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Performance Simulation of *Ipomoea involucrata* Dye Extracts for Dye Sensitized Solar Cells

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Authors' contributions

This work was carried out in collaboration among all authors. Authors AOB and OSO designed the study, while authors OAI, FSA, AMO and PO performed the experimental analysis. Authors ROK and AOA managed the analyses of the study. Author ROK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Dye sensitized solar cells (DSSCs) were fabricated using crude and purified extracts from *Ipomoea involucrata* leaves and flowers. The crude extract was obtained using a solvent system based on the combination of distilled water, ethanol and nitric acid. Furthermore, the purified extract comprising anthocyanins was obtained from the crude extracts. In order to study, the effectiveness of the dye, optical and electrical characteristics was determined using a UV-Vis spectrophotometer and solar simulator respectively. The highest power conversion efficiencies (PCEs) of 0.00412% and 0.00234% was obtained for crude and purified extracts respectively. Also, optical absorbance examined indicate similar absorption pattern for the crude extracts as well as purified extracts. A distinctive peak between 500 and 550 nm was observed for the crude flower extract. The widespread availability of these plants and ease of extraction of the extracts make them useful as absorbers in DSSCs. Consequently, simulation to determine the performance of the extracts was established using MATLAB.

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1. INTRODUCTION

Photovoltaic systems, a form of solar energy technology, act in a very unique and useful way. They tend to respond to light by converting a portion of it into electrical energy. However, there are ambivalent views about the ability of these systems to provide sufficient amount of energy for our global needs. Silicon based solar cells presently account for the 93% of the total photovoltaic (PV) markets: PV devices based on highly crystalline silicon have attained power conversion efficiency of 26.7%, [1] which is close to the maximum theoretical efficiency limit (31%) predicted by Shockley and Queisser [2]. However, the silicon necessary for solar cells is required to be extremely pure and is obtained through expensive high temperature and high vacuum processes [3]. These limitations have encouraged the development of alternative PV technologies based on low cost processing and materials. The Dye Sensitized Solar Cells (DSSCs) represent one of the most encouraging PV technologies substitute to traditional silicon based solar cells. DSSC exhibit several elements of interest: they can be fabricated utilizing procedures based on low cost solutions, such as inkjet, screen printing or doctor blading methods [4].

The principle of operation of DSSCs is subject to the exciton creation due to interaction between photon and dye molecule. The excitons generated split to form electrons and holes. The electrons are absorbed by the semiconductor and then transferred to the conductive layer while the holes are transferred in the opposite direction. Based on this working principle, dye sensitized solar cells were able to reach a photoelectron conversion efficiency of up to 10- 11% [5]. The photoelectrode is one of the most important elements for obtaining high photoelectric conversion efficiency. Also, the dye used as sensitizer, which also function as a part of the photoelectrode, plays a vital role in absorbing sunlight and converting solar energy into electrical energy [6]. Among the strengths of DSSC lies in their extremely high performance in indoor conditions under artificial light compared to other PV technologies: an indoor efficiency up to 28.9% has been achieved (under 1000 lux indoor illumination) which could provide sufficient power to allow the autonomous operation of small electronic devices [7]. Although many metal complexes have so much amazing features such as good absorption and highly efficient charge transfer, the great cost and highly complex preparation methods of the efficient ones gave more focus toward the natural dyes, which are easily extracted from various plants. Therefore, natural dyes have received an increasing interest due to their low cost, abundance, non-toxicity and complete biodegradation.

