



Jasmine flowers extract mediated green synthesis of TiO_2 nanoparticles and their photocurrent characteristics for dye-sensitized solar cell application

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Abstract

In this work, titanium dioxide nanoparticles (TiO_2 NPs) were green-synthesized using jasmine (*Jasminum sambac*) flower extracts as the medium with different solvent variation concentrations. The green synthesis was carried out using titanium isopropoxide (TTIP) as a precursor via the sol-gel method. The obtained TiO_2 NPs were characterized using infrared spectroscopy (FTIR), ultraviolet spectroscopy (UV-DRS), X-ray diffraction (XRD), field emission scanning electron microscopy/energy dispersive X-ray spectroscopy (FESEM/EDX), Raman spectroscopy, and high-resolution transmission electron microscopy/selected area diffraction (HRTEM/SAED). The characterization revealed that the green-synthesized TiO_2 NPs possess a pure tetragonal anatase phase, which belongs to the space group $I4_1/\text{amd}$. Dye-sensitized solar cell devices were further fabricated using the obtained TiO_2 NPs and sensitized with the commercial dye N719 and a kesumba (*Bixa orellana*) seed extract as an alternative, inexpensive, yet sustainable natural dye. The highest efficiency of 2.52% was obtained from TiO_2 NPs sensitized using commercial dye N719 and synthesized using jasmine flower extract containing 30% acetylacetone, followed by one containing 50% acetylacetone, which is higher than that of commercial TiO_2 (0.80%). The same materials sensitized using kesumba seed extract resulted in efficiency of 0.22%, 0.08%, and 1.22%, respectively. These findings offer insight and pave the way for more novel, environmentally friendly methods for developing green-synthesizing nanomaterials and natural dye derivatives, ultimately contributing to a sustainable future.

Keywords Dye-sensitized solar cell · Green synthesis · Natural dye · Plant extract · Power conversion efficiency

Introduction

Dye-sensitized solar cell (DSSC) is one of the third generations of solar cells that converts light to electricity using a photoelectrochemical principle [1]. Some advantages of the DSSC include easy fabrication, a green approach, low costs, and working well under low light intensity conditions [2]. Unfortunately, the main common problem is due to the low efficiency of these DSSCs [3]. The highest DSSC efficiency of 14% is currently achieved using ruthenium artificial dyes with material optimization and structural properties enhancement [4].

Titanium dioxide is one of the materials used as a semiconductor layer in the DSSC because of its excellent optoelectronic properties [5–7]. These properties, however, depend on their crystallographic phases, such as anatase, rutile, and brookite [8, 9], which in turn depends on their

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routes of synthesis [10]. In addition, TiO₂ has the drawback in terms of having a bandgap energy of 3.2 eV, which is considered a wide bandgap and uses UV light rather than visible light [11]. Because of that, many efforts have been conducted by many investigators in reducing this bandgap energy via doping [12], quantum confinement [13], and defect mediation [14].

In the advancement of DSSCs, nanomaterials play a key role in the DSSC device performance enhancement since they construct light-trapping architectures, create interlayer transmission bridges, and facilitate charge carrier transport pathways [15]. Because of that, the use of TiO₂ nanomaterials is preferred over the bulk one, one of which is TiO₂ NPs [16, 17]. There are many routes available to synthesize TiO₂ NPs, including the conventional physical top-down method [18] and chemical bottom-up process [19]. Some top-down conventional methods include lithography [20], laser ablation [21, 22] and mechanical techniques [23, 24]. Notwithstanding their simplicity, these approaches consume a high amount of energy and incur a high initial cost. In contrast, the bottom-up approaches, such as chemical vapor deposition (CVD) [25, 26], hydrothermal [27, 28], and conventional sol–gel method [29] result in well-defined shape and size, narrow size nanoparticle distribution, and cost-effectiveness. These techniques, however, have some disadvantages, including complex chemistry and toxic chemical waste [30].

Recently, environmentally friendly methods by employing natural extracts from plant parts [31, 32] have attracted special attention due to their green process, cost-effective, sustainable, and simple protocol [33]. During the green synthesis, the natural plant extract can act as a reducing and stabilizing agent [34]. In addition, the plant extract can impart its intrinsic properties contributed by the polysaccharides, flavanones, and terpenoids [35] contained in the extract. Several plant extracts utilized for green-synthesizing metal oxide NPs include *Terminalia catappa* [33, 36], *Carissa carandas* [36], *Bixa oreallana* [37–39], Mangosteen [32, 40], *Morus nigra* [41], and *Citrus limon* [42]. Jasmine, a genus of shrubs and vines in the olive family of *Oleaceae* [43, 44] has been used to green-synthesize cupric oxide NPs [45] and known to contain phytochemicals such as alkaloids and flavonoids [46, 47]. Aravind and his coworkers [48] have used jasmine flower extract to green-synthesize TiO₂ NPs for photocatalytic applications. None has been used for solar cell applications.

The most effective sensitizer for high DSSC efficiency is currently achieved by using a synthetic commercial sensitizer [49]. There are many different types of synthetic dyes, such as metallic complexes, porphyrins, and organic molecules, that have shown improvement in the conversion efficiencies [50]. These synthetic dyes, however, have

drawbacks because of their high synthesis cost, scarcity of metals, and environmental impact [51]. On the other hand, natural sensitizers from plant parts can be easily prepared and extracted with low production costs, and most importantly, they are non-toxic and environmentally friendly [52]. Even though natural sensitizers still have low power conversion efficiency, they may open the door for more novel, environmentally friendly dye derivatives [53]. One of the natural dyes readily available in Indonesia is kesumba (*Bixa orellana*) seeds. Kesumba seeds are widely used as a source of natural dyes for many purposes, such as cosmetics, food, and pharmaceutical industries, because of their non-toxic nature and easy extraction [54]. It has also been used as a sensitizer in a DSSC device [55]. Kesumba seeds contain several active chemical compounds, such as bixin, which has a red color and is soluble in water, and norbixin, which has a yellow color and is soluble in fat, and several other types of carotenoids in smaller amounts [56–58].

In this work, TiO₂ NPs were green-synthesized using a natural medium from jasmine flower extract as a capping agent, and the obtained TiO₂ NPs were used as a semiconductor layer in DSSC devices. For the first time, the DSSC was fabricated by combining green-synthesized TiO₂ NPs using jasmine flower extract, sensitized with kesumba seed extract, and compared with the commercial dye N719. The key results of this study are thus the characteristics of TiO₂ NPs green-synthesized using jasmine flowers extracted under different solvent concentration variations and the performance of the obtained TiO₂ NPs as a semiconductor layer in a DSSC device sensitized using natural and commercial dyes.

Materials and methods

Materials

The precursor for the synthesis was titanium tetra isopropoxide (TTIP, Ti{OCH(CH₃)₂}₄ Sigma Aldrich). Other chemicals include ethanol (Merck), acetylacetone (Sigma Aldrich), commercial TiO₂ (Merck), polyvinylidene fluoride (PVDF, Merck), N-Methyl-2-pyrrolidone (NMP, Merck), commercial dye N719 (C₃₈H₈₆O₈N₈S₂Ru, Solaronix), platinum paste (Platisol, Solaronix), and electrolyte solution (Iodolyte Z-50, Solaronix).

Preparation of Jasmine flower extracts

Jasmine flower extract was prepared according to the literature [43] with slight modification. Fresh jasmine flowers obtained from a local market were washed and dried at room temperature. 20 g of fresh jasmine flowers were

weighed and ground using a household blender in four different solvent variations of 100 mL ethanol with 0%, 10%, 30%, and 50% acetylacetone. Acetylacetone was used as a chelating agent because previous work has shown that acetylacetone is involved in complexation with titanium precursors, influencing the growth, stability, and crystallinity of TiO₂ nanoparticles [59]. The mixture was then filtered to separate the insoluble residue from the solvent, and jasmine flower extracts were obtained. The extracts were ready for use in the green synthesis of TiO₂ NPs.

Green synthesis of tio₂ nanoparticles

The environmentally friendly synthesis of titanium dioxide was carried out using the sol-gel method [60] with slight modifications. Five beaker glasses were prepared, and 10 mL of TTIP was poured into each glass. Ten mL of ethanol was added dropwise to the first beaker glass (labelled as Eth), and 10 mL of jasmine flower extract, as described in the previous section, was added dropwise to the remaining beaker glasses, labelled as J0, J10, J30, and J50, respectively. The mixture was agitated for 3 h, then centrifuged and filtered. The obtained wet gel was dried at 100 °C for 1 h, followed by calcination at 450 °C for 2 h. The dry powders of green-synthesized TiO₂ NPs from jasmine flower extract with solvent variation concentrations were obtained.

Natural dye preparation

Natural dye was prepared by extracting kesumba seeds following the literature [39] with slight modification. Several ripe kesumba seeds obtained from the local market were opened, and the seeds were removed. A total of 20 g of kesumba seeds were put into a beaker and crushed before being added with 100 mL of ethanol to form a mixture. The mixture was agitated for 2 h under a magnetic stirrer before being filtered to remove the remaining solids. Kesumba natural dye with a deep red color was obtained and stored in a dark container for further use as a sensitizer.

Fabrication of solar cells

Solar cell fabrication was carried out according to our previous work [33] with slight modification. A total of 12 devices were prepared: six were sensitized using N719, and the other six were sensitized using kesumba natural dye. Two ITO conductive glass substrates with a dimension of 2.50 cm x 2.50 cm and a thickness of 0.12 cm were ultrasonically cleaned in acetone and ethanol for each solvent variation concentrations of Eth, J0, J10, J30, and J50, plus the one from commercial TiO₂ (labelled as TC). One of the ITO glass substrates was prepared as a counter electrode, and the

other as a working electrode. The fabrication process began with the preparation of the counter electrode. The conductive side of the ITO glass substrate was determined using a multimeter with an average surface area resistance of 9 Ω/cm². Two small perforations, approximately 1 mm in diameter each, were drilled at the diagonal corners of the ITO glass substrate for each variation. An area of 1 cm² was created by covering the undeposited area of the conductive ITO glass substrate with a thin plastic tape for the slurry deposition. Further, platinum paste was deposited using the doctor blade coating method. After removing the plastic cover, the coated counter electrode was heated at 400 °C for 30 min.

For the working electrode, a 1 mL NMP solution was heated to 60°C in an enclosed container for 30 minutes. 50 mg of PVDF powder was gradually added to the solution under constant low stirring. After PVDF was added to the solution, the stirring was increased to 1000 rpm for an additional 30 minutes. This mixture was used as a solution and binder for TiO₂ deposition [61]. To do this, 10 µL of the binder was emptied into a container from each variation while heating it at 60°C, before 90 mg of TiO₂ was added to form a mixture. The mixture was stirred for 2 hours, until a dark grayish slurry was obtained. The slurry was coated onto the uncovered conductive side of the ITO glass substrate using the same method applied for the counter electrode under the same area. After removing the plastic tape cover, the coated substrate was dried in an oven at 65°C for 2 hours. For the commercial sensitizer, a 0.8 mM N719 was prepared by dissolving 50 mg N719 in 50 mL of ethanol [62]. The already dried working electrode was immersed in the commercial solution or the sensitizer for 12 hours and air dried. The device sensitized using a natural dye was labeled with the addition of 'B' to the previous sample code.

After the two electrodes were prepared, they were assembled using epoxy sealant, separated by a polymer sheet, and left to cure for 24 h. The electrolyte I₂/I₃⁻ was then injected through one of the small perforations until the entire volume was filled. The two small perforations were then sealed using the same epoxy, and the device was ready for performance examination. The schematic of this DSSC fabrication sequence is provided in Figure S1, supplementary.

Results and discussion

Functional groups identification

The functional groups in a molecule can be identified by measuring the absorption of infrared radiation by the molecule and then using this information to determine the functional groups present in the molecule [63]. In this work, the infrared spectra were obtained to reveal the characteristics

of extracted jasmine flowers, kesumba seeds, and commercial dye N719 as a comparison, and the results are given in Fig. 1(a). To observe any effect of jasmine flower extract during the green synthesis, the infrared spectra of TiO₂ NPs obtained from the green synthesis were also collected, as shown in Fig. 1(b). Additionally, to identify the binding mode of the molecule on the semiconductor, the dye anchored on TiO₂ NPS is also presented as shown in Fig. 1(c) for the N719 dye-anchored TiO₂ and Fig. 1(d) for kesumba natural dye-anchored TiO₂.

