Natural Waste to Electricity: Engineering Pomegranate Peels and Ag-Doped ZnO for Photovoltaic Applications

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Abstract

Utilization of natural waste for energy conversion offers the method for clean energy production with sustainable development. The pomegranate peels are the natural waste generated every day and we describe the conversion of this waste into electricity by a simple and cost-effective method. Dye Sensitized Solar Cells (DSSCs) offer simple and cost-effective method for the preparation of solar cells. The advantages include easy to fabrication, lower cost of the materials and electricity generation under low illumination indoor conditions. DSSCs involve two Transparent Conducting Oxide (TCO) photoelectrodes acting as photoanode and photocathode. In one photoelectrode, Semiconducting oxide (TiO_2/ZnO) and dye (Natural/Organometallic) are coated that acts as photo-absorbing materials. The role of dyes and semiconducting material play an important role in determining the photovoltaic conversion efficiency of fabricated solar cells. In this work, hydrothermal method has been adopted for the preparation of pure and silver doped ZnO nanoparticles using polyethylene glycol (PEG) as capping agent *via* wet chemical route. The structural and optical properties of the prepared samples were studied using X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FT-IR), Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis (EDAX) and UV-Visible absorption spectra. A Natural dye from the peels of pomegranate was extracted and dye sensitized solar cells were fabricated with pure and Ag-doped nanoparticles. Both the materials showed the photovoltaic conversion capabilities and showed photoconversion efficiencies. The solar cell fabricated with Ag-doped ZnO semiconducting nanoparticle showed higher short circuit current density as compared to the pure ZnO-nanoparticle synthesized in this study. The photoconversion efficiency of the DSSC based on Ag-doped ZnO showed 30% more conversion efficiency than the cell without silver doping.

1. Introduction

Fossil fuels are widely used in the power generation results in pollution to the environment by emitting toxic gases and causing global warming (Hoffert 2010, Höök & Tang 2013, Johnsson et al. 2019, Seddon et al. 2021, Wood & Roelich 2019). Electricity is a primary energy used by mankind and an ever-increasing demand every year. There are numerous efforts for improving the power production and utilization (Kalair et al. 2021, Panwar et al. 2011, Wali et al. 2021). Nuclear power production is a widely used option for the increasing power need due to urbanization (Forsberg 2009, Orhan et al. 2012). After the Fukushima nuclear disaster, the world is in aversion of nuclear power and Germany has already replaced its nuclear reactors with TW solar power (Labib & Harris 2015, Lochbaum et al. 2014, Mundo-Hernández et al. 2014). Sunlight to electricity conversion is the sustainable and clean energy solution for the future energy needs of the world. P-n-Junction based solar cells are used for the sunlight to electricity conversion and the present solar power production is dominated by the silicon solar cells (Behura et al. 2021, Gong et al. 2019). In spite of monopoly by silicon solar cells, they suffer some disadvantages like, the cost of production and absorption of sunlight in only red light of solar energy (Pizzini 2010, Wenham & Green 1996). This requires new materials and technologies for the wide absorption of sunlight and without

increasing the power production cost(Beard et al. 2014, Chalkias et al. 2021, Cunha et al. 2021, Kokkonen et al. 2021, Vlachopoulos et al. 2021).