Several research on the utilization of natural dyes as sensitizers for DSSCs have been carried out [8]. Sofyan et al. [9] studied natural dyes extract of fresh and dried plant leaves and discovered that spinach oleracea extract produced a higher performance after drying with an efficiency of 0.29%. It was discovered that plant seeds such as onion, rapa and Eruca sativa seeds used as dye sensitizers have efficiencies of 0.875%, 0.86%, and 0.725%, respectively [10]. Calogero et al. [11] carried out a research using red Sicilian orange juice dye as a sensitizer and a conversion efficiency of 0.66% was reported. An efficiency of 0.70% was reached when Rosella was used as a sensitizer for DSSCs [12]. Wang et al. [13] proposed the modified structure of coumarin derivative dye which produced an efficiency of 7.6%. The study of the structure and concentration of anthocyanins respectively by [14] and [15], in several natural dyes used as sensitizers for DSSCs showed that natural dyes with high amount of anthocyanin such as those extracted from blueberry and black raspberry, have exhibited improved performance. Chlorophyll (A) structure in *Punica granatum* peel extract gave a solar cell with 1.86% conversion efficiency [16]. Generally, natural bio-compounds, such as anthocyanins, carotenoids and cholorophylls, have numerous advantages over rare metal complexes for DSSC sensitization.

In this study, the optical and electrical characteristics of crude and purified extracts obtained from *Ipomoea involucrata* leaves and flower located in the premises of Lagos State University, Ojo, Lagos State, Nigeria was investigated. Also, further simulation on the electrical characteristics as well as phytochemical screening was taken into consideration.

2. MATERIALS AND METHODS

Ipomoea involucrata leaves and flowers were collected within the campus of Lagos State

University, Ojo, Nigeria. The samples (flowers and leaves) were air dried at room temperature for 4 hours. With the aid of liquidizer, the samples were pulverized. The pulverized samples were soaked separately using a solvent system that comprised of distilled water, methanol and M HNO_3 in ratio 10: 9: 1, respectively. One hundred grams of the pulverized sample was completely submerged in 120 ml of the solvent system and then covered in air tight glass bottle for 24 hours. Extraction occurred after 24 hours and the extract was decanted by evaporation in a water bath at 50 ± 5°C to obtain concentrated extract. The concentrated extracts were stored in dark bottles at room temperature. In order to obtain purified anthocyanin from the extracts, the method in [17] was utilized. The filtered extract was transferred into a separatory funnel and "washed" three times with equal volumes of ethylacetate to remove flavones. The third mixture of the extract and ethylacetate were mixed thoroughly in the separatory funnel and left overnight. The ethylacetate-free layer, containing the partially purified anthocyanin, was obtained. Then, equal volumes of the ethylacetate-free extract and that of 0.5% neutral lead acetate (Pb $(COO)_2$) solution were mixed and kept in the refrigerator at 4°C for 48 h to ensure complete precipitation of anthocyanin. After 48 h, supernatant and dark precipitate (anthocyanin) were obtained, the supernatant was discarded. Consequently, about 5 ml of 0.5% solution of sulfuric acid was added to the precipitate to remove lead as lead sulfate ($PbSO_4$), and the precipitate was simultaneously re-solubilized to give a red solution. The mixture was filtered to remove the $PbSO_4$ and the filtrate. The filtrate was concentrated in a water bath at 50 ± 5°C to obtain the purified anthocyanin. Subsequently, the TiO_2 film was prepared using the methods of [18] and the cells were prepared using the methods of [19]. The solar cells were assembled using the methods of [18]. The photovoltaic parameters of the completed solar cell were taken indoor by using a solar simulator.

2.1 Theoretical Simulation

Theoretically the photoelectrochemical behavior in the DSSC photoelectrode nanostructure was analyzed by [20]. The resulted equation relates the electron transport, electron recombination and electron photogeneration in thin films DSSC as:

$$D\frac{\partial^2 n(x)}{\partial x^2} - \frac{n(x)-n_o}{\tau} + \emptyset_o \alpha exp(-\alpha x) = \frac{\partial n}{\partial t} \quad (1)$$

where $n(x)$is the number of excessive electrons photogeneration concentrations at position *x* in the photoelectrode interface layer, n_o represents concentration of electrons below the equilibrium of the dark conditions, *D* correspond to the diffusion coefficient of the electron. The parameters τ, $\emptyset_o$and α represent the lifetime of the free electrons in the conduction band, the intensity Flux illumination of photons and light absorption coefficient of the thin film. In this paper, we use internal parameters in the DSSC (*Φ*, *α*, *m*, *L*, *D*) from previous researches which are written in Table 1 [21].