As shown in Fig. 1(a), a broad and intense absorption is demonstrated by the extract of kesumba seed. Typical phenol compound with O-H group is observed at 3000–3600 cm⁻¹, typical of C=C group with aromatic compound ring is observed at 1570.12 cm⁻¹, typical of alkane compound with C-H stretching is observed at 1417.74 cm⁻¹, typical of alcohol compound with medium weak intensity C-O stretching is observed at 1069.57–1181.45 cm⁻¹, typical of alkene compound with C=C bending is observed at 751.31–872.83 cm⁻¹. The characteristic peaks of flavonoids are observed at 3366 cm⁻¹, 1650 cm⁻¹, and 679 cm⁻¹ [44,

48], which could indicate the presence of quercetin and related compounds. It is believed that the yellow colors in the jasmine flower extract could be due to hydroxy and methoxy derivatives of flavones and isoflavones [64, 65] and are believed to affect the crystal growth and formation during the green synthesis [66].

As for the jasmine flower extract, the kesumba seed extract shows several absorption bands. The presence of -OH group with a strong and broad absorption is observed at 3000–3600. This strong absorption is accompanied by the presence of C-H stretching, C=C stretching, and C-H bending vibrations observed at 2930, 1615, and 1383 cm⁻¹, respectively [37, 38]. Further, as has been shown in our previous work [33], the spectrum of commercial dye reveals the presence of the -OH and C-H groups at 3000–3600 and 2500–3000 cm⁻¹, respectively [67]. The presence of thiocyanate (NCS), carbonyl (C=O), bipyridine (C=C), tetrabutylammonium from carboxylic acid and carboxylate groups is observed at 2100, 1710, 1542, 1464, and 1256 cm⁻¹, respectively [68]. Other functional groups of C-N, C-O, aromatic

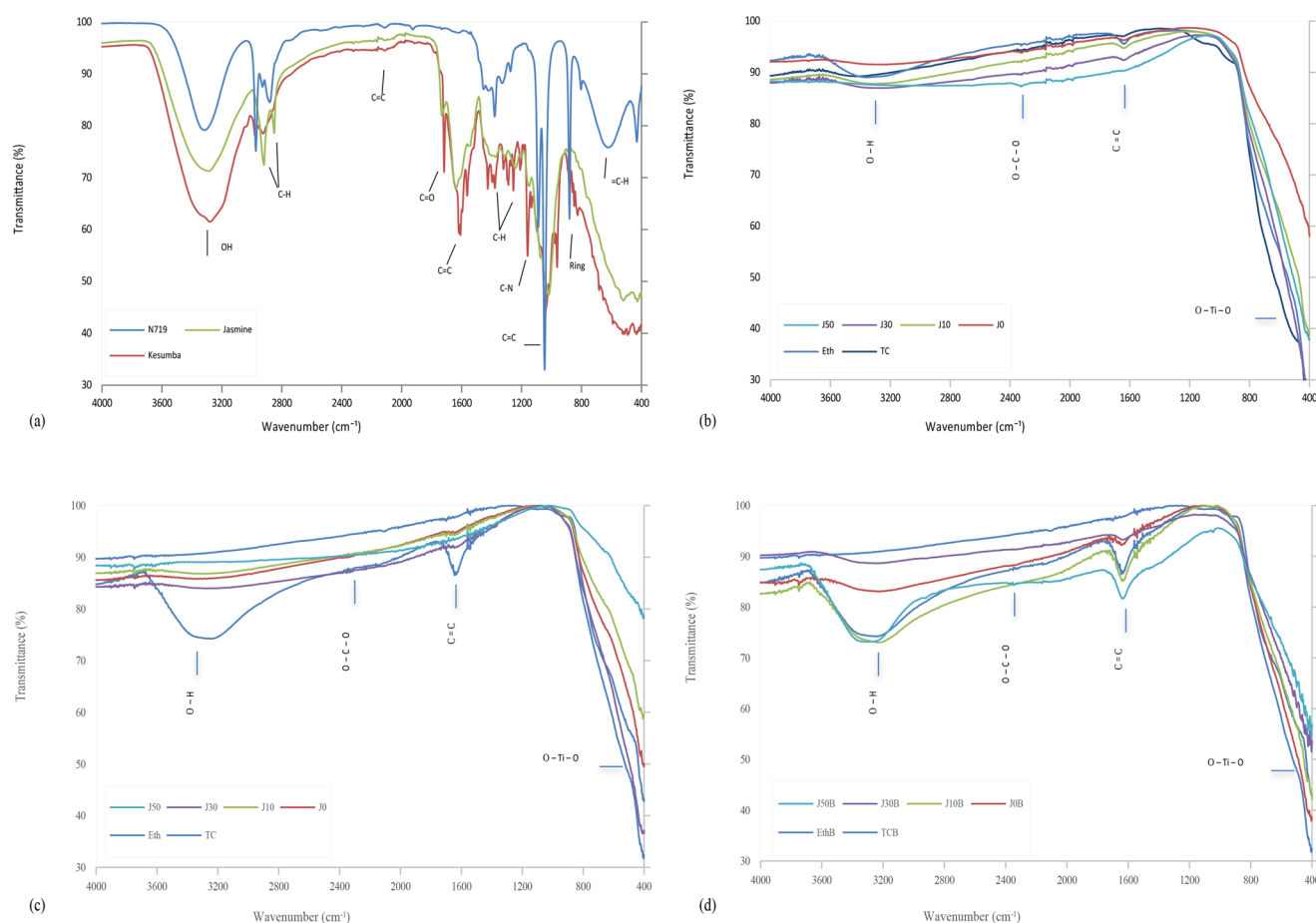


Fig. 1 Infrared spectra of (a) commercial dye N719, jasmine flower extract, natural dye from kesumba seed extract, (b) commercial TiO₂ (TC), TiO₂ NPs synthesized using ethanol only (Eth), and TiO₂ NPs

green-synthesized using jasmine flower extract with 0% (J0), 10% (J10), 30% (J30), and 50% (J50) acetylacetone, (c) N719 dye-anchored TiO₂ NPs, and (d) kesumba natural dye-anchored TiO₂ NPs

para ring, and =C-H with pronounced peaks are observed at 1087, 1046, 880, and 623 cm^{-1} , respectively [69].

The infrared spectra of TiO_2 NPs were recorded to investigate any effect of the green medium used during synthesis. As shown in Fig. 1(b), the presence of stretching vibrations of hydrogen-bonded water molecules and hydroxyl groups, bending vibrations of O-H group, and the Ti-O-Ti bridging stretching mode is detected at 3370, 1630, and 650 cm^{-1} , respectively [70], for commercial TiO_2 . The presence of OH groups is expected from the TiO_2 NPs interaction with environmental moisture [71, 72]. Similarly, the TiO_2 from the synthesis using pure ethanol (Eth) only shows the same characteristic as that of commercial TiO_2 . The same is true for the spectra of green-synthesized TiO_2 NPs prepared at different solvent variation concentrations of jasmine flower extracts, plus an additional very weak absorption at 2326 cm^{-1} , possibly due to the O-C-O linear vibrations from the green synthesis [33]. The presence of a certain amount of carbon in TiO_2 NPs may affect morphology, crystallinity, and bandgap energy, as reported by others [73, 74]. Similarly, the infrared spectra of dye-anchored TiO_2 NPs were collected to identify the binding mode of the molecule on the semiconductor. As shown in Fig. 1(c) for N719 dye-anchored TiO_2 NPs and Fig. 1(d) for kesumba natural dye-anchored TiO_2 NPs, the infrared spectra show the same characteristics as those of bare TiO_2 NPs. However, the dye-anchored TiO_2 NPs show a more pronounced absorption at the wavelength 3000–3600 cm^{-1} from stretching vibration of the OH group and C=C stretching at 1615 cm^{-1} . It is then concluded that these pronounced absorptions are due to the dye that is anchored on the TiO_2 NPs surface.

Optical characteristics

Optical properties such as absorption, complex refractive index, and transition are strongly dependent on the material's bandgap [75]. In this work, the optical characteristics of TiO_2 NPs were characterized using UV-Vis DRS, where the diffuse reflection of radiation in the ultraviolet to visible range of a sample is measured [76]. The results in the form of TiO_2 NPs reflectance spectra with solvent concentration variations and the one from commercial TiO_2 are provided in Figure S2, supplementary. These UV-Vis DRS spectra were further analyzed to reveal their optical characteristics by applying the Kubelka–Munk relation [77] expressed as in Eq. 1,

$$(F(R_\infty) \cdot h\nu)^{1/\gamma} = B(h\nu - E_g) \quad (1)$$

where h is the Planck constant, ν is the photon's frequency, E_g is the band gap energy, $F(R_\infty)$ is the Kubelka–Munk function, and B is a constant. The nature of the allowed

electron transitions will affect the γ factor: the γ value will be equal to $\frac{1}{2}$ for a direct transition and equal to 2 for an indirect transition. In this instance, the left exponent in Eq. 1 will be equal to 2 for a direct transition and equal to $\frac{1}{2}$ for an indirect transition. Further, the Kubelka–Munk function, $F(R_\infty)$, is expressed as in Eq. 2,

$$F(R_\infty) = \frac{(1 - R_\infty)^2}{2R_\infty} \quad (2)$$

In this expression, R_∞ is the reflectance from the UV-DRS examination. The bandgap energy was further determined by first fitting the data in Tauc plot $(F(R_\infty) \cdot hc/\lambda)^{1/\gamma}$ vs. hc/λ with the assumption that the sample has an indirect allowed transition bandgap energy [78], and the results are provided in Fig. 2. By extrapolating the linear part of the Tauc plot to the intersection point of the x-axis, an estimated value of the band gap energy for each TiO_2 NPs was obtained.

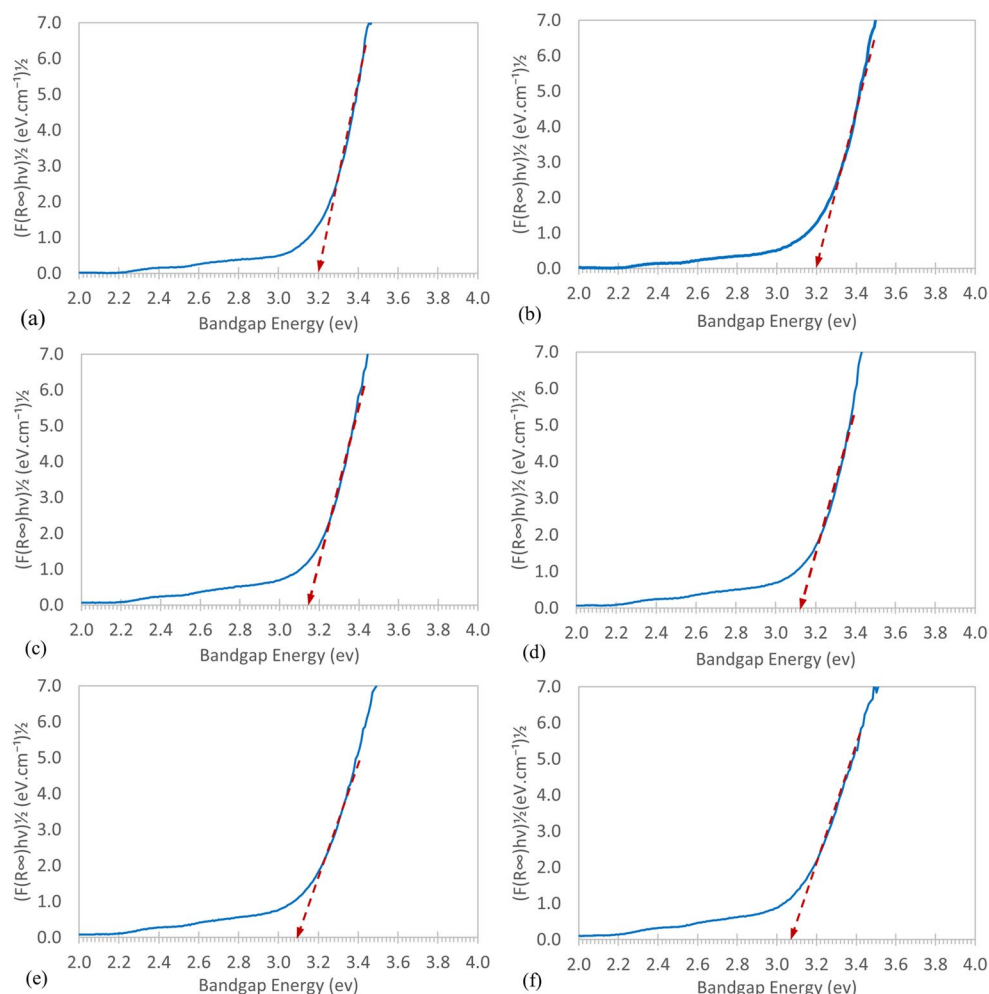
The bandgap energy for commercial TiO_2 (TC) and the one synthesized using ethanol only (Eth) is 3.2 eV, consistent with our previous results [33] and the results obtained by others [77]. The bandgap energy of TiO_2 NPs green-synthesized using jasmine flower extract only, jasmine flower extract with 10%, 30%, and 50% acetylacetone is 3.14, 3.12, 3.09, and 3.07 eV, respectively. The decrease in bandgap energy from 3.2 eV to 3.14 eV for the TiO_2 NPs synthesized using ethanol only and those containing green medium demonstrates the effect of the green medium on the optical characteristics of TiO_2 NPs. The same is true for the use of acetylacetone as a chelating agent, with a shift from 3.14 eV to 3.07 eV. It can then be summarized that, indeed, the use of jasmine flower extract and acetylacetone decreases the bandgap energy and hence confirms the function of jasmine flower extract as a capping agent [42, 79] and acetylacetone as a chelating agent [80].