Dye sensitized solar cells (DSSCs), also known as Grätzel cells offer sunlight to electricity conversion under indoor conditions as compared to the silicon solar cells(Galliano et al. 2021, Grätzel 2003a, 2009, Naim et al. 2021, Parisi et al. 2014, Peter 2011). There are multiple advantages that include simple to fabricate with low-cost materials, multiple wide absorption across the solar energy spectrum as compared to the silicon solar cells. DSSCs include two transparent conducting oxide photoelectrodes bound together and an electrolyte injected between them. DSSCs are fabricated using one FTO coated with a semiconductor (TiO_2/ZnO), dye (Natural/Organometallic), and another FTO plate coated with counter electrode (usually, Pt) and an electrolyte (I^-/I_3^-) injected between them. When light falls on the cell, dye material absorbs sunlight and transfers an electron to the TiO_2 , which in turn gives away an electron to the electrolyte. The electrolyte acts as the redox shuttle and does two works, by providing an electron to the power output and one electron for the dye regeneration. So, the electron generation and dye regeneration process happens continuously and results in the electricity generation(Campbell et al. 2007, Chen et al. 2009, Freitag et al. 2017, Grätzel 2003b, Patni & Pillai 2020). Grätzel *et al.* have first reported the utilization of TiO_2 as the semiconducting material with organometallic dye as a sunlight absorber, I^-/I_3^- as electrolyte and platinum as the counter electrode(Grätzel 1991, Kohle et al. 1997, O'regan & Grätzel 1991). During the dye sensitized solar cell fabrication and operation, dye and semiconductor play an important role for obtaining efficient power generation. Dyes including, natural(Ludin et al. 2014, Mary Rosana et al. 2020, Narayan 2012, Shalini et al. 2015), organometallic(Almalki et al. 2021, Chen et al. 2009, Chen et al. 2008, Chen et al. 2006, Joseph et al. 2016, Klein et al. 2005), and organic dyes(Abusaif et al. 2021, Joseph et al. 2019, Mahmood 2016, Mishra et al. 2009, Thomas et al. 2021) were reported for obtaining high power conversion efficiencies among the DSSCs. There are number of metal oxide nanoparticles utilized as the semiconductors for the better performance of DSSCs(Abdelnasser et al. 2020, Jose et al. 2009, Prakash 2012, Sadegh et al. 2021, Vittal & Ho 2017). Among the semiconductors, TiO_2 is commonly used semiconductor that absorbs in the ultraviolet region of the solar energy with the wide band gap of 3.2 – 3.5 eV(Boro et al. 2018, Hou et al. 2020). At present, the solar cell fabricated with TiO_2 and porphyrin dye reached the highest solar power conversion efficiency of 14.5%(Li & Diau 2013, Zeng et al. 2020).

Zinc oxide is the wide band gap metal oxide semiconductor that is transparent and absorbs in the ultraviolet visible region of the solar energy(Jaramillo-Páez et al. 2018, Radhika & Thomas 2017, Rokesh et al. 2018, Vittal & Ho 2017). It has achieved importance due to its unique features such as high chemical stability, absorption of radiation in a broad range and high photostability. It has potential applications in Optoelectronics, UV light emitters, Laser Technology, Sensors, Energy generation and photocatalysis(Kołodziejczak-Radzimska & Jesionowski 2014, Vittal & Ho 2017). Zinc Oxide (ZnO) can also be utilized as the semiconducting material in DSSC and many reports of ZnO nanoparticles for DSSC fabrication have been reported(Lanjewar & Gohel 2017).

In this present study, pure and Ag doped ZnO nanoparticles were prepared by a facile wet chemical route using polyethylene glycol (PEG) as capping agent. ZnO and Ag-doped ZnO were characterized by X-ray diffraction (XRD), Fourier Transform Infrared Spectra (FT-IR), Scanning Electron Microscope (SEM) with Energy Dispersive X-ray Analysis (EDAX) and UV-Visible absorption spectra. These studies revealed the structural and optical properties of the prepared samples. Natural dye from the peels of pomegranate was extracted using ethanol and the purified dye was used as a photosensitizer. The dye sensitized cells were fabricated using the pure and Ag-doped ZnO nanoparticles, and the pomegranate peel extract. Both the dye and ZnO nanoparticles showed the photovoltaic properties. Among the fabricated cells, Ag-doped ZnO nanoparticle used dye sensitized cell better conversion efficiency with high current densities as compared to the non-doped cell. The schematic of the solar cell fabricated in this work is shown in Figure 1. Herein, we report the synthesis, characterization and photovoltaic performance of pure and silver doped ZnO nanoparticles using natural dye obtained from peels of pomegranate.

2. Materials And Methods

2.1. Preparation of Natural Dye from Pomegranate Peels

Pomegranate peels (3 g) were washed thoroughly with DD water and air dried. These peels were powdered and soaked in absolute ethanol (50 mL). This mixture was shaken at regular intervals, and left overnight for dye extraction. The optimum conditions were determined using RSM method. The ethanolic extracts were filtered and concentrated under vacuum using rotavapor. The precipitated materials were filtered out and the dye solutions were filtered through micron filters. The anthocyanin contents were calculated using RSM method. The photoelectrodes were soaked in this dye solutions and dye sensitized cells were assembled for solar cell efficiency measurements.