Table 1. Simulation parameters

Parameter	Published value
L ($cm^{-1}s^{-1}$)	2.2361×10^{-3}
$\boldsymbol{\alpha}$ (cm^{-1})	5000
M	4.5
D (cm^{-1} s^{-1})	5.0×10^{-4}
$\boldsymbol{n_0}$	10^{16}
$\boldsymbol{\tau_{ms}}$	10
∅ (cm^{-2} s^{-1})	$1.0 \quad \times 10^{17}$
d (cm)	10×10^{-4}
T (K)	300

The simulation activity was done with the input of DSSC equation in m-file in MATLAB along with the absorption coefficient of each of the extracted dye. The equations related to the simulation model are as follows:

$$J_{sc} = \frac{q\emptyset L\alpha}{1-L^2\alpha^2}\left[-L\alpha + tanh\left(\frac{d}{L}\right) + \frac{L\alpha exp(-d\alpha)}{cosh\left(\frac{d}{L}\right)}\right] \quad (2)$$

$$V_{oc} = \frac{KTm}{q} ln\left[\frac{LJ_{sc}}{qDn_o tanh\left(\frac{d}{L}\right)} + 1\right] \quad (3)$$

$$J = J_{sc} - \frac{qDn_o}{L}\tanh\left(\frac{d}{L}\right)\left[exp\left(\frac{qv}{KTm}\right) - 1\right] \quad (4)$$

3. RESULTS AND DISCUSSION

The absorbance of the extracts was measured using a UV-Vis spectrophotometer. The representative absorbance spectrum for the crude and purified extracts is displayed in Fig. 1. Anthocyanins have the ability to absorb light and convert it into electrons. It is observed that the crude extracts display similar spectra with the leaves crude extract exhibiting a higher absorbance in the visible region in comparison to the crude flower extract. Also, a distinctive peak is observed for the crude flower extract (E1 F) between 500 and 550 nm. This distinctive peak is attributed to certain anthocyanin compounds (malvidin, delphidin and cyanidin derivatives) which absorb at that wavelength. In similar vein, after purification of the crude extracts to obtain only anthocyanins, the absorbance spectra indicate that the purified leaves extracts have a higher absorbance spectrum in comparison to the purified flower extract. Due to the fact that this anthocyanin compounds were not isolated in the extracts before taking the absorbance measurements, broader peaks were observed rather than sharp absorption peaks [22,23]. Consequently, the leaves purified extract exhibits a higher absorbance compared to the other extracts which can be linked to the presence of high concentration of anthocyanins in the extract which helps in the absorption of light. Also, the difference in the absorption spectra could be due to the different colours of the extracts [24]. The absorbance spectra obtained for the extracts indicate that the samples can be used as sensitizers in DSSCs application.

The devices were fabricated using TiO_2 as the semiconducting mesoporous layers and used in absorbing the crude and purified extracts. The current density - voltage characteristics of these cells are shown in Figs. 3 to 6. The overall efficiency (η) was calculated using the following equations:

$$FF = \frac{V_m \times J_m}{V_{oc} \times J_{sc}} \tag{5}$$

$$\eta = \frac{V_m \times J_{sc} \times FF}{P_{in}} \times 100\ \% \tag{6}$$

Where P_{in} is the incident power on the cell, J_{sc} is short-circuit current density at zero voltage, V_{oc} is the open-circuit voltage at zero current density, J_m is the maximum current density, V_m is maximum voltage, and FF is the fill factor. The electrical characteristics of the fabricated devices were taken with the aid of a solar simulator. Figs. 2 to 5 displays the current density – voltage curves from the crude and purified extracts of *Ipomoea involucrata* flowers and leaves. The highest power conversion efficiency of 0.00412% and 0.00234% was obtained for the crude and purified extracts respectively. The corresponding photovoltaic parameters are shown in Table 2. It is observed that the overall PCE for the flower extracts (crude and purified) is higher than the leaves extracts (crude and purified). These differences in PCE could be attributed to the level of anthocyanins in each extract. Consequently, the results obtained using anthocyanins are lower or comparable to those reported in other studies: Rhuc/sumas fruits (1.5%) [25], *Hibiscus sabdariffa* (0.033%) [15], *Brassica olercea* (0.13%) [26]. The performance of the fabricated devices may be

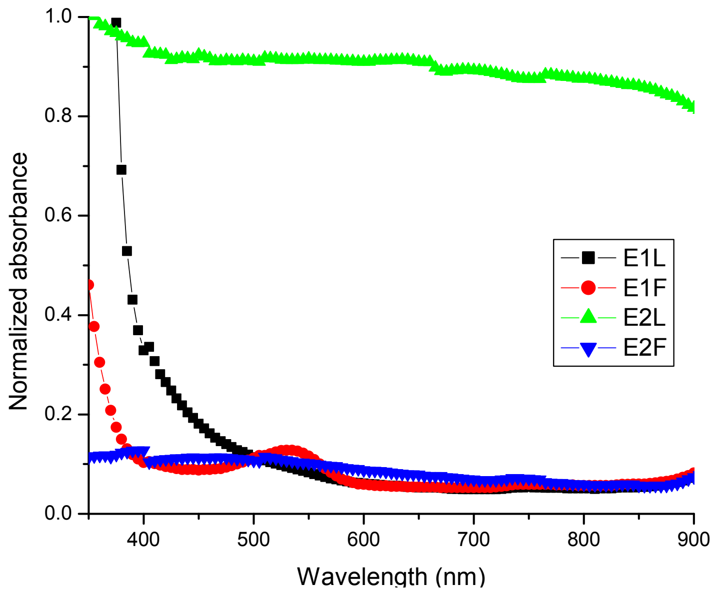

Fig. 1. Absorbance curve for *Ipomoea involucrata* flower and leaves extract (crude and purified)

**E1 L = Ipomoea involucrate leaves crude extract, E1 F = Ipomoea involucrate flower crude extract, E2 L = Ipomoea involucrate leaves purified extract, E2 F = Ipomoea involucrate flower purified extract* affected by the type of absorption between the anthocyanins and the TiO_2 pore structure [24]. It is assumed that the similarity in size between the pores and dye molecules results in more adsorption until the pores are filled with anthocyanins. Also, the anthocyanin structure can also affect the performance of the devices. It is predicted that a structure with longer R group will result in the hinderance for the anthocyanin to form bond with the oxide in TiO_2 [27,28]. Similarly, difference in dye structure and rate of charge injection into TiO_2 conduction band is responsible for the difference in the current densities [29]. The size of the barriers found in DSSCs and instability of the dyes which oxidizes in air tend to affect the power conversion efficiency [30]. Rahayu et al. [31] posits that increasing the absorbing ability of the dyes leads to improved performance of DSSCs. This is attributed to the fact that the dye serves as an absorber of incident light. Similarly, Zhou et al. [32] posits that when there is limited or no free space between the dyes, the physical contact between the iodine solution and TiO_2 could be attacked by the molecules. Thus, reduced reaction and lack of electron transfer from the anthocyanin to the TiO_2 conduction band hinders the efficiency of the devices which can be attributed to the low efficiency obtained from the present study.