Composition and surface morphology

Surface morphology is one of the factors that determines the conditions for reaction, adsorption, and diffusion, and information on the surface layer composition allows estimating the stability of the properties of the support upon contact with other active components [81]. A field emission scanning electron microscope (FESEM) equipped with energy dispersive X-ray spectroscopy (EDX) was used to elucidate the surface morphology and composition of the green-synthesized TiO_2 NPs, respectively. The results of the elemental composition characterized using EDX are provided in Fig. 3, whereas the surface morphology of all TiO_2 NPs is given in Fig. 4.

The elemental composition examination reveals that, as can be seen in Fig. 3, the prominent peaks of titanium (Ti)

Fig. 2 Tauc plots for bandgap energy determination of (a) commercial TiO_2 , (b) TiO_2 synthesized using ethanol only, and TiO_2 NPs green-synthesized using jasmine flower extract with (c) 0%, (d) 10%, (e) 30%, and (f) 50% acetylacetone



and oxygen (O) are established in the EDX spectra. The composition of titanium ranges from 65 to 68 wt%, whereas oxygen ranges from 32 to 35 wt%, which confirms the successful green synthesis of TiO_2 NPs using jasmine flower extract as a green medium and capping agent [82–84]. Preceding FESEM characterization, all TiO_2 NPs were coated using Au/Pd alloy because of their low conductivity. This Au/Pd coating is confirmed as unlabeled peaks detected around 2 keV in the EDX spectra.

For the surface morphology, as can be seen in Fig. 4, the electron image of commercial TiO_2 (TC) shows sphere-like particles in an agglomerated manner but with a homogeneous average particle size of around 150 nm, as confirmed by transmission electron image in Fig. 5 (a). For the regular synthesis using ethanol only (Eth), the round shapes are maintained with a homogeneous particle size. With the addition of jasmine flower extract as a medium in the green synthesis, as can be seen in Fig. 4 (c), the round shape particles remain, but with a particle size smaller than that of TiO_2 synthesized using ethanol only. However, with the addition

of acetylacetone, there is a tendency to form agglomeration and make the particle size larger.

The characteristics of particle size, influenced by varying media concentrations during the green synthesis, were further elucidated using high-resolution transmission electron microscopy (HRTEM) and selected area electron diffraction (SAED) patterns. These two techniques enable direct visualization of atomic structures within a sample, providing detailed information about the crystal structure, morphology, defects, and other nanoscale features. Transmission electron images for commercial TiO_2 and the one synthesized using ethanol only are given in Fig. 5 (a) and (b), whereas transmission electron images for TiO_2 NPs obtained from the green synthesis represented by samples J0 and J50 only are given in Fig. 5 (c) and (d), respectively.

The spacing between the crystal planes was further analyzed using the ImageJ software [85]. The crystal plane spacing for commercial TiO_2 (TC), the one synthesized using ethanol only (Eth), and those green-synthesized using jasmine flower extract represented by sample J0 and J50 only was obtained to be 0.5091 nm, 0.3418 nm, 0.3427 nm,

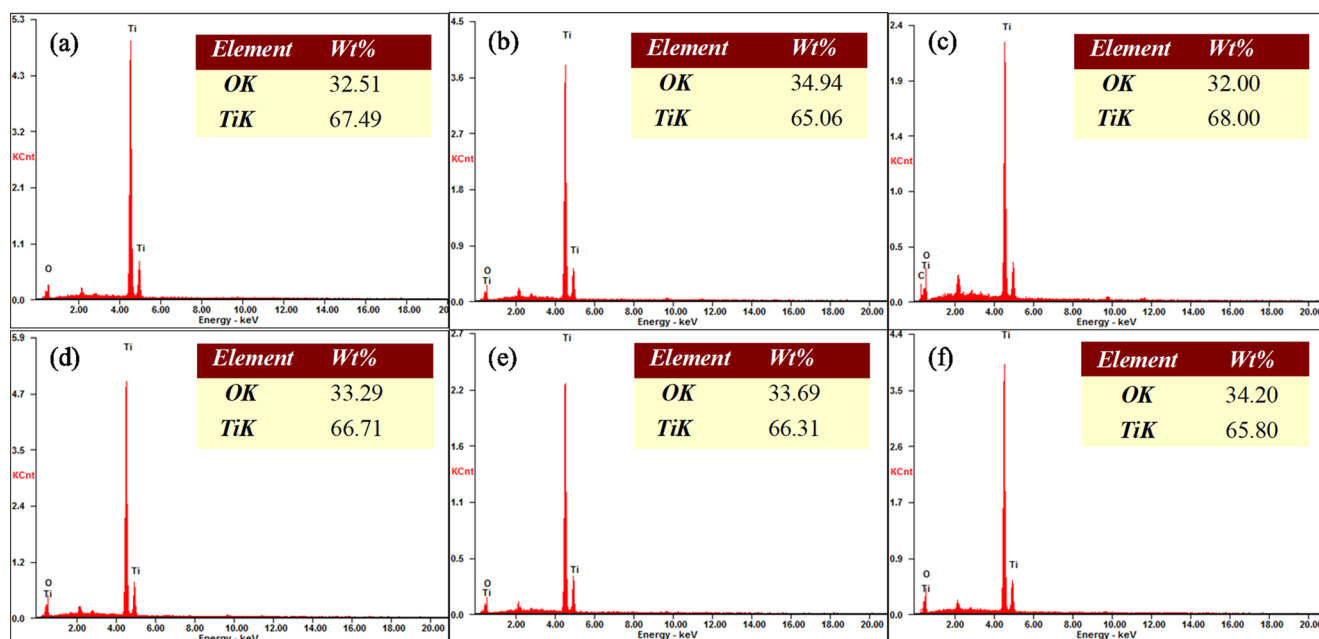
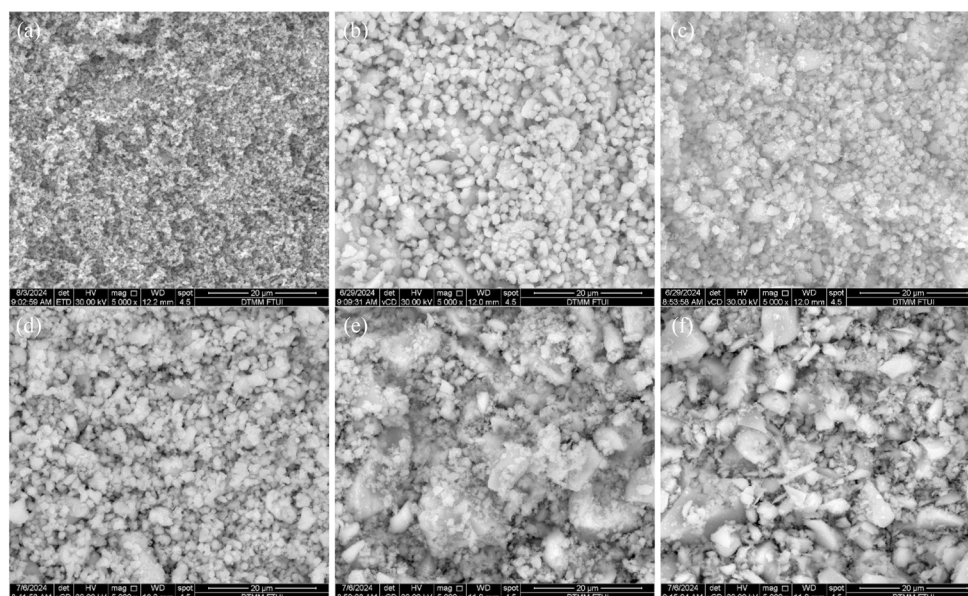


Fig. 3 Energy dispersive X-ray spectra of (a) commercial TiO₂ NPs, (b) TiO₂ synthesized using ethanol only, and TiO₂ NPs green-synthesized using jasmine flower extract with (c) 0%, (d) 10%, (e) 30%, and (f) 50% acetylacetone. Elemental compositions are given in the inset figure

Fig. 4 Electron images of TiO₂ NPs (a) commercial, (b) synthesized using ethanol only, (c) synthesized using jasmine flower extracts with 0%, (d) 10%, (e) 30%, and (f) 50% acetylacetone



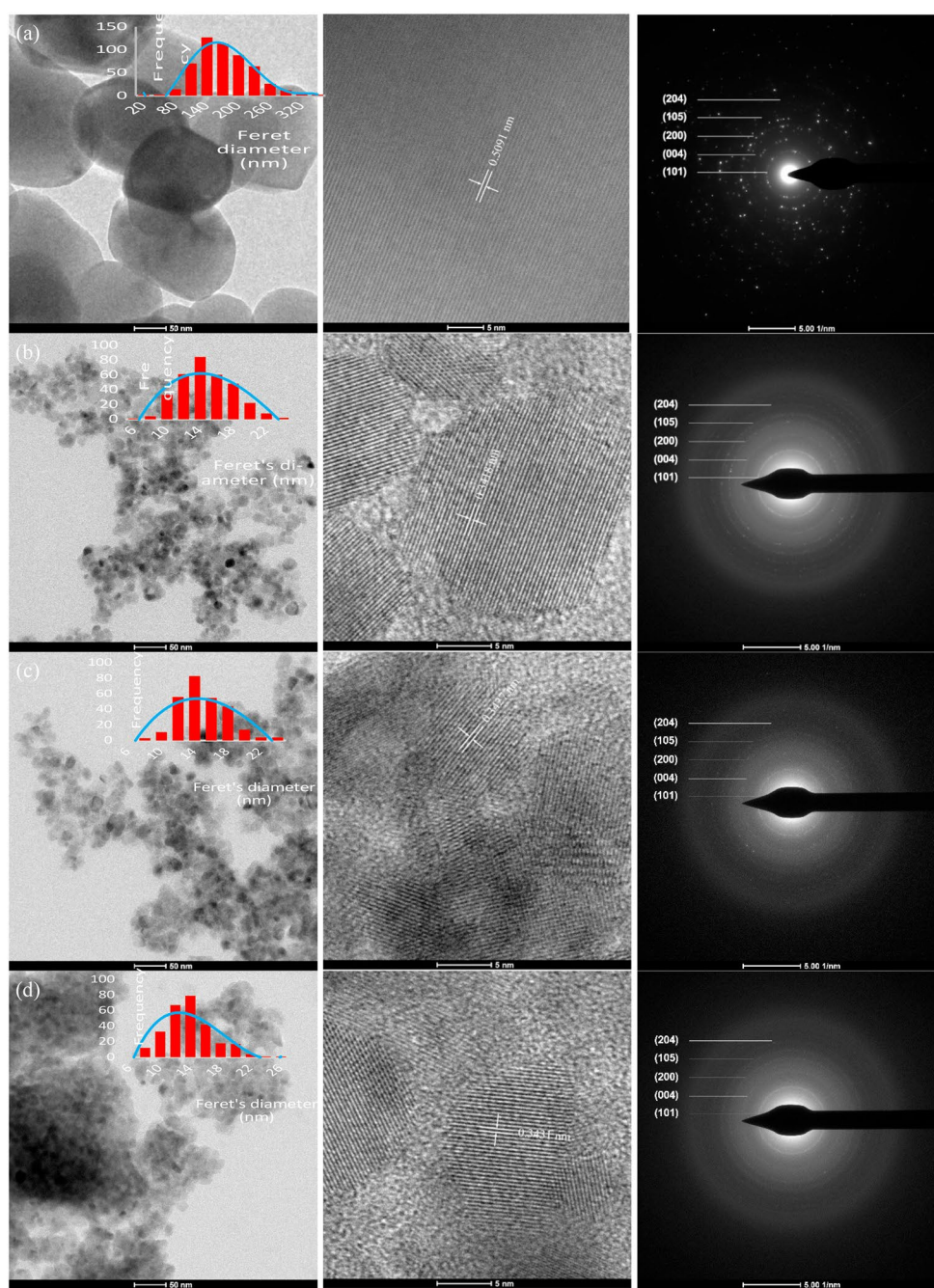
and 0.3431 nm, respectively, which are consistent with the results from X-ray diffraction. The homogeneous shape and small size of NPs are highly beneficial for photovoltaic activity: a smaller grain size results in a larger surface area, facilitating better interaction with photons. In this work, it is confirmed that, in the absence of a green medium, the formation of TiO₂ is primarily controlled by hydrolysis and condensation reactions [86]. In the presence of green medium, however, there will be another factor that controls the growth of TiO₂ NPs during the green synthesis, one of which is the presence of active contents in the jasmine

flower extract. The exact active contents, however, have yet to be further confirmed.