2.2. ZnO Nanoparticles Synthesis

PEG capped ZnO nanoparticles were synthesized as per the following procedure. Zinc acetate (0.1 M) along with PEG (1 g) was dissolved in double distilled water (200 mL) and stirred well. Then, sodium hydroxide (0.2 M) dissolved in double distilled water (200 mL) was added to the above solution drop wise until the pH of the solution reaches 11 - 12. The stirring was continued overnight and the precipitate was filtered, washed thoroughly with water and dried at 100 °C for 6 h. The dried product was calcined at 500 °C for 2 h to obtain the PEG capped ZnO nanoparticles.

2.2.1. Ag-doped ZnO Nanoparticle Synthesis

PEG capped Ag-doped ZnO nanoparticles were synthesized by adding *stoichiometric* amount of zinc acetate to 1%, 2%, 3%, 4% and 5% of silver nitrate with PEG (1 g) in DD water (200 mL) and stirred well. Then, sodium hydroxide (0.2 M) was dissolved in DD water (200 mL) and added to the above solution until the pH of the solution reaches 11 - 12. The stirring was continued overnight, the precipitate was filtered, washed with water and dried at 100 °C for 6 h. The dried product was calcinated at 500 °C degrees for 2 h to obtain the PEG capped Ag-doped ZnO nanoparticles.

2.3. Dye Sensitized Solar Cell Fabrication

The DSSCs were fabricated as per the following procedure. The FTO Glass plates (2 x 2 cm) was initially cleaned with ethanol and dried. The conducting side of the glass was identified using a multimeter and this surface was used for the photoelectrode fabrication. The glass plates were stuck with cellophane tape on all four sides and the photoanode was prepared by doctor-blade technique. The prepared zinc oxide powder was mixed with ethanol and converted into a fine paste. The prepared paste was smoothly coated with much care onto the conducting side of the cleaned glass plates using a glass rod. The plates were placed in furnace, heated to a temperature of 420 °C for a period of 20 min, and cooled further to room temperature. The cooled glass plates were dipped in the pomegranate peel extracted dye solution taken in a small petri dish for overnight at room temperature. The dipped glass plate was tightly covered and used during measurement. The similar procedure was adopted for preparing the photoanodes with silver doped zinc oxide semiconductor. To assemble the cell, a counter electrode is required. To prepare a counter electrode, the procured chloroplatinic acid solution was coated onto the FTO glass plate and sintered at 420 °C for a period of 15 min. The dye coated electrode was washed gently with ethanol to remove the excess dye present and air dried. Two drops of iodine/iodide electrolyte was gently introduced in between the photoanode and counter electrode to form a complete DSSC device. The fabricated device with the pomegranate dye was subjected to photovoltaic measurement using a solar simulator under conditions of 85 mW/cm² and the current density-voltage characteristics were recorded. The same procedure was adopted to fabricate the cells with silver doped semiconductor.

2.4. Characterization Methods

The natural dye extracted from the peels of pomegranate was characterized by absorption and FT-IR studies. The synthesized ZnO samples were characterized using Philips PW 3710 X-ray diffractometer and scanning electron microscopy (SEM) JEOL-JSM 6360 with EDAX, respectively. The optical studies were carried out using Perkin Elmer LS-35 Spectrometer. FT-IR spectra were recorded using the thin pellets (referenced against a KBr pellet) on a Thermo Nicolet 50 FT-IR in the 400 – 4000 cm frequency region. The photovoltaic performance of DSSCs were measured using Newport, Oriel Class A, 91195A-solar simulator.

3. Results And Discussion

3.1. Preparation of Natural Dye from Pomegranate Peels

The natural dye from peels of pomegranate was prepared by powdering the pomegranate peels and extracting the dye using ethanol followed absorption of dyes on the semiconductor surface as shown in Figure 2.

3.1.1. Optimization of Parameters of the Dye Extraction using RSM

For effective extraction of dyes, the temperature, time and amount of raw material were optimized using Response Surface Methodology (RSM). Central Composite Design method is selected from which the point where maximum yield could be obtained by varying various parameters. In this model one parameter is kept a constant and the other two are varied from which maximum yield can be obtained.