Further investigation to determine the effectiveness of the dyes as sensitizers in DSSCs was embarked upon theoretically using the method of Södergren et al. (1994) and the PCEs of the devices was obtained and reported in Table 3. Also, Figs. 6 to 9 shows the current density – voltage curves for the simulated devices with different dye components. The results obtained from the simulation using MATLAB shows that the crude (leaves and flower) extracts exhibit high PCEs. Also, the low PCE obtained by the purified leaves extract could be attributed to the fact that other compounds that aided in improving the PCE for the crude leaves extract has been washed out limiting the effectiveness of the purified leaves extract. The simulation results indicate that the dyes can be utilized as sensitizers. A summary of the phytochemical screening is summarized in Table 4 which indicates the presence of certain compounds in the extracts.

Table 2. Photovoltaic parameters for the fabricated devices

Sample	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	PCE (%)
E1 L	0.00447	2.00059	0.36	0.00193
E1 F	0.00353	1.99942	0.73	0.00412
E2 L	0.00354	1.99986	0.51	0.00217
E2 F	0.00415	2.00003	0.47	0.00234

**E1 L = Ipomoea involucrata leaves crude extract, E1 F = Ipomoea involucrata flower crude extract, E2 L = Ipomoea involucrata leaves purified extract, E2 F = Ipomoea involucrata flower purified extract*

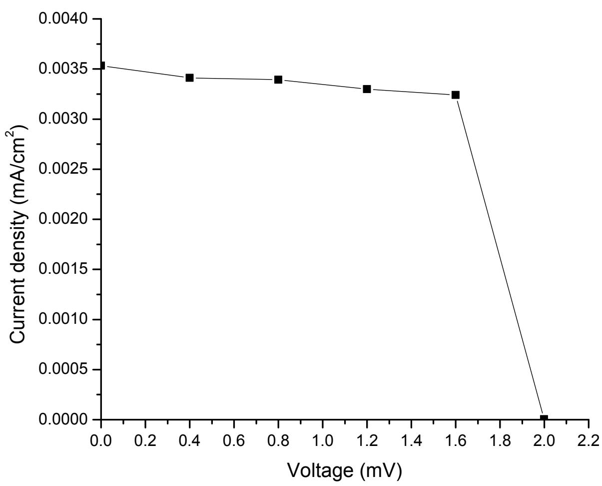

Fig. 2. Current density – voltage curve for *Ipomoea involucrata* flower crude extract

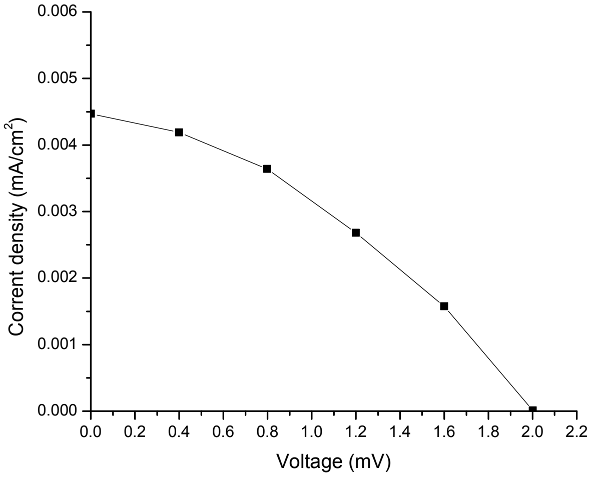

Fig. 3. Current density – voltage curve for *Ipomoea involucrata* leaves crude extract

