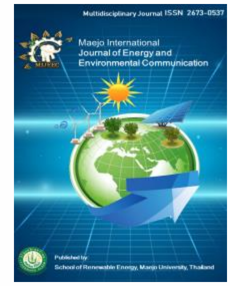
Maejo International Journal of Energy and Environmental Communication 5-1 (2023) 20-25

Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Investigating the effect of solvent on the efficiency of natural pigment-based dye-sensitized solar cells

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A R T I C L E I N F O

Article history:
Received 27 January 2023
Received in revised form
21 February 2023
Accepted 27 February 2023

Keywords:
Ficus benjamina
Solvents
Natural dye
DSSC
Biosolar

A B S T R A C T

Dye-sensitized solar cells (DSSCs) have gained attention recently due to their potential in renewable energy. DSSCs explore natural dyes as an alternative to conventional ruthenium-based dyes. This study chose *Ficus benjamina*, a plant known for its rich pigment, as the natural dye source. The extraction process involved ethanol, methanol, and double distilled water. Using these solvents, we aimed to determine which solvent would be most effective in extracting the dye and ultimately enhancing the efficiency of the DSSCs. The efficiency (η) clocked in at 0.198%, with an open-circuit voltage (V_{OC}) of 61.6 mV and a short-circuit current (I_{SC}) of 0.424 mA for the *F. benjamina* dye. When compared to other solvents, methanol stood out distinctly. Specifically, the efficiency of the DSSC prepared with methanol-extracted dye improved by 15.67% when contrasted with the double distilled water and 11.05% when juxtaposed with ethanol. This study used a UV spectrophotometer to investigate the extracted dyes' characteristics. This instrument allowed us to meticulously analyzed the dyes' absorption properties, providing further insights into their potential applications in DSSCs. Consequently, our research underscores the potential of natural dyes, particularly from *F. benjamina*, in DSSCs. The study can balance sustainability and efficiency in solar cell technology with the right solvent (methanol).

1. Introduction

The rising global energy demand, fueled by industrialization, urbanization, and population growth, largely relies on ecologically costly fossil fuels (Vu et al., 2022). These fuels contribute significantly to global warming through carbon dioxide emissions, resulting in climate anomalies like melting polar caps and intensified natural disasters (Pradechboon and Junluthin, 2022). These changes threaten both natural ecosystems and human societies with challenges such as food and water shortages. Renewable energy emerges as a potential solution (Junluthin et al., 2021; Unpaprom et al., 2021), but for effective adoption, it must be cost-effective, biodegradable, and sustainable in the long term (Manmai et al., 2022). Adopting renewable energy like solar, wind,

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and geothermal can reduce CO_2 emissions and potentially stabilize the planet's climate. While our current energy challenges are significant, transitioning to renewables offers a sustainable pathway forward (Bhuyar et al., 2022; Khammee et al., 2022). Solar cells technology has demonstrated solar energy harvesting with significantly good efficiencies (Hamzat et al., 2022), and the technology has constantly been evolving by making iterative improvements to the power conversion efficiency of the cell.

Solar Photovoltaics (PV) technology is well-established, but factors like the production cost complexity of manufacturing make it difficult to use PV cells for various applications (Ng et al., 2022). Therefore, several PV designs were explored to overcome these challenges. Dye-sensitized solar cells (DSSC) have attracted substantial attention over the past decade for their straightforward manufacturing method, high cost-to-efficiency ratio, and ability to deform their shape (Khammee et al., 2020; Mejica et al., 2020a). However, DSSCs struggle to maintain stability and lower photo-conversion efficiencies than crystalline silicon-based PV cells (Lee et al., 2015). Over the years, several techniques were adopted to improvise the efficiency of DSSCs (Mejica et al., 2020a), noticeably interested in developing a photoanode capable of photocatalytic dye degradation (Preeyanghaa et al., 2022).