Table 1. The variable range chosen for the parameters.

Parameters	Range
Temperature	25 – 45 °C
Time	30 – 90 mins
Raw material weight	0.5 - 2 g

3.1.2. RSM graph for variation of time and temperature.

From the graph shown in Figure 3, the peak value indicated in red shows the highest yield obtained while performing the experimental runs. Here, raw material weight is kept constant and the other parameters are varied simultaneously. We can observe that yield of 38% had been obtained by placing raw materials weight at 1.25 g and the rest two *i. e.* temperature and time were varied. Central composite design method has been used where we get highest peak as well as the lowest peak.

3.1.3. RSM graph for temperature and time variation.

As seen in Figure 4, time is kept constant and the other two parameters are varied accordingly based on their range. The graphs are obtained by using the software design expert. The highest yield obtained is 38%

3.1.4. RSM graph for time and raw material variation.

Figure 5 shows the variation of time and raw material while temperature was kept constant at 35 °C while the other two parameters, time and raw materials were varied. We can observe the optimized yield when time is 60 mins and raw material weight is 1.25 g. The optimized yield after performing the runs is 38%.

Table 2. RSM optimization table.

			Factor 1	Factor 2	Factor 3	Response 1	
Std	Run	Block	A: Temperature (°C)	B: Time (mins)	C: Raw materials (g)	Actual (%)	Predicted (%)
1	5	Block 1	25	30	0.5	9	8.7
2	10	Block 1	45	30	0.5	13.8	14.1
3	14	Block 1	25	90	0.5	13.4	13.1
4	13	Block 1	45	90	0.5	10	10.3
5	18	Block 1	25	30	2	15.9	16.7
6	19	Block 1	45	30	2	18	19.4
7	7	Block 1	25	90	2	21	21.8
8	16	Block 1	45	90	2	14.9	16.3
9	1	Block 1	25	60	1.25	16.2	16.2
10	9	Block 1	45	60	1.25	17.6	16.1
11	20	Block 1	35	30	1.25	9.3	8.6
12	6	Block 1	35	90	1.25	10.5	9.7
13	15	Block 1	35	60	0.5	17.1	17.7
14	12	Block 1	35	60	2	31.5	29.4
15	4	Block 1	35	60	1.25	37.2	36.9
16	3	Block 1	35	60	1.25	35.5	36.9
17	11	Block 1	35	60	1.25	37	36.9

18	17	Block 1	35	60	1.25	37.5	36.9
19	8	Block 1	35	60	1.25	38	36.9
20	2	Block 1	35	60	1.25	36	36.9

From Table 2, we can observe that three parameters have been chosen which has to be optimized. Here the predicted vales are based on the software Response Surface Methodology (RSM). The highest yield is obtained at the temperature = 35 °C, time = 60 mins, raw material weight = 1.25 g, and 38% dye yield is obtained from experimental runs.

Quantification of anthocyanin present in the dye is also found out using the formula

$$\text{Anthocyanin Content(mg/100g)} = (A \times MW \times DF \times V \times 100) / (e \times l \times m_{\text{sample}})$$

were,

A – Absorbance = 0.1628

MW - Molecular Weight of Anthocyanin = 449.2 g/mol

DF - Dilution Factor = 1

V - Solvent Volume = 200 mL

e - molar absorptivity (26900)

l - Cell path Length (1 cm)

m - dry sample weight = 1.25g

After substitution of the values,

The anthocyanin content found in pomegranate peel crude dye was found to be **43.5 mg/100g**.

3.2. Characterization of Natural dye from Pomegranate Peels

3.2.1. UV-Visible Absorption Spectra

The absorption spectra of dye extracted from pomegranate peels was recorded in ethanol. The absorption spectrum is characterized by the absorption peaks at 320, 400 nm and a shoulder at 530 nm. All the peaks are characteristics of $\pi - \pi^*$ -transitions of the anthocyanin pigment present in the dye(Mary Rosana et al. 2020). The absorption spectrum is shown in the Figure 6.

