbers in the observed spectra, and corresponding functional groups are presented in table 1. These observable bands in the spectra agree with the earlier reported FTIR results on the carotenoids (neoxanthin), flavonoids, phenolic, chlorophyll, and its derivatives [40–44]. The broadest band centered at 3336 cm⁻¹ is ascribed to O–H groups or H–bond, indicating the presence of the phenolic compounds in the extract [42–44]. In the spectra beyond the fingerprint region, the response of the spectra at 2975, 2930, and 2889 cm⁻¹ are due to antisymmetric and symmetric aliphatic saturated C–H stretching vibrations in methyl (–CH₃) and methylene (–CH₂) groups [40, 42–44]. The prominent band observed at 1652 cm⁻¹ (inset of figure 8 and table 1) was associated with the vibration of N–H bending of the amide I or flavonoids and amino acids stretching vibration of C=O and C=C, or (C=C) group and aromatic ring in the extracted dye [40, 42–44]. The band at 1547 cm⁻¹ is associated due to the N–H stretching of the amide II [40]. A minor but well-detectable band is observed at 1927 cm⁻¹ (C=C=C) for the allene group. This group indicates the presence of neoxanthin pigment in the sample [41]. A shoulder-type band at 1483 cm⁻¹ (inset of

Figure 7. Derivative of absorbance with energy at 3.0 g ml⁻¹ of wood apple leaves up to 22 days.

Figure 8. ATR-FTIR spectrum of ethanolic wood apple leaves extract with inset in the wavenumber range 1700–1100 cm⁻¹.
Table 1. Band positions and type of bands observed through FTIR spectroscopy for extracted dye from wood apple leaves.

| S. No. | Band positions (cm⁻¹) | Type of bonds and possible functional group | References |
|--------|-----------------------|---------------------------------------------|------------|
| 1      | 3336                  | OH-group of phenolic compounds              | [40, 44]   |
| 2      | 2975, 2930, 2889      | C–H stretching vibrations of methyl (CH₃) and methylene (CH₂) group | [40, 44] |
| 3      | 1927                  | C=C=C of allene group of neoxanthin         | [41]       |
| 4      | 1652                  | N–H bending vibrations of amide I or C=O, C=C-stretching vibration of flavonoids and amino acids | [40, 44] |
| 5      | 1347                  | N–H stretching of the amide II or C=CH aromatic bond or C=N | [40]       |
| 6      | 1483                  | C=O stretching of the chlorine and quinone ring | [40]       |
| 7      | 1453                  | CH₃ antisymmetric or C=O stretch            | [42, 44]   |
| 8      | 1417                  | C–OH or COO– carboxylic group vibration     | [42]       |
| 9      | 1382                  | C–H bending vibration of CH₃ or alkane      | [44]       |
| 10     | 1326                  | O–H bending vibration of phenols or amide III vibration and the CH₂ wagging modes | [40, 44] |
| 11     | 1275                  | C–O vibrations of the ester or phenols groups | [40, 42] |
| 12     | 1153                  | C–O anti-symmetric stretching               | [40]       |
| 13     | 1085, 1044            | C–O stretching vibration of alkoxy groups   | [42, 44]   |
| 14     | 877                   | C–H of aromatic compounds or C–C stretching vibration | [42, 44] |
| Compound detected | 1652, 1547, 1275, 1153, 1044 | Chlorophyll and its derivatives           | [40]       |
|         | 877, 1044, 1382, 1326, 1453, 1547, 1927, 2930, 2975, 2889, 3336 | Carotenoids (Neoxanthin)                  | [41]       |
|         | 3336, 1652            | Flavonoids and phenolic compound           | [42, 43]   |

The presence of bands at 1085, 1044, 1417, and 1453 cm⁻¹ confirms the ability of dye extract to make a capping ligand for TiO₂ particles [15].