Crystallographic properties

X-ray diffraction is a powerful method for determining the crystallographic properties of a material. In this work, the crystallographic properties of TiO₂ NPs obtained from the green synthesis prepared at different concentrations of jasmine extracts, plus the one from commercial TiO₂ as a comparison, were examined using powder X-ray diffraction, and

Fig. 5 Transmission electron images with particle size distribution (left), HRTEM with lattice fringe (middle), and SAED pattern (right) of TiO₂ (a) commercial, (b) synthesized using ethanol only, and (c) and (d) green-synthesized using jasmine flower extract represented by sample J0 and J50 only



the results are given in Fig. 6. The diffractogram of commercial TiO₂ shows very sharp peaks around 25.3°, 38.4°, 48.1°, 55.0°, 62.6°, 68.7°, 74° corresponding to the (101), (004), (200), (211), (204), (116) and (215) planes, respectively, with no other impurities detected. These peaks belong to the tetragonal anatase phase with space group $I4_1/amd$ (ICSD 98-000-9853). All TiO₂ NPs diffractograms from the green synthesis also reveal the same prominent peaks as the commercial TiO₂ (ICSD 98-015-4604) with no other phase detected. For the one synthesized using ethanol only, a small amount of impurity was detected at around 19.3° and 30.8°

due to the presence of brookite phase (ICSD 98-015-4605) [33, 87]. These findings are in line with our previous works and the results obtained by others [88–90].

As can be seen from the X-ray diffractograms, the peaks from each solvent variation concentration reveal a highly crystalline nature of the structure, as indicated by sharp and intense peaks. Additionally, no new peaks are detected, indicating the formation of a pure anatase phase with the use of jasmine flower extract. In this instant, the use of green medium has not disrupted the crystallographic formation of TiO₂ NPs during the green synthesis. However, as shown in

Fig. 6 Superimposed X-ray diffractograms of commercial TiO₂ (TC), TiO₂ NPs synthesized using ethanol only (Eth), TiO₂ synthesized using jasmine flower extract only (J0), TiO₂ green-synthesized using jasmine flower extract with 10% (J10), 30% (J30), and 50% (J50) acetylacetone. The arrows indicate the formation of the brookite phase

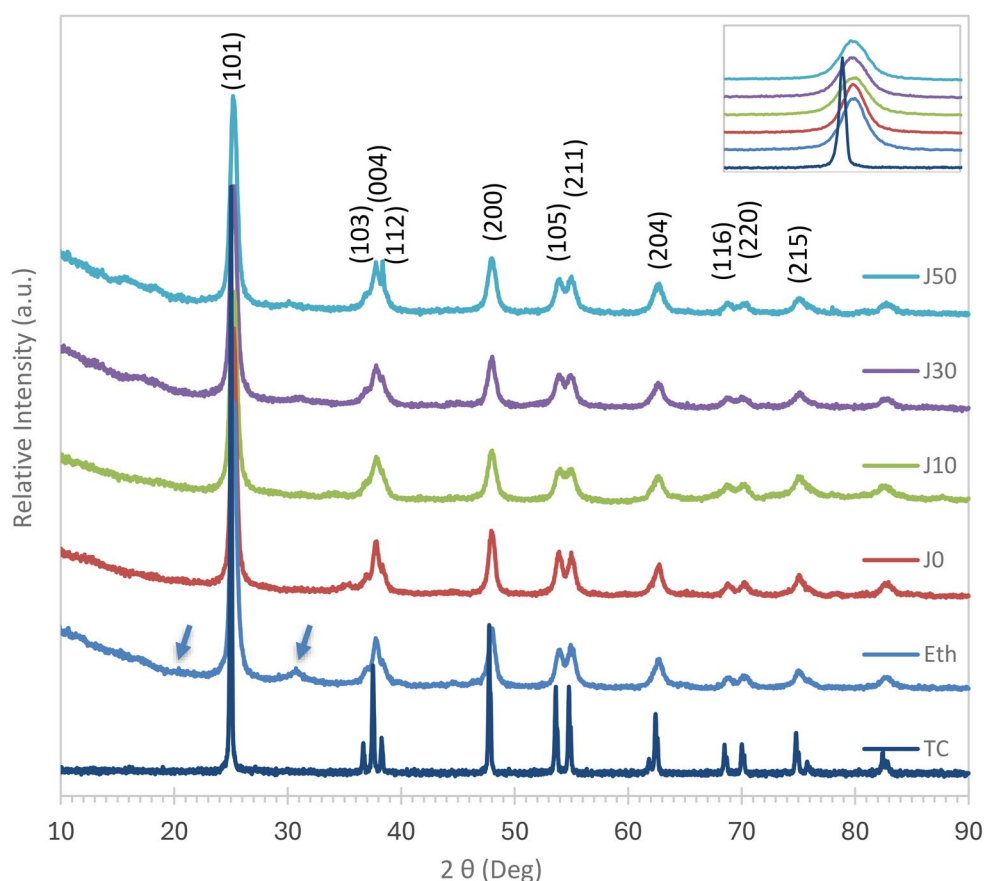


Table 1 Lattice parameters of the refined phase in each TiO₂ NPs green-synthesized using Jasmine flower extract and the one from commercial TiO₂

Sample	Lattice parameter			Goodness of fit (χ^2)	Crystallite size (nm)
	a (Å)	c (Å)	V (Å) ³		
TC	3.7840(2)	9.5115(7)	136.1905	1.05	96.46(0.00)
Eth	3.7858(5)	9.4990(2)	136.1514	1.96	11.76(0.70)
J0	3.7854(4)	9.5020(1)	136.1496	2.13	11.87(0.03)
J10	3.7880(6)	9.4970(2)	136.2730	2.39	9.41(0.79)
J30	3.7920(3)	9.5160(6)	136.8337	2.31	9.69(0.37)
J50	3.7840(5)	9.4940(1)	135.9393	2.33	9.53(0.20)

the plane (101) of the inset Fig. 6, a slight shift of the peaks is observed in all the green-synthesized TiO₂ NPs to a higher angle compared to commercial TiO₂. This shift is attributed to crystallite size and lattice strain, which affect the Bragg peak by increasing the peak width and intensity, and shifting the peak angle accordingly [91], as also observed in our previous work [33].

To further deepen our understanding of the effect of solvent variation on the concentrations of the green medium on the crystallographic properties of TiO₂ NPs, Rietveld analysis was performed using Highscore Plus [92, 93] on all TiO₂ NPs diffractograms. The results in the form of lattice constants and the goodness of fit (χ^2) after Rietveld analysis are

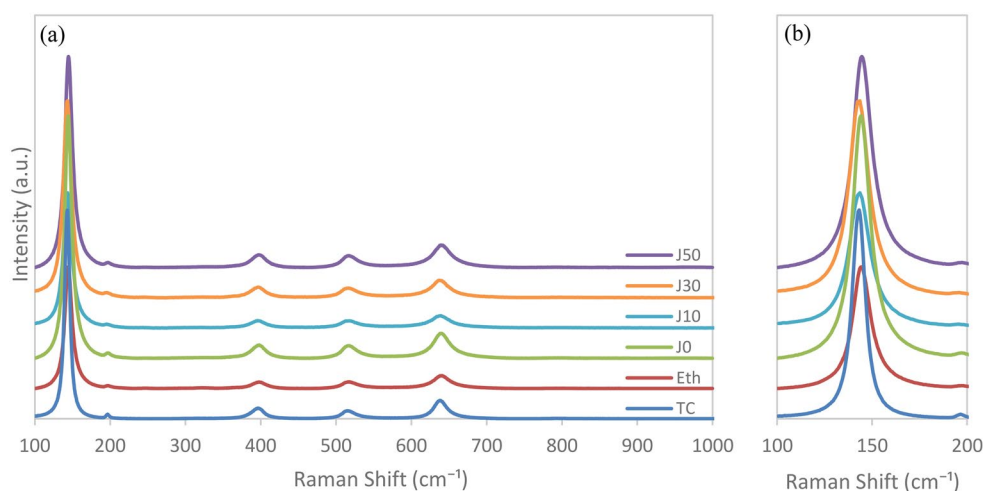
given in Table 1. As can be seen from the analysis results, there is almost no difference in the lattice parameters and thus in the unit cells after refinement due to the green medium. There is a significant difference in crystallite size between green-synthesized TiO₂ NPs and commercial TiO₂, with a p-value of 0.0089, analyzed using one-way analysis of variance in MatLAB[®]. However, in this work, the crystallite size of the synthesized TiO₂ NPs is independent of the treatment.

Raman spectroscopy

Raman spectroscopy is a versatile technique for obtaining detailed information on chemical structures. In this work, Raman spectroscopy was employed to examine the chemical structure of TiO₂ NPs further and to confirm the characterization results obtained from X-ray diffraction. The Raman spectra of TiO₂ NPs obtained from the one synthesized using ethanol only and those from the green synthesis with solvent variation concentrations are given in Fig. 7. The Raman spectra of commercial TiO₂ (TC) are also provided for comparison.

The spectrum of commercial TiO₂ shows a strong characteristic of the anatase phase with no other phases detected. These characteristics are indicated by the peaks centering

Fig. 7 (a) Raman spectra of TiO₂ commercial (TC), synthesized using ethanol only (Eth), green-synthesized using jasmine flower extract only (J0), synthesized using jasmine flower extract with 10% (J10), 30% (J30), and 50% (J50) acetylacetone at 1000–100 cm⁻¹. (b) The region zoomed at 200–100 cm⁻¹



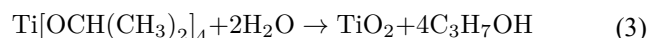
at 143 cm⁻¹, 197 cm⁻¹, 396 cm⁻¹, 514 cm⁻¹, and 637 cm⁻¹, which are attributed to the anatase phase [41, 94, 95]. It can then be confirmed that the commercial TiO₂ contains 100% anatase. The spectrum of sample TiO₂ NPs synthesized using ethanol only (Eth) reveals that it has the same characteristics as the commercial TiO₂. The characteristics of a small brookite phase detected by XRD analysis mentioned in the previous section are confirmed by a weak peak at around 326 cm⁻¹ [96]. All Raman spectra of TiO₂ NPs obtained from the green synthesis follow the same trend as the commercial TiO₂ and are present in the pure anatase phase. A slight blue shift, however, is detected as indicated by the corresponding five characteristics with the principal peak locating around 144 cm⁻¹ and other peaks at 197–199 cm⁻¹, 397 cm⁻¹, 516 cm⁻¹ and 638 cm⁻¹. This blue shift is attributed to a decrease in the particle size, as reported in other previous works [33, 97]. All the characteristics obtained from these Raman spectra agree with those revealed by the earlier X-ray diffraction examinations, as shown in Fig. 6.

Green synthesis mechanism

As previously stated, in the absence of a green medium during synthesis, the formation and growth of TiO₂ NPs are controlled solely by hydrolysis and condensation reactions. In the presence of jasmine flower extract, however, other factors influence the formation and growth of TiO₂ NPs, namely the active chemical components of the jasmine flower extract. It has been known that green synthesis based on biological precursors is affected by various reaction parameters such as solvent, temperature, pressure, and solvent conditions such as acidic, basic, or neutral [98]. Furthermore, for the synthesis of metal oxide nanoparticles, plant biodiversity has been broadly considered due to the availability of effective phytochemicals in the plant extracts, such as ketones, aldehydes, flavones, amides, terpenoids, carboxylic acids, phenols, and ascorbic acids that are capable of reducing metal salts into

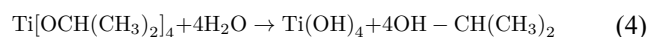
metal nanoparticles [99]. Therefore, to better understand the mechanism behind the green synthesis of TiO₂ NPs, a proposed formation mechanism is necessary based on the hydrolysis reaction in the presence of jasmine flower extract as a green medium. In this work, the formation of TiO₂ NPs involves several reaction steps, which are initiated by the formation of titanium hydroxide species. This reaction is followed by the reduction of titanium due to the presence of active chemical components in the jasmine flower extract. The final step establishes nucleation and growth, followed by growth control and stabilization. The steps are schematically provided in the following mechanisms.