3.2.2. FT-IR Spectra

The FT-IR spectra of the dye was recorded in mineral oil using Nujol-Mull. The anthocyanins contain aromatic ring, -C=O, -C-O-C- functional groups. The -C-H aromatic stretching frequencies are observed at 3446 cm^{-1} . The -C=O stretching frequencies are observed at 1637 cm^{-1} . The -C-O-C-stretching frequency due to ester groups are observed at 1046 cm^{-1} (Ahliha et al. 2017, Patni et al. 2020). From the absorption and FT-IR spectra we can understand that the anthocyanin groups present in the dye extracted from peels of the pomegranate are mainly responsible for the photovoltaic properties. The functional groups present in the dye can anchor on to ZnO and efficient electron will be there under sunlight illumination. The FT-IR spectra of the dye is shown in Figure 7.

3.3. Characterization of ZnO and Ag-doped ZnO Nanoparticles

3.3.1. XRD Analysis

The XRD pattern of PEG capped (8a) pure and (8b-f) Ag (1-5 %) doped ZnO nanoparticles recorded in the range of 20° to 80° and are shown in Figure 8. All diffraction peaks were for ZnO with the hexagonal wurtzite structure. The diffraction peaks at 2θ values are 31.8° , 34.6° , 36.4° , 47.9° , 56.9° , 63° , 66.6° , 68.3° , 69.3° , 72.5° and 77.3° corresponding to (100), (002), (101), (102), (110), (103), (200), (112), (201), (004) and (202), hkl lattice planes, respectively. The data obtained matches with the standard JCPDS file no. 036-1451 (Manikandan et al. 2017). In Figure 8f, two additional weak peaks were obtained at 38.2° and 44.4° corresponds to (111) and (200) lattice planes of face centered cubic (fcc) structure of Ag. This matches with the standard JCPDS file no. 4-0783 (Zheng et al. 2007).

3.3.2. FT-IR Spectra

FT-IR spectra of (9a) PEG (9b) PEG capped pure and (9c) Ag (3%) doped ZnO nanoparticles were recorded in the range $400\text{--}4000\text{ cm}^{-1}$ and are shown in Figure 9. Various functional groups and metal-oxide bonds present in the compound were analyzed using FT-IR analysis. In the FT-IR spectra, a significant peak at 432 cm^{-1} is attributed to the ZnO stretching mode (Babu et al. 2014, Parvin et al. 2012). The peak at 923 cm^{-1} indicates the aromatic C=C stretching mode (Gayen et al. 2011). The Absorption band at 3422 cm^{-1} attributes to the O-H group stretching mode, which indicates the existence of a small quantities of water absorbed by the ZnO nanostructure (Nakamoto 2006). The peak at 2347 cm^{-1} is due to the atmospheric CO_2 . The peaks at 1391 cm^{-1} and 1535 cm^{-1} depicts the stretching modes of C-O and C=O groups. Stronger and wider absorption bands are observed in the region $1128\text{--}830\text{ cm}^{-1}$ due to doping. All these observations reveal the formation of PEG capped silver doped ZnO nanoparticles.

3.3.3. UV-Visible Spectral Analysis

Absorption spectra of the PEG capped pure and Silver (1-5%) doped ZnO samples were measured by UV-Visible spectra (Pal &Giri 2010). Figure 10 shows the UV-Visible spectra of PEG capped pure and Silver (1-5%) doped ZnO nanoparticles. PEG capped pure ZnO nanoparticles showed strong UV absorption around

382 nm that could be related to the wurtzite crystal structure of ZnO (Wahab et al. 2007). PEG capped Ag doped ZnO nanoparticles exhibit the absorption band towards higher wavelength. Changes in the absorption peak due to doping exhibited changes in the band structure. The absorption band shift represents the change in the optical energy gap (Mittal et al. 2014).

3.3.4. SEM and EDAX Analysis

The surface morphological study and elemental composition of the prepared samples was performed using scanning electron micrographs (SEM) and energy dispersive X-ray analysis (EDAX). Figure 11 (a-c) shows the SEM and EDAX pattern of pure ZnO nanoparticles. From the SEM images, Figure 11a and 11b, the ZnO nanoparticles were formed with spherical shape and without agglomeration. PEG ensures the formation of well separated spherical shaped nanoparticles. Figure 11c shows the EDAX of ZnO nanoparticles. It indicates the percentage of zinc as 70% and oxygen percentage as 18% that confirms the formation of ZnO nanoparticles.