The current density (J) and power density (P) versus voltage (V) characteristics curves for the assembled DSSC using wood apple leaves dye are shown in figure 9. These curves were observed on the cell (DSSC I) on day 1 (the day after fresh extract), 9, 10, 16, 21, and 22 (figures 9(a), (b)) and another cell (DSSC II) on day 1 (7 days old extracted dye used), 2, 9 and 14 (figure 9(c)). The value of the short-circuit current density (JSC) and open-circuit voltage (VOC) were obtained from the J–V curves (figure 9(a)). The maximum current density (JMP) and voltage (VMP) were obtained for all days from the J–V curves corresponding to the points of maximum power in the P–V curve, as clearly represented in figure 9(a). The fill factor (FF) and overall efficiency (η%) for both cells were calculated using JSC, VOC, JMP, and VMP through the following formulas [1]:

\[
FF = \frac{J_{MP} \times V_{MP}}{J_{SC} \times V_{OC}}
\]

and

\[
\eta = \frac{J_{SC} \times V_{OC} \times FF}{P_{in}} \times 100 \% 
\]

where, P_{in} is the incident light intensity in W/cm².
The observed key performance parameters ($V_{OC}$, $J_{SC}$, $V_{MP}$, $J_{MP}$, FF, and $\eta$) of DSSC I and II for all days were presented in tables 2 and 3. These experimental parameters ($V_{OC}$, $J_{SC}$, $V_{MP}$, $J_{MP}$, and $\eta$) decrease as time increases for both these DSSCs (figure 9, tables 2 and 3), and these have been ascribed to dye degradation. However, the dye absorbance slightly changes with time (figure 5). The decrease in $V_{OC}$ indicates that electrolyte limitation also appears to contribute to the $J_{SC}$ degradation and, consequently, the $\eta$. However, the FF values increased as time increased for both these DSSCs. This enhancement in FF can be ascribed to the better electric contact formation between the electrolyte and the counter electrode through the dye degradations [47]. The maximum efficiency $\eta = 0.07 \times 10^{-4}\%$ for the fresh extract (day 1) and decreases continuously with time to $0.01 \times 10^{-6}\%$ on day 22 for the DSSC I and $0.02 \times 10^{-6}\%$ on day 1 and $0.01 \times 10^{-7}\%$ on day 14 for DSSC II. Therefore, observed key parameters of DSSCs are decreasing with time due to the degradation of chlorophyll a photosensitizer present in the extracted dye from the wood apple leaves, as observed in the UV-Vis spectra. It is

| Time (Day) | $P_{in}$ (Lux) | $V_{OC}$ ($\mu$V) | $J_{SC}$ ($\mu$A cm$^{-2}$) | $V_{MP}$ ($\mu$V) | $J_{MP}$ ($\mu$A cm$^{-2}$) | FF | $\eta \times 10^{-4}$ (%) |
|-----------|----------------|-------------------|-----------------|-----------------|-----------------|----|---------------------|
| 1         | 1860           | 1651.50           | 1.869           | 800             | 1.012           | 0.26| 0.07               |
| 9         | 1500           | 86.46             | 0.095           | 39              | 0.052           | 0.25| 0.02 $\times 10^{-2}$ |
| 10        | 1652           | 40.71             | 0.048           | 27              | 0.023           | 0.26| 0.06 $\times 10^{-3}$ |
| 16        | 1355           | 19.79             | 0.014           | 12              | 0.011           | 0.48| 0.01 $\times 10^{-3}$ |
| 21        | 1617           | 17.67             | 0.010           | 9               | 0.007           | 0.36| 0.06 $\times 10^{-4}$ |
| 22        | 1618           | 7.51              | 0.004           | 3               | 0.004           | 0.40| 0.01 $\times 10^{-4}$ |