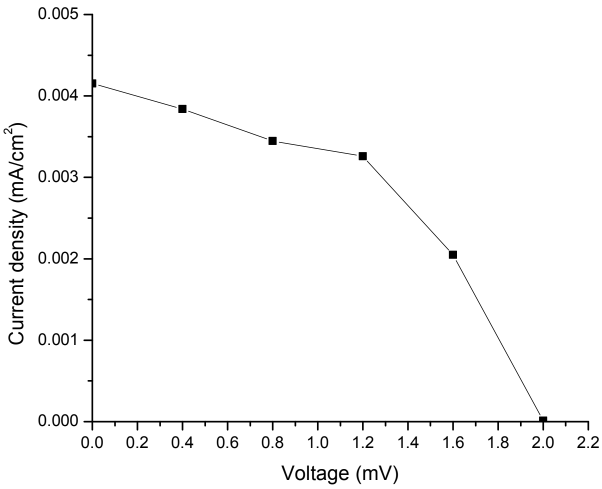

Fig. 4. Current density – voltage curve for *Ipomoea involucrata* flower purified extract

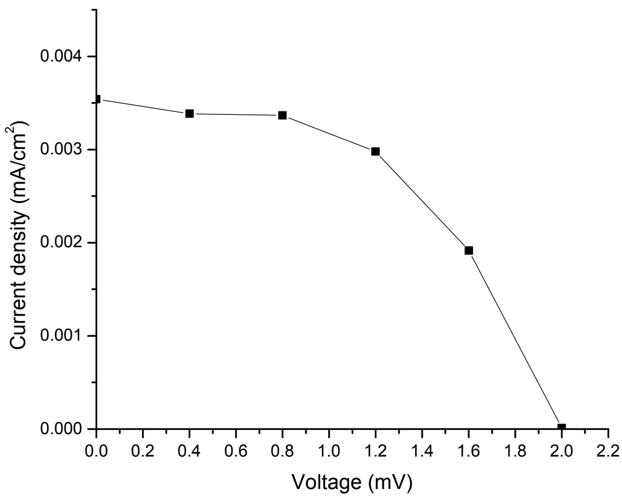

Fig. 5. Current density – voltage curve for *Ipomoea involucrata* leaves purified extract

Table 3. Photovoltaic parameters for the simulated devices

Sample	J_{sc} (mA/cm^2)	V_{oc} (mV)	PCE (%)
E1 L	0.00036	0.54	0.00461
E1 F	0.00036	0.54	0.00461
E2 L	0.00081	0.63	0.00102
E2 F	0.00010	0.39	0.00128

Table 4. Phytochemical screening of crude extracts

Sample	Saponins	Tanins	Flavonoid	Alkaloids	Anthraquinones	Salkowski's test
E1 L	++	+	-	-	-	+
E1 F	+++	-	++	-	-	-

Present (++), slightly present (+), no trace (-)

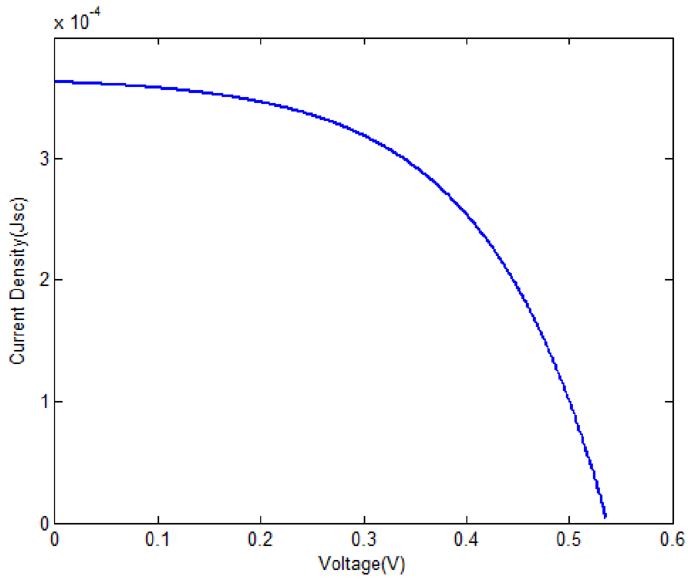

Fig. 6. Current density – voltage curve for *Ipomoea involucrata* leaves crude extract