Figure 12a and 12b shows the SEM images of Ag-doped ZnO nanoparticles. Due to the silver doping the spherical shape of ZnO nanoparticles changed to oval shape as observed in the SEM images. PEG capping ensures the formation of well separated oval-shaped nanoparticles. Figure 12c shows the EDAX of silver doped ZnO nanoparticles. The percentage of zinc was found to be 58%, and oxygen percentage was found to be 12% and silver percentage was 2.7%. The SEM images and EDAX indicates the formation of oval shaped Ag-doped ZnO nanoparticles.

3.4. Photovoltaic Performance

The current-voltage characteristics of the fabricated DSSCs were measured at 1 sun radiation and are shown in Figure 13. The photovoltaic parameters are listed in Table 3. The DSSC cell with ZnO semiconductor shows the current density, $J_{SC} = 5.6 \text{ mA/cm}^2$, output voltage, $V_{OC} = 0.71 \text{ V}$, fill factor, $ff = 0.46$ and the power conversion efficiency, $\eta = 1.8\%$. The J_{SC} , V_{OC} , ff and efficiency values can be compared with that of the previously reported in the literature work. The anthocyanin from pomegranate leaves and ZnO fabricated DSSC have shown the $J_{SC} = 1.89 \text{ mA/cm}^2$, $V_{OC} = 0.555 \text{ V}$, $ff = 0.49\%$ and $\eta = 0.548\%$ (Chang & Lo 2010). The DSSC fabricated with pomegranate juice and ZnO semiconductor have shown the $J_{SC} = 5.1 \text{ mA/cm}^2$, $V_{OC} = 0.312 \text{ V}$, $ff = 0.272\%$ and $\eta = 0.43\%$ (Sirimanne et al. 2006), and with TiO_2 semiconductor have shown the $J_{SC} = 2.2 \text{ mA/cm}^2$, $V_{OC} = 0.370 \text{ V}$, $ff = 0.45\%$ and $\eta = 0.36\%$ (Bazargan et al. 2011). The DSSC fabricated with silver-doped ZnO semiconductor shows the current density, $J_{SC} = 0.68 \text{ mA/cm}^2$, output voltage, $V_{OC} = 7.9 \text{ V}$, fill factor, $ff = 0.39$ and the power conversion efficiency, $\eta = 2.1\%$.

The performance of ZnO based DSSCs are higher than the DSSCs reported in the literature. The dye purification followed optimization of maximum dye extraction and utilization for the DSSC fabrication enhances the DSSC performance. The lack of aggregation and the formation of spherical nanoparticles as inferred from the HR-SEM data can also contribute to the enhanced DSSC performance. From the

photovoltaic data, we can observe that there is 30% increase in the power conversion efficiency of DSSC based on Ag-doped ZnO semiconductor. The increase in the photovoltaic performance of Ag-doped ZnO is due to the powerful electron injection facilitated by the Ag-ion present in the ZnO semiconductor. The oval-shaped Ag-doped ZnO without the aggregation as seen from the SEM data can also contribute to the efficiency of DSSC.

Table 3. Photovoltaic Performance of DSSCs.

Dye	J_{sc} (mA/cm ²)	V_{oc} (V)	ff (%)	η (%)	Reference
Pome. Leaves -Anthocyanin	1.89	0.555	0.49	0.548	(Chang &Lo 2010)
Pomegranate Dye + ZnO	5.1	0.312	0.27	0.43	(Sirimanne et al. 2006)
Pomegranate Dye + ZnO	2.52	0.63	0.61	0.97	(Chauhan et al. 2016)
Pomegranate Dye + TiO ₂	2.2	0.370	0.45	0.366	(Bazargan et al. 2011)
Pure ZnO + Pome. Dye	5.6	0.71	0.46	1.8	<i>Present Work</i>
Ag-Doped ZnO + Pome. Dye	7.9	0.68	0.39	2.1	<i>Present Work</i>