Figure 9. Current density ($J$) and power density ($P$) versus voltage ($V$) characteristics curve for assembled cell observed on (a) day 1 after extraction (DSSC I), (b) day 9 to day 22 (DSSC I), and (c) day 1 (from 7 days old extraction) to day 14 (DSSC II).
also clear from tables 2 and 3 that the pheophytin enhanced the stability and FF but reduced the overall performance compared to the chlorophyll. The distortion of DSSCs performance may be due to the presence of hydroxy group (–OH), which comes from either ethanol or moisture. It can detach the dye from TiO2 and thus leads to chemical instability [13]. The obtained values of $I_{SC}, V_{OC}, J_{sc}$, and $\eta$ compared to other DSSCs employing organic sensitizers [4–7, 48–53]. The value of $I_{SC}$ for the cell sensitized with the wood apple leaves dye becomes better than DSSCs employing TiO2 (18NR-T) sensitized by chlorophylls dye extracted from natural plants (spinach, grass jelly leaves, and broccoli) [49], DSSC employing PEDOT: PSS/PEG sensitized by anthocyanin extracted dye from banana flowers [51], and DSSCs employing TiO2 sensitized by chlorophyll and anthocyanin extracted dyes from natural jatropha leaves and purple chrysanthemum, respectively [53]. The value of $V_{OC}$ for the cell sensitized with the wood apple leaves dye is better than the chlorophylls dye extracted from spinach, grass jelly leaves, and broccoli [49]. The fabricated DSSC shows better efficiency than the DSSCs employing TiO2 sensitized the avocado peel [50], jatropha leaves, and purple chrysanthemum-based [53]. However, the values of $V_{OC}$ and FF in this study are far from satisfactory, which causes lower efficiency. The $V_{OC}$ is associated with the difference between the energy level of the TiO2 conduction band and the redox potential of the electrolyte, and charge recombination occurs at the interface of photoanode/electrolyte [4]. Therefore, they should also be considered to comprehend such a low value of $V_{OC}$. Thus, the output parameters for cells depend on the type of sensitizers, type of photoanode, and their compatibility.

4. Conclusion

Dye has been extracted from fresh wood apple leaves in the ethanolic medium. TLC, UV-Vis, and FTIR spectroscopy analysis indicates the presence of carotenoids (neoxanthin), chlorophyll a, chlorophyll b, and its derivative (pheophytin) mainly in the dye extract. The factor of the DSSCs performance was reduced due to the degradation of dye. The dye-sensitized cell degradations have been conducted over 1–22 days using the fresh and degraded wood apple dye. The open-circuit voltage ($V_{OC}$) and short circuit current density ($I_{SC}$) radically decrease with time, thus degrading the cells’ efficiency. However, the degradation rate in DSSC I (fresh dye) was significantly higher than in DSSC II (old dye). A degraded DSSCs suffered from high defect recombination may be induced by Mg ions migrating from chlorophyll dye into DSSC.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare no conflict of interest.

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Table 3. Key performance parameters of the investigated DSSC II for different time and illuminations.

| Time (Day) | $P_{in}$ (Lux) | $V_{OC}$ (µV) | $I_{SC}$ (µA cm$^{-2}$) | $V_{MP}$ (µV) | $J_{MP}$ (µA cm$^{-2}$) | FF | $\eta$ ($\times 10^{-4}$) (%) |
|-----------|----------------|---------------|------------------------|---------------|------------------------|----|-----------------------------|
| 1         | 1755           | 76.39         | 0.12                   | 33            | 0.066                  | 0.24 | 0.02 $\times 10^{-2}$      |
| 2         | 1555           | 39.52         | 0.11                   | 21            | 0.065                  | 0.31 | 0.01 $\times 10^{-2}$      |
| 9         | 1617           | 37.21         | 0.04                   | 18            | 0.032                  | 0.39 | 0.06 $\times 10^{-3}$      |
| 14        | 1448           | 17.69         | 0.01                   | 12            | 0.010                  | 0.68 | 0.01 $\times 10^{-3}$      |
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