With no green medium, the formation of TiO₂ is merely controlled by hydrolysis and condensation reactions [100]:

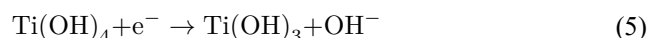


During the green synthesis, the active components in the jasmine flower extract play a role in controlling the growth of TiO₂ NPs. In this instant, the reduction of TTIP to TiO₂ involved several reaction steps [101]:

1. Formation of titanium hydroxide species:



2. Reduction of titanium precursor:

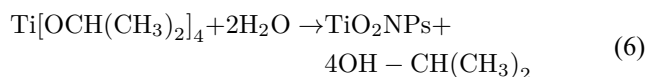


3. Nucleation and growth:

During nucleation and growth, the reduced titanium species form nuclei and subsequently grow into TiO₂ NPs, involving a series of redox reactions that involve taking oxygen from the surrounding environment.

4. Growth control and stabilization:

During this step, the active compounds in the jasmine flower extract can be adsorbed onto the surface of the forming TiO₂ NPs, which will, in turn, control and stabilize the formation of TiO₂ NPs by preventing agglomeration and providing surface modifications. In the last step, the overall formation of TiO₂ NPs can then be summarized as:



Electrochemical characteristics

Electrochemical impedance spectroscopy is a valuable technique for characterizing solar cells, as it enables the examination of their characteristics under various conditions and material components [102]. In this work, the electrochemical characteristics of the DSSC device were examined using EIS under room light conditions, and the results, in the form of Nyquist and Bode imaginary plots, are shown in Fig. 8. As can be seen in the figure, the electrochemical characteristics of all DSSC devices exhibit a similar semicircle, representing the interface resistance of electrons, but with varying values indicated by the differences in the semicircle radius. A semicircle radius in a Nyquist plot indicates a charge transfer resistance [103, 104].

For the DSSC device sensitized using the commercial N719 dye, the smallest semicircle radius in ascending order is given by sample Eth, followed by samples J50,

J30, J0, J0, and TC. For the device sensitized using natural dye extracted from kesumba seeds, in ascending order, the smallest semicircle radius is given by sample EthB, followed by samples TCB, J10B, J30B, J0B, and J50B. The impedance spectra can be interpreted and modeled using equivalent circuits, with each component explained below. Each equivalent circuit consisted of several components, as shown in the inset of Fig. 8(a). Ohmic resistance (R_1), charge transfer resistance at the counter-electrode/electrolyte (R_2), charge transfer resistance at the photoelectrode/electrolyte (R_3), resistance at the Warburg (W_s) diffusion of the redox I^-/I_3 couple in electrolyte (W_s), the constant phase element of capacitance corresponding to R_1 (C_1), and the constant phase element of capacitance corresponding to R_2 (C_2). The electrochemical parameters of the DSSC device measured under room light conditions are summarized in Table 2. However, these electrochemical characteristics do not necessarily have a linear relationship with the obtained power conversion efficiency, as shown by the photovoltaic activities in the next section. As for the Nyquist plots, the same trends can be observed in the Bode imaginary plots, which represent the imaginary parts of the impedance as a function of frequency. The Bode imaginary plots reveal that the peaks related to the recombination processes at the TiO₂/electrolyte interface [105, 106] shift toward higher frequencies.

Photovoltaic performance

The characteristics of TiO₂ NPs as a photoanode in the DSSC device were characterized using a source meter equipped

Fig. 8 Impedance spectra of the DSSC device measured under room light conditions with Nyquist representation (a, b) and Bode imaginary plots (c, d) of the devices sensitized using commercial dye N719 (left) and kesumba seed extract (right)

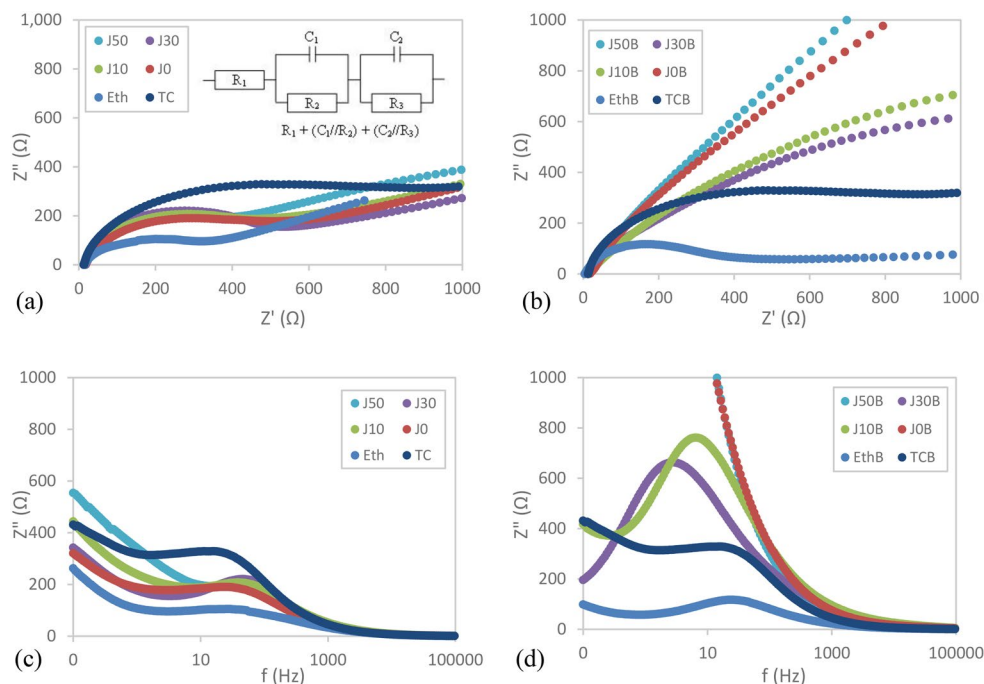
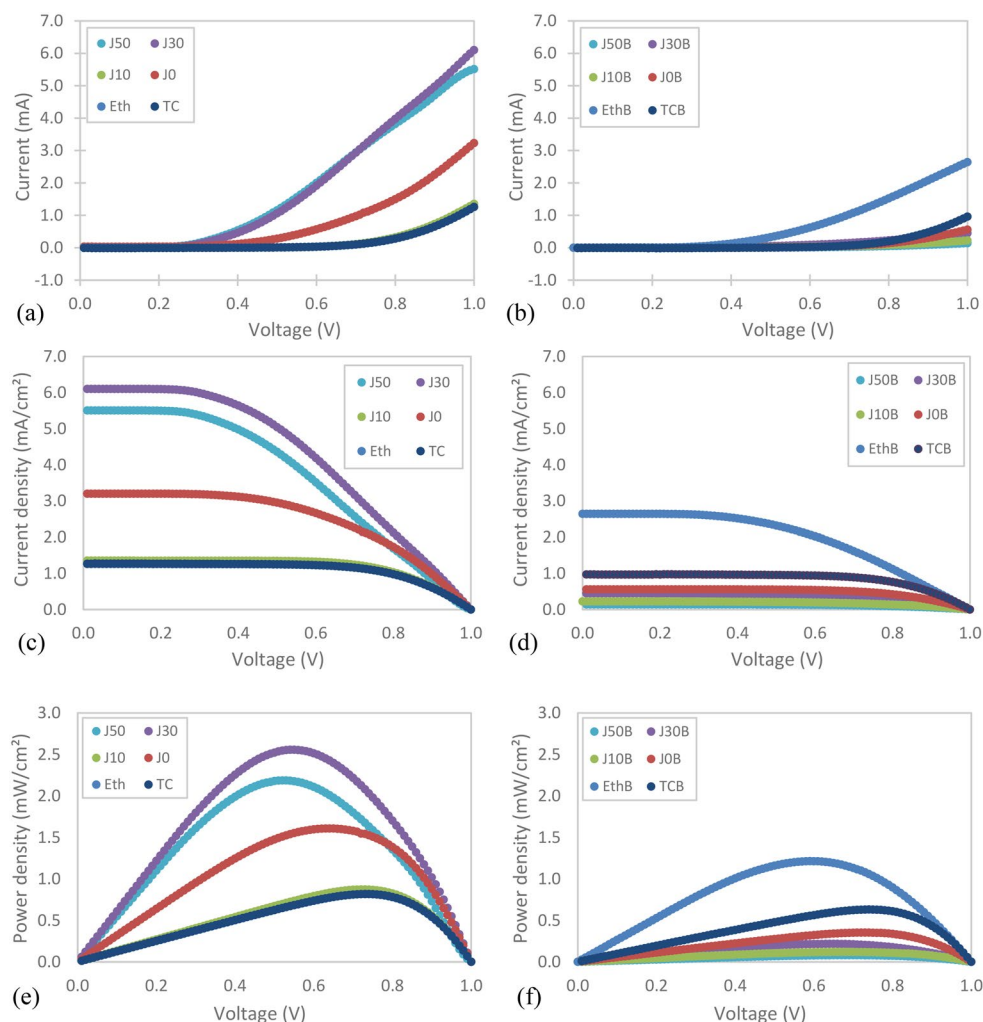


Table 2 Electrochemical parameters of the DSSC device measured under room light conditions

Sample	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)	W_s (Ω)	Sample	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)	W_s (Ω)
TC	13	350	898	276	TCB	14	450	1201	329
Eth	16	180	420	383	EthB	4	125	342	1077
J0	18	250	571	374	J0B	19	2500	7800	1462
J10	16	150	567	512	J10B	17	900	2322	1211
J30	15	200	553	419	J30B	13	1500	2640	137
J50	17	150	491	553	J50B	16	5500	11,900	2603

Fig. 9 I–V characteristic (a), current density (b), and power density (c) curves of the DSSC devices fabricated using TiO_2 obtained from the green synthesis and the commercial TiO_2 . All DSSC devices sensitized using natural dye are symbolized with the addition of letter B



with a solar simulator to reveal their photovoltaic activity under a standard illumination of 100 mW/cm^2 . The characterization results in the form of I–V characteristic, current density (J–V), and power density (P–V) curves are given in Fig. 9(a), (b), and (c), respectively, and were further examined to calculate the power conversion efficiencies (PCE) of the DSSC device. The summary of these performance characteristics is presented in detail in Table 3.

The device fabricated from commercial TiO_2 (TC) and sensitized using the commercial dye N719 has a PCE of 0.80%, while the one sensitized using a natural dye from kesumba seed extract has a PCE of 1.22%. For the device

fabricated from TiO_2 NPs obtained via regular synthesis with no green medium and sensitized using the commercial dye, the PCE is 0.80%, whereas the device sensitized using kesumba seed extract yields a PCE of 0.63%. For the DSSC device fabricated using TiO_2 NPs obtained from the green synthesis, the PCE value is consistently larger than the PCE value from commercial TiO_2 and from the one synthesized using ethanol only. The best performance in terms of the highest PCE is given by TiO_2 NPs green-synthesized using jasmine flowers extracted in the presence of 30% acetylacetone with a PCE value of 2.52%.

Table 3 Performance of the DSSC device sensitized using commercial N719 and Kesumba natural dye. The DSSC device sensitized using Kesumba natural dye is symbolized with the addition of the letter B

Sample	J_{SC} (mA/cm ²)	I_{Max} (mA/cm ²)	V_{Max} (V)	FF	η (%)
TC	1.27	1.18	0.68	0.63	0.80
TCB	2.65	2.10	0.58	0.46	1.22
Eth	1.26	1.19	0.67	0.63	0.80
EthB	1.00	0.85	0.74	0.63	0.63
J0	3.40	2.50	0.64	0.47	1.60
J0B	0.56	0.45	0.78	0.63	0.35
J10	1.35	1.24	0.70	0.64	0.87
J10B	0.22	0.18	0.68	0.56	0.12
J30	6.20	4.50	0.56	0.41	2.52
J30B	0.44	0.32	0.68	0.49	0.22
J50	5.00	4.50	0.48	0.43	2.16
J50B	0.14	0.12	0.64	0.55	0.08

As shown in Table 3, the green medium alone is able to increase the PCE from 0.80% (Eth) to 1.60% (J0). However, with the addition of acetylacetone, the PCE decreases to 0.87% (J10). The PCE value is then increased with the addition of more acetylacetone, reaching 2.52% (J30), but subsequently decreases to 2.16% (J50). Hence, in this work, the optimal chelating agent concentration for the green synthesis of TiO₂ NPs in DSSC devices sensitized with N719 was found to be 50% acetylacetone. On the contrary, the device sensitized using a natural dye extracted from kesumba seeds exhibits opposite trends, where the PCE value decreases with the addition of acetylacetone in the green medium. In this instance, it seems that the use of acetylacetone in the green synthesis has a detrimental effect on the natural dye of kesumba seeds. It is expected that the natural dye stability and deposition consistency might have affected the PCE results [87]. Further work, however, has yet to be carried out on this difference.