DSSCs use dye molecules as sensitizers to harvest light energy and convert it into electrical energy. The dye molecules are often loaded on wide bandgap semiconductor material such as titanium dioxide (TiO_2) or zinc oxide (ZnO) nanostructures. Transparent conductive oxides (TCO), such as Indium or fluorine-doped tin oxide (FTO), are electrode substrates. Platinum is favored as a DSSC counter electrode due to its superior catalytic abilities. The counter electrode's reaction rate must be twice that of the working one. Using an iodine-based redox pair (I^-/I_3^-) as an electrolyte, sunlight exposure to DSSCs leads to dye molecule excitation and electron transfer through the TiO_2 working electrode to the counter electrode. Simultaneously, the electrolyte recharges the dye molecules, with the counter electrode sustaining the reaction's continuity (Kavitha et al., 2017). In the meantime, electrolytes lend one electron to dye molecules to restore them and undergo reduction.

Redox electrolytes based on copper complexes have demonstrated remarkable efficiency, reaching 13.1% under 100 mW/cm^2 (Munoz-Rojas and Moya, 2017). This efficiency escalates to 32% when exposed to an indoor light intensity of 1000 lux. The current research delves into understanding the impact of different solvents - ethanol, methanol, and double-distilled water (dd-water) - on extracting natural dyes from Ficus benjamina leaves. The concentration of the pigments in the freshly prepared natural dye was quantified and analyzed with the photoelectric performance of the developed DSSCs. Furthermore, a UV-Vis Spectrophotometer was utilized to examine the absorbance properties of the formulated dye solution.

2. Material and methods

2.1 Reagents

High-purity chemicals, including ethanol, acetonitrile, potassium iodide, ethylene glycol, Tween 20 surfactant, acetic acid, iodine, and titanium dioxide, all with a 99.99% concentration, were sourced from Union Science. Additionally, Fluorine-doped Tin Oxide (FTO glass) with a resistance specification of 10 ohms per square meter was acquired from a supplier in Hangzhou, Zhejiang, China.

2.2 Dye extraction

Dye extract was made from Weeping Fig (*F. benjamina*) leaves. They were blended with ethanol after cleaning and drying the leaves in the dark. The solution rested in darkness briefly before vacuum filtration. The pigment-rich filtrate was stored in a cool, dark place to protect the chlorophyll (Figure 1), and preparation methods were adopted (Khammee et al., 2020; Mejica et al., 2020a).

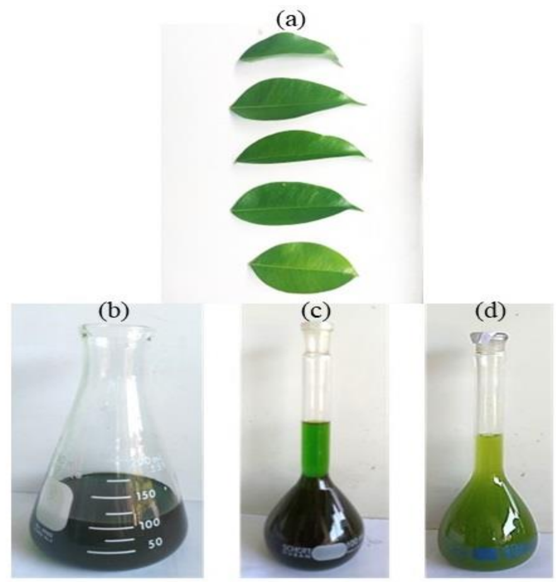

Figure 1. (a) Leaves of *F. benjamina* (weeping fig), Dye extract prepared using (b) Ethanol, (c) Methanol (d) double distilled Water (dd-water)

2.3 Photoanode preparation

A mesoporous TiO2 thin film photoanode was created by finely grinding TiO2 powder and mixing it with acetic acid and surfactant. This TiO2 paste was then applied to FTO glass using the Doctor's Blade method and sintered to establish the mesoporous layer.

2.4 Dye application

The prepared dye solution was meticulously dropped onto the photoanode for absorption. It was then allowed to dry in a dark setting for several hours. This procedure was performed twice to enhance dye molecules' adsorption on the photoanode.

2.5 Counter electrode preparation

A blend of activated carbon powder and ethanol was created for the counter electrode. This mixture was subsequently spread onto aluminum foil utilizing the Doctor's Blade technique and subjected to elevated heat for drying.

2.6 Electrolyte formulation

Utilizing the I^-/I_3^- redox pair as the chosen liquid electrolyte, it was developed through a straightforward procedure based on Gu et al. (2017) tailored for compact DSSC assembly. Notably, electrolytes rooted in iodine-based redox pairs are noted for their superior performance and have been extensively researched compared to other liquid electrolytes.