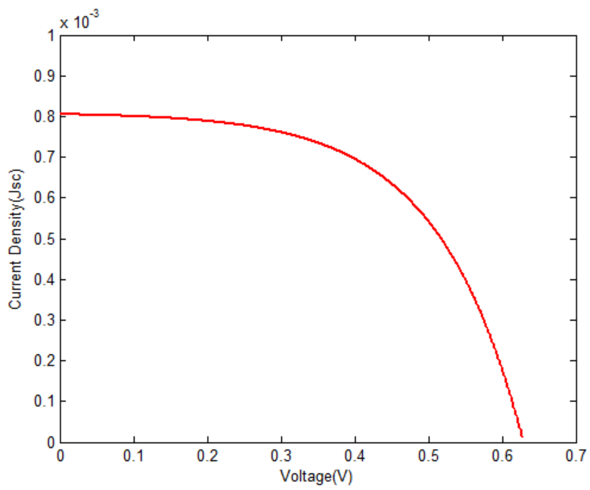

Fig. 7. Current density – voltage curve for *Ipomoea involucrata* leaves purified extract

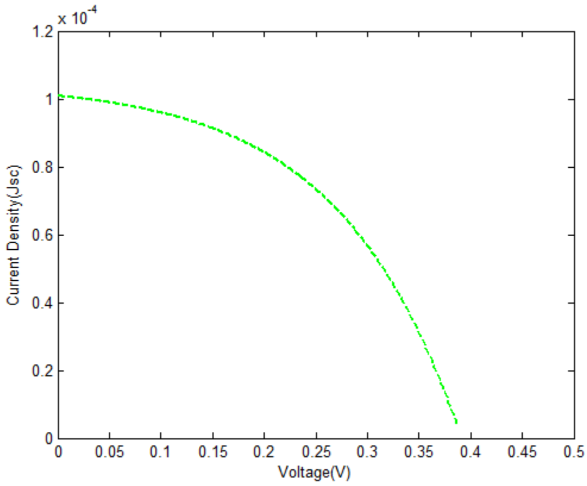

Fig. 8. Current density – voltage curve for *Ipomoea involucrata* flower purified extract

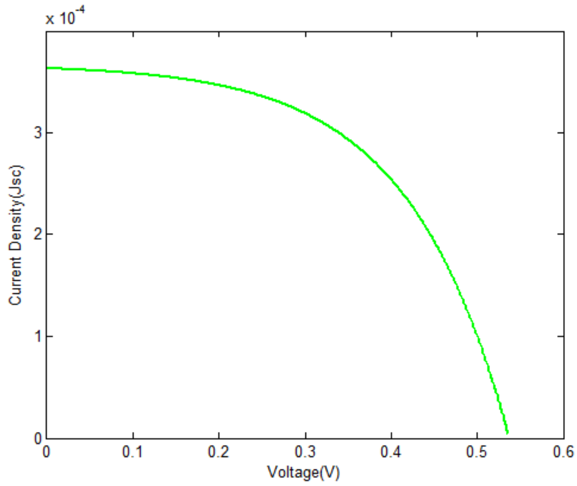

Fig. 9. Current density – voltage curve for *Ipomoea involucrata* flower crude extract

4. CONCLUSION

In summary, investigations based on the utilization of naturally occurring dyes from *Ipomoea involucrata* flowers and leaves for DSSC fabrication were embarked upon. Purified dyes extracted from the flowers have exhibited the highest efficiency. This is because the level of anthocyanins is attributed to be higher though exhibiting low current density. Also, the simulation results indicate that the dyes can be utilized as absorbers in DSSCs as crude and purified extracts, although, other studies to improve on the device performance and stability should be embarked upon. However, the low current densities attained from this study as compared to commercially available Ru based dyes could be attributed to the presence of impurities resulting from imprecise extraction processes. Consequently, isolation and purification of the different isomers of anthocyanins could help address the challenges associated and potentially enhance the power conversion efficiency.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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