The PCE value obtained in this work is still relatively low, however, the current PCE values are better than those of our other work from TiO₂ NPs green-synthesized using mango-steen pericarps extract (2.46%) [107] and some PCE values obtained by other groups. For example, the work of Arifin et al. resulted in a PCE value of 1.29% [67], Jeganathan et al. obtained a PCE value of 1.32% [108], whereas Sadikin obtained a PCE value of 1.47% [109]. The work of Hossain et al. [110] revealed a PCE value of 0.33, while Pavithra et al. [111] obtained PCE values of 0.0182%, 0.0019%, and 0.0039% for pristine, flower, and seed of *Calotropis gigantea* extracts mediated green-synthesized TiO₂, respectively. Some works from other investigators obtained better PCE values, such as the work of Sharma et al., who obtained a PCE value of 4.81% [112] and Patil et al., who obtained a PCE value of 4.43% [113]. Nevertheless, the current results in utilizing natural plant extracts as media in an eco-friendly method for synthesizing nanomaterials are

promising. Furthermore, although the use of acetylacetone has a detrimental effect on the natural dye of kesumba seeds as a sensitizer, the use of natural dye for the development of environmentally friendly new derivative dyes, specifically for future sustainability, remains promising. The future of green synthesis aligns with the global push for sustainable and eco-friendly technologies because the green synthesis methods use natural reducing and capping agents, which eliminate the need for toxic chemicals, making the process safer for both the environment and human health [114]. In terms of their application, the future of DSSCs may depend on their integration into wearable electronics, smart windows, and indoor energy harvesting, where their ability to function in low-light conditions gives them an edge over traditional solar cells [115].

Conclusion

The jasmine flowers, extracted using different concentrations of ethanol containing 0, 10, 30, and 50% acetylacetone, were successfully used as a green medium in green-synthesizing TiO₂ NPs. In general, the optical characteristics, such as bandgap energy, decrease with the use of green media and chelating agents. The same is true for crystallite size. The obtained TiO₂ NPs were further successfully used as semiconductors in dye-sensitized solar cell devices sensitized using both natural dyes extracted from kesumba seeds and commercial N719. The highest efficiency of 2.52% was obtained from the TiO₂ NPs green-synthesized using jasmine flowers extracted under 30% acetylacetone, followed by TiO₂ NPs green-synthesized using jasmine flowers extracted under 50% acetylacetone (2.16%). The use of acetylacetone as a chelating agent, in this work, has a detrimental effect on natural sensitizers from the kesumba seed extract. Nevertheless, the use of a natural sensitizer from kesumba seeds improves the PCE of commercial TiO₂ as compared to the commercial dye (0.80% vs. 1.22%). These findings are promising for green-synthesizing nanomaterials and the use of natural dyes in the environmentally friendly development of DSSC devices.

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investigation and data curation. Mouna M'rad: investigation and data curation. Akhmad H. Yuwono: writing– review and editing. Donanta Dhaneswara: writing– review and editing. Bambang Priyono: writing– review and editing. Jeffrey W. Fergus: formal analysis, validation, writing– review and editing.

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Data availability Data will be made available upon request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. K., Sharma, V., Sharma, S.S.: Dye-Sensitized solar cells: Fundamentals and current status. Springer New York LLC. (2018). <https://doi.org/10.1186/s11671-018-2760-6>
2. S., Rahman, et al.: Research on dye sensitized solar cells: Recent advancement toward the various constituents of dye sensitized solar cells for efficiency enhancement and future prospects. *Jun. 28* (2023). Royal Society of Chemistry [10.1039/d3ra00903c](https://doi.org/10.1039/d3ra00903c)
3. M., Aftabuzzaman, S., Sarker, C., Lu, Kim, H.K.: In-depth understanding of the energy loss and efficiency limit of dye-sensitized solar cells under outdoor and indoor conditions, *J Mater Chem A Mater. 9*(44). 24830–24848, Nov. (2021). <https://doi.org/10.1039/d1ta03309c>
4. A., Błaszczyk, K., Joachimiak-Lechman, S., Sady, T., Tański, M., Szindler, Drygala, A.: Environmental performance of dye-sensitized solar cells based on natural dyes. *Sol. Energy. 215*, 346–355 (2021). <https://doi.org/10.1016/j.solener.2020.12.040>
5. N.A., Karim, U., Mehmood, H.F., Zahid, Asif, T.: Nanostructured photoanode and counter electrode materials for efficient Dye-Sensitized Solar Cells (DSSCs), *Jun. 01*, 2019, Elsevier Ltd. <https://doi.org/10.1016/j.solener.2019.04.057>
6. L.K., Tyas, R., Suryana, F., Nurosyid, Ilahi, N.A.: Comparison of Titanium Dioxide (TiO₂) nanoparticle-nanofiber and nanofiber-nanoparticle on the application of dye-sensitized solar cell (DSSC), in *Journal of Physics: Conference Series*, Institute of Physics Publishing, Feb. (2017). <https://doi.org/10.1088/1742-6596/795/1/012019>
7. A., Drygala: Influence of TiO₂ film thickness on photovoltaic properties of dye-sensitized solar cells, in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Feb. (2021). <https://doi.org/10.1088/1755-1315/642/1/012001>
8. A., Roy, S., Mukhopadhyay, P.S., Devi, Sundaram, S.: Poly-aniline-Layered Rutile TiO₂ Nanorods as Alternative Photoanode in Dye-Sensitized Solar Cells, *ACS Omega*, vol. 4, no. 1, pp. 1130–1138, Jan. (2019). <https://doi.org/10.1021/acsomega.8b02628>
9. X., Yan, L., Feng, J., Jia, X., Zhou, Lin, Y.: Controllable synthesis of anatase TiO₂ crystals for high-performance dye-sensitized solar cells. *J. Mater. Chem. Mater. 1*(17), 5347–5352 (May 2013). <https://doi.org/10.1039/c3ta01621h>
10. G., Zerjav, K., Zizek, J., Zavasnik, Pintar, A.: Brookite vs. rutile vs. anatase: What's behind their various photocatalytic activities? *J. Environ. Chem. Eng. 10*(3) (Jun. 2022). <https://doi.org/10.1016/j.jece.2022.107722>
11. S., Saraf, et al.: Photoelectrochemical analysis of band gap modulated TiO₂ for photocatalytic water splitting. *Int. J. Hydrogen Energy. 42*(15), 9938–9944 (Apr. 2017). <https://doi.org/10.1016/j.ijhydene.2017.01.232>
12. R., Sharma, M., Khanuja, S.N., Sharma, Sinha, O.P.: Reduced band gap & charge recombination rate in se doped A-Bi₂O₃ leads to enhanced photoelectrochemical and photocatalytic performance: Theoretical & experimental insight. *Int. J. Hydrogen Energy. 42*(32), 20638–20648 (Aug. 2017). <https://doi.org/10.1016/j.ijhydene.2017.07.011>
13. M., Tahir, S., Tasleem, Tahir, B.: Recent development in band engineering of binary semiconductor materials for solar driven photocatalytic hydrogen production, *Jun. 11*, 2020, Elsevier Ltd. <https://doi.org/10.1016/j.ijhydene.2020.04.071>
14. P.K., Samanta: Band gap engineering, quantum confinement, defect mediated broadband visible photoluminescence and associated quantum States of size tuned zinc oxide nanostructures. *Optik (Stuttg). 221* (Nov. 2020). <https://doi.org/10.1016/j.ijleo.2020.165337>
15. D., Zheng, X., Yang, L., Čuček, J., Wang, T., Ma, Yin, C.: Revolutionizing dye-sensitized solar cells with nanomaterials for enhanced photoelectric performance. *J. Clean. Prod. 464* (Jul. 2024). <https://doi.org/10.1016/j.jclepro.2024.142717>
16. A.A., Hendi, et al.: Dye-sensitized solar cells constructed using titanium oxide nanoparticles and green dyes as photosensitizers. *J. King Saud Univ. Sci. 35*(3) (Apr. 2023). <https://doi.org/10.1016/j.jksus.2023.102555>
17. A., Aboulouard, et al.: Mar., Dye sensitized solar cells based on titanium dioxide nanoparticles synthesized by flame spray pyrolysis and hydrothermal sol-gel methods: A comparative study on photovoltaic performances, *Journal of Materials Research and Technology*, vol. 9, no. 2, pp. 1569–1577, (2020). <https://doi.org/10.1016/j.jmrt.2019.11.083>
18. K., Xu, Chen, J.: High-resolution scanning probe lithography technology: A review. Apr 01. (2020). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1007/s13204-019-01229-5>
19. R., Bekkari, L., laânab, D., Boyer, R., Mahiou, Jaber, B.: Influence of the Sol gel synthesis parameters on the photoluminescence properties of ZnO nanoparticles. *Mater. Sci. Semicond. Process. 71*, 181–187 (Nov. 2017). <https://doi.org/10.1016/j.msssp.2017.07.027>
20. P., Bhagoria, E.M., Sebastian, S.K., Jain, J., Purohit, Purohit, R.: Nanolithography and its alternate techniques, in *Materials Today: Proceedings*, Elsevier Ltd, pp. 3048–3053. (2019). <https://doi.org/10.1016/j.matpr.2020.02.633>
21. M.A., Valverde-Alva, et al.: Nov., Synthesis of silver nanoparticles by laser ablation in ethanol: A pulsed photoacoustic study, *Appl Surf Sci*, vol. 355, pp. 341–349, (2015). <https://doi.org/10.1016/j.apsusc.2015.07.133>