2.7 Fabrication of DSSC

The DSSC fabrication method is displayed in Figure 2. Cell assembly starts by attaching copper contacts to FTO glass deposited with TiO_2 photoanode. Then polyethylene membrane soaked in iodide electrolyte is sandwiched between a photoanode and a counter electrode made of aluminum foil coated with a thin layer of activated carbon.

2.8 Evaluating DSSC's photoelectric traits

The solar simulator was employed to gauge the assembled cells' photoelectric conversion efficiency (PCE). DSSCs, encompassing an effective area of 3 cm^2, were positioned under the simulator operating at 190 mW cm^{-2}. Through the MCP41010 microcontroller, resistance was incrementally increased, and the cell's voltage and current responses were documented. The PCE was ascertained using formula (1):

$$\eta = \frac{J_{SC} \times V_{OC} \times FF}{P_{in}} \quad (1)$$

Here, JSC, VOC, FF, and P represent the short-circuit current density, open-circuit voltage, fill factor, and power incident. The fill factor (FF) provides the proportion of the cell's peak power output to its theoretical peak, determined using formula (2):

$$FF = \frac{P_m}{(I_{SC} \times V_{OC})} = \frac{I_m \times V_m}{(I_{SC} \times V_{OC})} \quad (2)$$

The experiment was carried out in triplicate, displaying the results as mean ± standard deviation (SD).

3. Results and discussion

3.1 Photovoltaic performance of the cell

The photovoltaic performance of a cell is central to determining its capability to transform solar energy into functional electrical power (Nathanson, 2021). Numerous variables factor into this evaluation, underscoring the need to understand essential metrics when appraising the cell's efficacy and potential uses. One fundamental tool in this assessment is the current-voltage (I-V) Curve. This curve, which depicts the relationship between the current (I) and voltage (V) under light conditions, offers crucial insights into a cell's operational behaviors (Hofinger et al., 2021). Two primary performance parameters arise from this curve: the Isc and the Open-Circuit Voltage (Voc). Isc represents the cell's maximum current without external resistance, with higher values pointing to enhanced sunlight capture (Tayel et al., 2022). In contrast, Voc, the peak voltage when no current is under illumination, can illuminate the potential energy discrepancy in the cell's materials.

Another key performance parameter is the FF. Acting as an indicator of the cell's "squareness," the closer the I-V curve resembles a rectangle, the higher the FF, denoting superior cell performance. This factor is calculated by contrasting the maximum power point against the product of Isc and Voc. Power conversion efficiency (η) is an invaluable metric, signifying the fraction of sunlight energy converted into electric power (Rana and Saha, 2022). An elevated η indicates the cell's prowess in harnessing more power from identical sunlight exposure. Beyond these intrinsic metrics, external elements like temperature, light intensity, and spectral range can sway a cell's photovoltaic prowess (Kurumisawa et al., 2019). For example, elevated temperatures can diminish cell efficiency.

Equally pivotal is the role of materials utilized in the cell. As seen with the *F. benjamina* dye, certain materials can profoundly impact performance. These materials' capacity to tap into varying segments of the solar spectrum and their mutual interactions can significantly affect overall efficiency (Mariotti et al. 2020). A comprehensive analysis of a cell's photovoltaic performance necessitates an intricate approach, mulling its inherent attributes and the external factors influencing it. One can refine the design and materials through rigorous assessments, steering toward optimal energy conversion (Nathanson, 2021). The PV attributes of DSSCs are intrinsically linked to their I-V characteristics. A deep dive into these attributes reveals key performance indicators, notably the short-circuit current (Isc), Voc, FF), and the overarching power conversion efficiency (η).

Incorporating *F. benjamina* dye in the cells has emerged as a linchpin for optimizing this efficiency. By analyzing the I-V curve meticulously, one can ascertain the nuanced performance dynamics and the potential for enhancements in DSSCs. This analytical approach sets the stage for meticulous optimization of the PV response, driving innovations toward superior energy conversion in forthcoming designs. The photovoltaic metrics of the freshly prepared cells underscore the robustness of *F. benjamina* dye-infused DSSCs in consistently transforming solar energy into electrical power. Table 1 elucidates the pivotal photovoltaic characteristics of these DSSCs. The results indicate that methanol solvent for dye extraction has the highest power conversion efficiency (η) of 0.198% for *F. benjamina* based dye extract.