4. Conclusions

In summary, we have described a simple and cost-effective method for the conversion of natural waste from pomegranate peels into electricity. The natural dye from pomegranate peels was extracted by grinding the peels into powder and extracting with ethanol. The natural dye extracts were characterized by UV-Visible and FT-IR spectra. ZnO and Ag doped ZnO nanoparticles were synthesized by a facile hydrothermal method. The particle shape and size of ZnO and Ag-doped ZnO were controlled by using polyethylene glycol (PEG) as the capping agent. The structural and optical properties of prepared samples were studied using XRD, FT-IR, SEM-EDAX and UV-Visible analysis. The SEM analysis of ZnO nanoparticles showed the formation of spherical shaped nanoparticles without agglomeration. The EDAX analysis of ZnO nanoparticles indicated the formation of ZnO nanoparticles with 70% of zinc and 18% of oxygen. The SEM images of Ag-doped ZnO indicated the formation of oval-shaped nanoparticles due to Ag-doping. The EDAX analysis indicated the formation of Ag-doped ZnO with 58% of zinc, 18% of oxygen and 2.7% of silver. The DSSC cell with ZnO semiconductor showed the current density, $J_{sc} = 0.71$ mA/cm², output voltage, $V_{oc} = 5.6$ V, fill factor, $ff = 0.46$ and the power conversion efficiency, $\eta = 1.8\%$. The DSSC fabricated with silver-doped ZnO semiconductor showed the current density, $J_{sc} = 0.68$ mA/cm², output voltage, $V_{oc} = 7.9$ V, fill factor, $ff = 0.39$ and the power conversion efficiency, $\eta = 2.1\%$. The performance of DSSCs is higher than the DSSC performance of the similar pomegranate based solar cells. From the photovoltaic data, we can observe that there is 30% increase in the power conversion efficiency of DSSC based on Ag-doped ZnO semiconductor. The increase in the photovoltaic performance

of Ag-doped ZnO is due to the powerful electron injection facilitated by the Ag-ion doped into ZnO nanoparticle.

In conclusion, the present study offers a simple and cost-effective method for the production of electricity from natural dye obtained from the peels of pomegranate generated everyday as the waste. We believe that the method offers simple, easy to fabrication and cost-effective as clean power production source in societies sustainable development. Also, it reduces the environmental pollution and inspires other researchers to generate power by utilizing more of such natural waste materials. As the energy demand increases every day, the sustainable development can be fulfilled by utilizing renewable energy resources such as sun. The work described in this article utilizes both waste material and renewable source for the generation of electricity.

5. Declarations

Conflict of Interest

Authors declare that there is no conflict of interest related to this work.

Ethical Approval

Not Applicable. As the work doesn't involve humans/animals.

Consent to Participate

Not Applicable.

Authors Contributions

Vincent Joseph Kanniyambatti Lourdusamy designed the work, carried out experiments and written manuscript. Mary Rosana Nalzala Thomas isolated natural dyes. Vijai Anand Kabali synthesized ZnO nanoparticles. Dhilip Kumar Rajaiah helped in the characterization.

Availability of data and materials

All data generated or analyzed during this study are included in this article

Author Declaration

The manuscript is written with the contributions of all the authors and all the authors have given approval for the submission of the manuscript.

Source of Support

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Figures

Figure 1

Schematic of natural waste to electricity conversion system.

Figure 2

Scheme for the dye extraction and photoelectrode assembly.

Figure 3

RSM graph for variation of time and temperature.

Figure 4

RSM graph for temperature and time variation.

Figure 5

RSM graph for time and raw material variation.

Figure 6

Absorption spectra of the dye extracted from peels of pomegranate

Figure 7

FTIR spectra of the dye extracted from peels of pomegranate

Figure 8

XRD of PEG capped (a) pure ZnO and (b-f) Ag (1-5 %) doped ZnO nanoparticles

Figure 9

FTIR spectra of (a) PEG (b) PEG Capped ZnO (c) Silver-Doped ZnO Nanoparticles.

Figure 10

Absorption spectra of the PEG capped pure ZnO and Silver (1-5%) doped ZnO nanoparticles.

Figure 11

(a-c) SEM and EDAX of ZnO nanoparticles

Figure 12

(a-c) SEM and EDAX of silver doped ZnO nanoparticles.

Figure 13

Current-Voltage characteristics of ZnO and Ag-doped ZnO solar cells under 1 sun radiation.

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