22. S.A., Abdulateef, et al.: Jul., Preparation of CuO nanoparticles by laser ablation in liquid, in AIP Conference Proceedings, American Institute of Physics Inc., (2016). <https://doi.org/10.1063/1.4948853>
23. G.R., Khayati, Janghorban, K.: Preparation of nanostructure silver powders by mechanical decomposing and mechanochemical reduction of silver oxide. *Trans. Nonferrous Met. Soc. China* (English Edition). **23**(5), 1520–1524 (May 2013). [https://doi.org/10.1016/S1003-6326\(13\)62625-4](https://doi.org/10.1016/S1003-6326(13)62625-4)
24. B.C., Yadav, S., Singh, Yadav, T.P.: Titania prepared by ball milling: Its characterization and application as liquefied petroleum gas sensor, *Synthesis and Reactivity in Inorganic, Metal-Organic and Nano-Metal Chemistry*, vol. 45, no. 4, pp. 487–494, (2015). <https://doi.org/10.1080/15533174.2012.749892>
25. J., Ding, et al.: Aerosol assisted chemical vapour deposition of nanostructured ZnO thin films for NO₂ and ethanol monitoring. *Ceram. Int.* **46**(10), 15152–15158 (Jul. 2020). <https://doi.org/10.1016/j.ceramint.2020.03.051>
26. D., Ji, X., Wen, T., Foller, Y., You, F., Wang, Joshi, R.: Chemical vapour deposition of graphene for durable anticorrosive coating on copper. *Nanomaterials*. **10**(12), 1–9 (Dec. 2020). <https://doi.org/10.3390/nano10122511>
27. R., Jana, A., Dey, M., Das, J., Datta, P., Das, Ray, P.P.: Improving performance of device made up of CuO nanoparticles synthesized by hydrothermal over the reflux method. *Appl Surf Sci.* **452**, 155–164 (Sep. 2018). <https://doi.org/10.1016/j.apsusc.2018.04.262>
28. E., Mitchell, et al.: Probing on the hydrothermally synthesized iron oxide nanoparticles for ultra-capacitor applications. *Powder Technol.* **272**, 295–299 (Mar. 2015). <https://doi.org/10.1016/j.powtec.2014.12.021>
29. R., Mahdavi, Talesh, S.S.A.: Sol-gel synthesis, structural and enhanced photocatalytic performance of al doped ZnO nanoparticles. *Adv. Powder Technol.* **28**(5), 1418–1425 (May 2017). <https://doi.org/10.1016/j.apt.2017.03.014>
30. S., Kumar, P., Bhushan, Bhattacharya, S.: Fabrication of nanostructures with Bottom-up approach and their utility in diagnostics, therapeutics, and others. In: *Energy, Environment, and Sustainability*, pp. 167–198. Springer Nature (2018). https://doi.org/10.1007/978-981-10-7751-7_8
31. G., Rao Kandregula, K., Ganapathi Rao, C., Ashok, K., Venkateswara Rao, C., Shilpa Chakra, P., Tambur: Green Synthesis of TiO₂ Nanoparticles Using Aloe Vera Extract Green Synthesis of TiO₂ Nanoparticles Using Aloe Vera Extract, [Online]. (2015). Available: <https://www.researchgate.net/publication/282502800>
32. F., Septiningrum, et al.: Mangosteen pericarp extract mediated synthesis of Ag/TiO₂ nanocomposite and its application on organic pollutant degradation by adsorption-photocatalytic activity. *Curr. Res. Green. Sustainable Chem.* **8** (Jan. 2024). <https://doi.org/10.1016/j.crgsc.2023.100394>
33. N., Sofyan, A.M., Jamil, A., Ridhova, A.H., Yuwono, D., Dhaneswara, Fergus, J.W.: Graphene oxide doping in tropical almond (terminalia Catappa L.) fruits extract mediated green synthesis of TiO₂ nanoparticles for improved DSSC power conversion efficiency. *Heliyon*. **10**(8) (Apr. 2024). <https://doi.org/10.1016/j.heliyon.2024.e29370>
34. O.V., Kharissova, H.V.R., Dias, B.I., Kharisov, B.O., Pérez, V.M.J., Pérez: The greener synthesis of nanoparticles. *Apr.* (2013). <https://doi.org/10.1016/j.tibtech.2013.01.003>
35. A.M., El Shafey: Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review, *Green Processing and Synthesis*, vol. 9, no. 1, pp. 304–339, Mar. (2020). <https://doi.org/10.1515/gps-2020-0031>
36. R., Rajendhiran, V., Deivisigamani, J., Palanisamy, S., Masan, Pitchaiya, S.: Terminalia catappa and carissa carandas assisted synthesis of TiO₂ nanoparticles - A green synthesis approach, in *Materials Today: Proceedings*, Elsevier Ltd, Nov. pp. 2232–2238. (2021). <https://doi.org/10.1016/j.matpr.2020.10.223>
37. S.S., Patil, M.M., Nitalikar, khulbe, P.: Design, Development and Optimization of Bixa Orellana Extract Loaded Silver Nanoparticle. *Advances in Pharmacology and Pharmacy*. **12**(2), 125–134 (Apr. 2024). <https://doi.org/10.13189/app.2024.120205>
38. B., Maitra, et al.: Biosynthesis of Bixa orellana seed extract mediated silver nanoparticles with moderate antioxidant, antibacterial and antiproliferative activity. *Arab. J. Chem.* **16**(5) (May 2023). <https://doi.org/10.1016/j.arabjc.2023.104675>
39. I.C., Maurya, S., Singh, S., Senapati, P., Srivastava, Bahadur, L.: Green synthesis of TiO₂ nanoparticles using Bixa orellana seed extract and its application for solar cells. *Solar Energy*. **194**, 952–958 (Dec. 2019). <https://doi.org/10.1016/j.solener.2019.10.090>
40. E.Y., Ahn, S.W., Shin, K., Kim, Park, Y.: Facile green synthesis of titanium dioxide nanoparticles by upcycling mangosteen (*Garcinia mangostana*) pericarp extract. *Nanoscale Res. Lett.* **17**(1) (Mar. 2022). <https://doi.org/10.1186/s11671-022-03678-4>
41. S., Hussain, et al.: Feb., Green Synthesis of TiO₂ Nanoparticle in *Morus nigra* Leaves; Characterization and Biological Potential. *Pol J Environ Stud.* **33**(3), 2707–2714 (2024). <https://doi.org/10.15244/pjoes/175060>
42. S., Singh, I.C., Maurya, A., Tiwari, P., Srivastava, Bahadur, L.: Green synthesis of TiO₂ nanoparticles using Citrus limon juice extract as a bio-capping agent for enhanced performance of dye-sensitized solar cells. *Surfaces and Interfaces*. **28**, (Feb. 2022). <https://doi.org/10.1016/j.surfin.2021.101652>
43. Y., Yin, et al.: UPLC-DAD/Q-TOF-MS based ingredients identification and vasorelaxant effect of ethanol extract of jasmine flower. *Evidence-based Complementary and Alternative Medicine*. **2014**, (2014). <https://doi.org/10.1155/2014/707908>
44. T., Gu, et al.: Insight into the corrosion Inhibition performance of Jasmine flower extract on copper in sulfuric acid medium using experimental and theoretical calculation methods. *J. Taiwan. Inst. Chem. Eng.* **150** (Sep. 2023). <https://doi.org/10.1016/j.jtice.2023.105047>
45. V.G., et al.: Exploring the efficacy of biosynthesized cupric oxide nanoparticles from *Jasminum sambac* flower extract in wastewater treatment: Experimental investigations and potential applications. *Desalin. Water Treat.* **319** (Jul. 2024). <https://doi.org/10.1016/j.dwt.2024.100570>
46. J., Lin, Y., Chen, P., Zhang, M., Ren, H., Xu, Wang, X.: A novel quality evaluation index and strategies to identify scenting quality of jasmine tea based on headspace volatiles analysis. *Food Sci Biotechnol.* **22**(2), 331–340 (Apr. 2013). <https://doi.org/10.1007/s10068-013-0085-x>
47. A., Temraz, P.L., Cioni, G., Flamini, A., Braca: Chemical Composition of the Essential Oil from *Jasminum pubescens* Leaves and Flowers, (2009)
48. M., Aravind, et al.: Critical green routing synthesis of silver NPs using Jasmine flower extract for biological activities and photocatalytic degradation of methylene blue. *J. Environ. Chem. Eng.* **9**(1) (Feb. 2021). <https://doi.org/10.1016/j.jece.2020.104877>
49. K., Kakiage, Y., Aoyama, T., Yano, K., Oya, J.I., Fujisawa, Hanaya, M.: Highly-efficient dye-sensitized solar cells with collaborative sensitization by silyl-anchor and carboxy-anchor dyes. *Chem. Commun.* **51**(88), 15894–15897 (Sep. 2015). <https://doi.org/10.1039/c5cc06759f>
50. A., Sen, M.H., Putra, A.K., Biswas, A.K., Behera, Groß, A.: Insight on the choice of sensitizers/dyes for dye sensitized solar cells: A review, May 01. Elsevier Ltd. (2023). <https://doi.org/10.1016/j.dyepig.2023.111087>
51. A., Mishra, M.K.R., Fischer, P., Büuerle: Metal-Free organic dyes for dye-Sensitized solar cells: From structure: Property relationships to design rules. *Mar.* **23** (2009). <https://doi.org/10.1002/anie.200804709>

52. M.Z., Iqbal, S.R., Ali, Khan, S.: Progress in dye sensitized solar cell by incorporating natural photosensitizers. *Solar Energy*. **181**, 490–509, (Mar. 2019). <https://doi.org/10.1016/j.solener.2019.02.023>
53. A., Mahapatra, P., Kumar, A.K., Behera, A., Sen, Pradhan, B.: Comparative study of natural dye-sensitized solar cells using inedible extracts from kumkum, kamala and malabar spinach fruits. *J Photochem Photobiol A Chem*. **436**, (Mar. 2023). <https://doi.org/10.1016/j.jphotochem.2022.114385>
54. M., Younes, et al.: Safety of Annatto E and the exposure to the Annatto colouring principles bixin and Norbixin (E 160b) when used as a food additive. *EFSA J*. **17**(3) (Mar. 2019). <https://doi.org/10.2903/j.efsa.2019.5626>
55. G., Calogero, et al.: Photoelectrochemical and spectrophotometric studies on dye-sensitized solar cells (DSCs) and stable modules (DSCMs) based on natural apocarotenoids pigments. *Dyes Pigm.* **155**, 75–83 (Aug. 2018). <https://doi.org/10.1016/j.dyepig.2018.03.021>
56. T., Taham, F.A., Cabral, Barrozo, M.A.S.: Extraction of bixin from Annatto seeds using combined technologies. *J. Supercrit. Fluids*. **100**, 175–183 (May 2015). <https://doi.org/10.1016/j.supflu.2015.02.006>
57. I., Handayani, A.T., Septiana, Sustriawan, B.: Natural pigments and antioxidants properties of Annatto extract at various pH of distilled water solvent and extraction times. *Food Res.* **8**(2), 489–494 (Apr. 2024). [https://doi.org/10.26656/fr.2017.8\(2\).394](https://doi.org/10.26656/fr.2017.8(2).394)
58. T., Van Cuong, Chin, K.B.: Effects of Annatto (Bixa orellana L.) seeds powder on physicochemical properties, antioxidant and antimicrobial activities of pork patties during refrigerated storage. *Korean J. Food Sci. Anim. Resour.* **36**(4), 476–486 (Aug. 2016). <https://doi.org/10.5851/kosfa.2016.36.4.476>
59. L.A., Almeida, A., Dosen, J., Viol, Marinkovic, B.A.: TiO₂-Acetylacetone as an efficient source of superoxide radicals under reduced power visible light: Photocatalytic degradation of Chlorophenol and Tetracycline. *Catalysts*. **12**(2) (Feb. 2022). <https://doi.org/10.3390/catal12020116>
60. P.S., Jassal, D., Kaur, R., Prasad, Singh, J.: Green synthesis of titanium dioxide nanoparticles: Development and applications. *J. Agric. Food Res.* **10** (Aug. 2022). <https://doi.org/10.1016/j.jafr.2022.100361>
61. M., Saleem, et al.: Wet-Chemical synthesis of TiO₂/PVDF membrane for energy applications. *Molecules*. **28**(1) (Jan. 2023). <https://doi.org/10.3390/molecules28010285>
62. J.H., Yum, E., Baranoff, S., Wenger, M.K., Nazeeruddin, Grätzel, M.: Panchromatic engineering for dye-sensitized solar cells. *Energy Environ. Sci.* **4**(3), 842–857 (Mar. 2011). <https://doi.org/10.1039/c0ee00536c>
63. Z., Wang, X., Feng, J., Liu, M., Lu, Li, M.: Functional groups prediction from infrared spectra based on computer-assist approaches. *Microchem. J.* **159** (Dec. 2020). <https://doi.org/10.1016/j.microc.2020.105395>
64. M., Sampath, Vasanthi, M.: Isolation, Structural Elucidation of Flavonoids from Polyalthia Longifolia (Sonn.) Thawaites and Evaluation of Antibacterial, Antioxidant and Anticancer Potential. *Int J Pharm Pharm Sci.* **5**(1), 336–341 (2013)
65. M.C., Dias, D.C.G.A., Pinto, Silva, A.M.S.: Plant flavonoids: Chemical characteristics and biological activity. *Molecules*. **26**(17), (Sep. 2021). <https://doi.org/10.3390/molecules26175377>
66. A., Zdyb, Krawczyk, S.: Natural Flavonoids as Potential Photosensitizers for Dye-Sensitized Solar Cells. *Ecological Chemistry and Engineering S.* **26**(1), 29–36 (Mar. 2019). <https://doi.org/10.1515/eces-2019-0016>
67. Z., Arifin, S., Soeparman, D., Widhiyanuriyawan, Suyitno, S.: Performance Enhancement of Dye-Sensitized Solar Cells Using a Natural Sensitizer. *Inter. J Photoenergy*. **2017**, (2017). <https://doi.org/10.1155/2017/2704864>
68. C.Y., Cai, S.K., Tseng, M., Kuo, K.Y., Andrew Lin, H., Yang, Lee, R.H.: Photovoltaic performance of a N719 dye based dye-sensitized solar cell with transparent macroporous anti-ultraviolet photonic crystal coatings. *RSC Adv.* **5**(124), 102803–102810 (2015). <https://doi.org/10.1039/c5ra21194h>
69. F., Hirose, M., Shikaku, Y., Kimura, Niwano, M.: IR study on N719 dye adsorption with high temperature dye solution for highly efficient dye-Sensitized solar cells. *J. Electrochem. Soc.* **157**(11), B1578 (2010). <https://doi.org/10.1149/1.3485036>
70. N.C.T., Martins, J., Ângelo, A.V., Girão, T., Trindade, L., Andrade, Mendes, A.: N-doped carbon quantum dots/TiO₂ composite with improved photocatalytic activity. *Appl. Catal. B.* **193**, 67–74 (Sep. 2016). <https://doi.org/10.1016/j.apcatb.2016.04.016>
71. Z., Zhao, Z., Li, Zou, Z.: Understanding the interaction of water with anatase TiO₂ (101) surface from density functional theory calculations, *Physics Letters, Section A: General. Atomic and Solid State Physics.* **375**(32), 2939–2945 (Jul. 2011). <https://doi.org/10.1016/j.physleta.2011.06.022>
72. C., Sun, L.M., Liu, A., Selloni, G.Q., Lu, Smith, S.C.: Titania-water interactions: A review of theoretical studies. *J Mater Chem.* **20**(46), 10319–10334 (Dec. 2010). <https://doi.org/10.1039/c0jm01491e>
73. M., Aravind, M., Amalanathan, Mary, M.S.M.: Synthesis of TiO₂ nanoparticles by chemical and green synthesis methods and their multifaceted properties. *SN Appl. Sci.* **3**(4) (Apr. 2021). <https://doi.org/10.1007/s42452-021-04281-5>
74. S., Sagadevan, et al.: Jan., A comprehensive review on green synthesis of titanium dioxide nanoparticles and their diverse biomedical applications. *Green Processing and Synthesis.* **11**(1), 44–63 (2022). <https://doi.org/10.1515/gps-2022-0005>
75. A.R., Zannata: Revisiting the optical bandgap of semiconductors and the proposal of a unified methodology to its determination. *Sci. Rep.* **9**(1), 11225 (Aug. 2019). <https://doi.org/10.1038/s41598-019-47670-y>
76. R., Ríos-Reina, Azcarate, S.M.: How chemometrics revives the UV-Vis spectroscopy applications as an analytical sensor for spectralprint (Nontargeted) analysis. *Chemosensors.* **11**(1) (Jan. 2023). <https://doi.org/10.3390/chemosensors11010008>
77. P., Makula, M., Pacia, Macyk, W.: How To Correctly Determine the Band Gap Energy of Modified Semiconductor Photocatalysts Based on UV-Vis Spectra, Dec. 06, 2018, American Chemical Society. <https://doi.org/10.1021/acs.jpcclett.8b02892>
78. G., Nagaraj, A.D., Raj, A.A., Irudayaraj, Josephine, R.L.: Tuning the optical band gap of pure TiO₂ via photon induced method. *Optik (Stuttg.)*. **179**, 889–894 (Feb. 2019). <https://doi.org/10.1016/j.ijleo.2018.11.009>
79. D.G., Calatayud, M., Rodríguez, Jardiel, T.: Controlling the morphology of TiO₂ nanocrystals with different capping agents. *Boletín de la Sociedad Española de Cerámica y Vidrio.* **54**(4), 159–165 (Jul. 2015). <https://doi.org/10.1016/j.bseccv.2015.07.001>
80. L., Weng, X., Bao, Sagoe-Crentsil, K.: Effect of acetylacetone on the Preparation of PZT materials in sol/gel processing. *Mater. Sci. Eng.* **B96**, 307–312 (2002)
81. L.N., Stepanova, O.B., Belskaya, A.N., Salanov, A.N., Serkova, Likholobov, V.A.: SEM study of the surface morphology and chemical composition of the MgAl- and MgGa-layered hydroxides in different steps of platinum catalysts Pt/Mg(Al, Ga)Ox synthesis. *Appl Clay Sci.* **157**, 267–273 (Jun. 2018). <https://doi.org/10.1016/j.clay.2018.03.003>
82. R.S., Dubey, K.V., Krishnamurthy, Singh, S.: Experimental studies of TiO₂ nanoparticles synthesized by sol-gel and solvothermal routes for DSSCs application. *Results Phys.* **14** (Sep. 2019). <https://doi.org/10.1016/j.rinp.2019.102390>
83. P., Anandgaonker, G., Kulkarni, S., Gaikwad, Rajbhoj, A.: Synthesis of TiO₂ nanoparticles by electrochemical method and their antibacterial application. *Arabian Journal of Chemistry.* **12**(8),