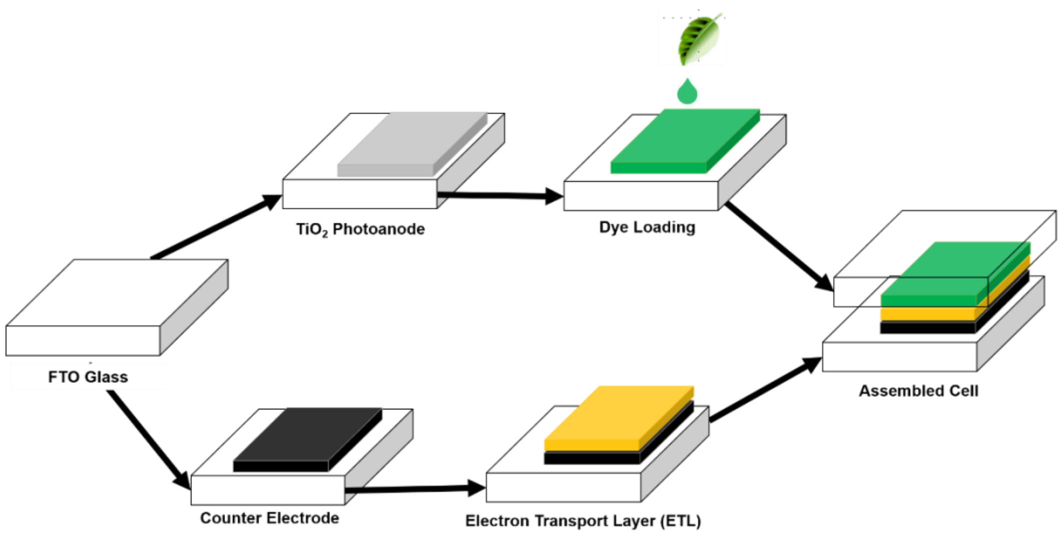

Figure 2. Schematic of DSSC cell assembly

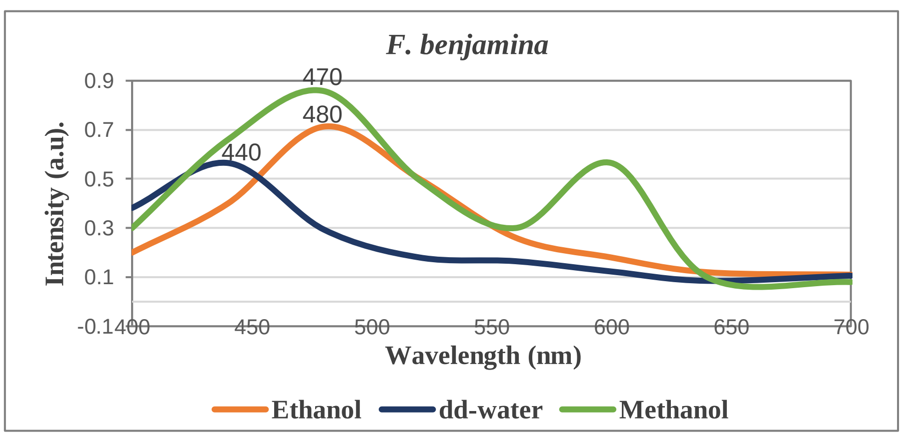

Figure 3. UV-Vis absorption spectra of dye extracted from *F. benjamina* using ethanol, methanol and dd-water as a solvent

Table 1. DSSC Performance Comparison

Dye	Solvent	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)	Reference
F. benjamina	Ethanol	0.2511	0.0089	14.98	0.016	**This Work**
	Methanol	0.0616	0.0447	31.72	0.198	
	dd-H_2O	0.6026	0.0060	12.88	0.012	
Verdant-turmeric	Ethanol	0.540	1.02	60	0.33	Hossain et al. (2017)
	Methanol	0.555	0.970	65	0.31	
Acanthus sennii chiov.	Ethanol + 1% HCl	0.507	0.491	60.4	0.150	Ayalew et al. (2016)
	Distilled water + 1% HCl	0.475	0.351	60.6	0.101	
Lyceum Shawii	Ethanol	0.580	0.420	42	0.100	Abdel-Latif et al. (2015)
Doum pericarp	Ethanol	0.37	0.005	63	0.012	Mohammed and Uthman, (2015)
	Distilled water	0.50	0.010	66	0.033	