- 1815–1822 (Dec. 2019). <https://doi.org/10.1016/j.arabjc.2014.12.015>
84. A., Mansoor, M., Mehmood, M., Ishtiaq, Jamal, A.: Synthesis of TiO₂ nanoparticles and demonstration of their antagonistic properties against selected dental caries promoting bacteria. *Pak J Med Sci.* **39**(5), 1249–1254 (Sep. 2023). <https://doi.org/10.12669/pjms.39.5.7851>
85. C.A., Schneider, W.S., Rasband, Eliceiri, K.W.: NIH image to imageJ: 25 years of image analysis. *Nat. Methods.* **9**(7), 671–675 (2012). <https://doi.org/10.1038/nmeth.2089>
86. S., Mustapha, et al.: Application of TiO₂ and ZnO nanoparticles immobilized on clay in wastewater treatment: A review. *Appl. Water Sci.* **10**(1) (Jan. 2020). <https://doi.org/10.1007/s13201-019-1138-y>
87. N., Sofyan, A., Ridhova, A.H., Yuwono, A., Udhiarto, Fergus, J.W.: Synthesis of TiO₂ nanoparticles at low hydrothermal temperature and its performance for DSSC sensitized using natural dye extracted from *Melastoma malabathricum* L. seeds. *Int J Energy Res.* **43**(11), 5959–5968 (Sep. 2019). <https://doi.org/10.1002/er.4710>
88. R.S., Dubey, K.V., Krishnamurthy, Singh, S.: Experimental studies of TiO₂ nanoparticles synthesized by sol-gel and solvothermal routes for DSSCs application. *Results Phys.* **14** (Sep. 2019). <https://doi.org/10.1016/j.rinp.2019.102390>
89. S., Bhattarai, et al.: A detailed review of perovskite solar cells: Introduction, working principle, modelling, fabrication techniques, future challenges. *Micro Nanostruct.* **172** (Dec. 2022). <https://doi.org/10.1016/j.micrna.2022.207450>
90. R., Baby, P.D., Nixon, N.M., Kumar, M.S.P., Subathra, Ananthi, N.: A comprehensive review of dye-sensitized solar cell optimal fabrication conditions, natural dye selection, and application-based future perspectives. *Environmental Science and Pollution Research.* **29**(1), 371–404 (Jan. 2022). <https://doi.org/10.1007/s11356-021-16976-8>
91. A., Khorsand Zak, W.H., Abd. Majid, M.E., Abrishami, Yousefi, R.: X-ray analysis of ZnO nanoparticles by Williamson-Hall and size-strain plot methods. *Solid State Sci.* **13**(1), 251–256 (Jan. 2011). <https://doi.org/10.1016/j.solidstatesciences.2010.11.024>
92. Y., Zhang, L., Zhong, Duan, D.: Single-step hydrothermal synthesis of strontium titanate nanoparticles from crystalline anatase titanium dioxide. *Ceram. Int.* **41**(10), 13516–13524 (Dec. 2015). <https://doi.org/10.1016/j.ceramint.2015.07.145>
93. D.F., Triviño-Bolaños, Camargo-Amado, R.J.: Synthesis and characterization of porous structures of rutile TiO₂/Na_{0.8}Ti₄O₈/Na₂Ti₆O₁₃ for biomedical applications. *MethodsX.* **6**, 1114–1123 (Jan. 2019). <https://doi.org/10.1016/j.mex.2019.04.002>
94. A., Khalid, et al.: Feb., Unmodified titanium dioxide nanoparticles as a potential contrast agent in photon emission computed tomography. *Crystals (Basel).* **11**(2), 1–10 (2021). <https://doi.org/10.3390/cryst11020171>
95. O., Frank, M., Zukalova, B., Laskova, J., Kürti, J., Koltai, Kavan, L.: Raman spectra of titanium dioxide (anatase, rutile) with identified oxygen isotopes (16, 17, 18). *Physical Chemistry Chemical Physics.* **14**(42), 14567–14572 (Nov. 2012). <https://doi.org/10.1039/c2cp42763j>
96. A., Di Paola, M., Bellardita, Palmisano, L.: Brookite, the least known TiO₂ photocatalyst. *Catalysts.* **3**(1), 36–73 (Jan. 2013). <https://doi.org/10.3390/catal3010036>
97. H.C., Choi, Y.M., Jung, Bin Kim, S.: Size effects in the Raman spectra of TiO₂ nanoparticles. *Vib. Spectrosc.* **37**(1), 33–38 (Jan. 2005). <https://doi.org/10.1016/j.vibspec.2004.05.006>
98. J., Singh, T., Dutta, K.H., Kim, M., Rawat, P., Samddar, Kumar, P.: Green synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *J. Nanobiotechnol.* **16**(1) (Oct. 2018). <https://doi.org/10.1186/s12951-018-0408-4>
99. A.E., García-Ovando, J.E., Ramírez Piña, E.U., Esquivel Naranjo, J.A., Cervantes, Chávez, Esquivel, K.: Biosynthesized nanoparticles and implications by their use in crops: Effects over physiology, action mechanisms, plant stress responses and toxicity. *Plant. Stress.* **6** (Dec. 2022). <https://doi.org/10.1016/j.stress.2022.100109>
100. S., Qourzal, A., Assabane, Ait-Ichou, Y.: Synthesis of TiO₂ via hydrolysis of titanium tetraisopropoxide and its photocatalytic activity on a suspended mixture with activated carbon in the degradation of 2-naphthol. *J. Photochem. Photobiol Chem.* **163**(3), 317–321 (May 2004). <https://doi.org/10.1016/j.jphotochem.2003.12.013>
101. R., Saini, Kumar, P.: Green synthesis of TiO₂ nanoparticles using *Tinospora cordifolia* plant extract & its potential application for photocatalysis and antibacterial activity. *Inorg. Chem. Commun.* **156** (Oct. 2023). <https://doi.org/10.1016/j.inoche.2023.111221>
102. M.A., Varnosfaderani, Strickland, D.: Online electrochemical impedance spectroscopy (EIS) Estimation of a solar panel. *Vacuum.* **139**, 185–195 (May 2017). <https://doi.org/10.1016/j.vacuum.2017.01.011>
103. U., Mehmood, et al.: Electrochemical impedance spectroscopy and photovoltaic analyses of Dye-Sensitized solar cells based on Carbon/TiO₂ composite counter electrode. *J. Electrochem. Soc.* **163**(5), H339–H342 (2016). <https://doi.org/10.1149/2.0111606jes>
104. A., Mortadi, E., El Hafidi, M., Monkade, Moznine, R.E.: Investigating the influence of absorber layer thickness on the performance of perovskite solar cells: A combined simulation and impedance spectroscopy study. *Mater. Sci. Energy Technol.* **7**, 158–165 (Jan. 2024). <https://doi.org/10.1016/j.mset.2023.10.001>
105. S., Sarker, H.W., Seo, Kim, D.M.: Electrochemical impedance spectroscopy of dye-sensitized solar cells with thermally degraded N719 loaded TiO₂. *Chem. Phys. Lett.* **585**, 193–197 (2013). <https://doi.org/10.1016/j.cplett.2013.08.101>
106. A., Mortadi, E.M., El Hafidi, H., Nasrellah, M., Monkade, Moznine, R.E.: Investigation of bandgap grading on performances of perovskite solar cell using SCAPS-1D and impedance spectroscopy. *Solar Energy Adv.* **4** (Jan. 2024). <https://doi.org/10.1016/j.saja.2024.100056>
107. N., Sofyan, et al.: Photocurrent Characteristics of TiO₂ Nanoparticles Green Synthesized Using Mangosteen Pericarps Waste Extract for Dye-Sensitized Solar Cell Application, [Online]. Available: <https://ssrn.com/abstract=5061564>
108. C., Jeganathan, T.C., Sabari Girisu, S., Vijaya, Anandan, S.: Improved charge collection and photo conversion of bacteriorhodopsin sensitized solar cells coupled with reduced graphene oxide decorated one-dimensional TiO₂ Nanorod hybrid photoanodes. *Electrochim. Acta.* **319**, 909–921 (Oct. 2019). <https://doi.org/10.1016/j.electacta.2019.07.036>
109. S.N., Sadikin, M.Y.A., Rahman, A.A., Umar, Aziz, T.H.T.: Improvement of dye-sensitized solar cell performance by utilizing graphene-coated TiO₂ films photoanode. *Superlattices Microstruct.* **128**, 92–98 (Apr. 2019). <https://doi.org/10.1016/j.spmi.2019.01.014>
110. M.K., Hossain, et al.: Effect of dye extracting solvents and sensitization time on photovoltaic performance of natural dye sensitized solar cells. *Results Phys.* **7**, 1516–1523 (Apr. 2017). <https://doi.org/10.1016/j.rinp.2017.04.011>
111. S., Pavithra, et al.: Photocatalytic and photovoltaic applications of green synthesized titanium oxide (TiO₂) nanoparticles by *Calotropis gigantea* extract. *J. Alloys Compd.* **960** (Oct. 2023). <https://doi.org/10.1016/j.jallcom.2023.170638>
112. G., Sharma, C., Dawo, K., Mulchandani, U.K., Kumawat, R.K., Singhal, Lal, C.: Revealing the photophysics of N719 dye based dye-sensitized solar cell. *Opt. Mater. (Amst).* **142**, 114113 (2023). <https://doi.org/10.1016/j.optmat.2023.114113>

113. J.V., Patil, S.S., Mali, J.S., Shaikh, A.P., Patil, P.S., Patil, Hong, C.K.: Influence of reduced graphene oxide-TiO₂ composite nanofibers in organic Indoline DN350 based dye sensitized solar cells. *Synth. Met.* **256** (Oct. 2019). <https://doi.org/10.1016/j.synthmet.2019.116146>
114. S.N., Tamilselvan, Shanmugan, S.: Towards sustainable solar cells: unveiling the latest developments in bio-nano materials for enhanced DSSC efficiency, Jun. 01, Oxford University Press. (2024). <https://doi.org/10.1093/ce/zkae031>
115. S.S., Malhotra, M., Ahmed, M.K., Gupta, Ansari, A.: Metal-free and natural dye-sensitized solar cells: Recent advancements and future perspectives. Aug. **07** (2024). Royal Society of Chemistry [10.1039/d4se00406j](https://doi.org/10.1039/d4se00406j)

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