3.2 UV-Vis characterization

UV-Vis is a different low-cost, rapid, and easy method of characterization that is typically used in Nano-Materials (NMs) research. Certain Magnetic Nano-Materials (MNMs) possess optical properties which are sensitive to size, shape of the agglomeration, state of agglomeration concentration, shape and the refractive index close to the surface of the NM which makes UV-Vis spectroscopy an important method to study these materials. The absorption characteristics of natural dye extracted using different solvents are studied using a UV-Vis photo-spectrometer and the results are shown in Figure 3.

Absorbance spectra show 400 – 550 nm and 600 – 750 nm peaks. This absorbance range indicates the signature of chlorophyll pigment (Kim et al., 2013). Further, the line shape of absorbance peaks for chlorophyll is in close conjunction with the literature (Ayalew et al., 2016; Hossain et al., 2017). The spectra depict maximum absorbance λmax at 440, 470 and 480 nm for dd-water, methanol and ethanol, respectively; this shows lower chlorophyll concentrations in dd-water. On the other hand, ethanol and methanol showed similar absorbance characteristics, whereas ethanol with strong absorbance at 480 nm. Figure 4 captures Mortar and piston, plant extract and dye solution used for grinding plant leaves with solvent, which is later used to estimate pigments in the solution. The solvent is added to the raw plant extract solution to make it up to 100ml. The solution in the cuvette represents the sample used for UV characterization.

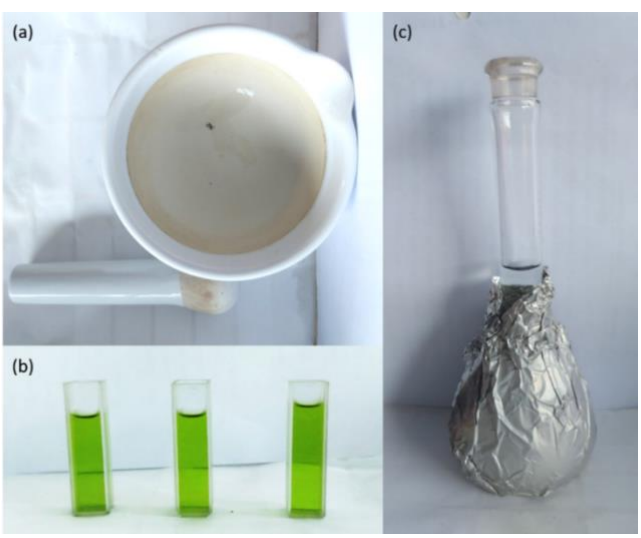

Figure 4. (a) Mortar and Piston (b) Plant extract on cuvette, and (c) Prepared dye solution

3.3 Solvent effects on natural pigment solar cells

Investigating the impact of solvent on natural pigment-based dye-sensitized solar cells yields wide-ranging implications. It promises a transformative influence on renewable energy generation, driving the advancement of solar energy harvesting technologies (Mejica et al., 2022b). Optimizing solvent selection enhances the efficiency of these cells, potentially revolutionizing their design to employ eco-friendly natural pigments for direct electricity generation from sunlight. Moreover, the versatility of dye-sensitized solar cells extends to diverse applications. Understanding solvent effects paves the way for integration into portable electronics like wearables, smart textiles, and chargers, offering sustainable on-the-go power sources (Ayalew et al., 2016; Hossain et al., 2017). Similarly, solvent insights aid the creation of efficient solar-integrated building materials in building-integrated photovoltaics, negating the need for conventional panels and promoting self-sufficient structures.

In regions lacking traditional electricity access, optimized solvents can drive natural pigment-based DSSCs to power small devices, serving off-grid and rural energy needs. Additionally, these cells present an engaging educational platform, simplifying renewable energy concepts through natural pigments. From now on, further research into solvent-solute interactions could spawn innovative systems enhancing light absorption and electron injection efficiency. This investigation enriches solar technology's efficiency, sustainability, and mainstream adoption by leveraging insights to explore a broader range of pigments and facilitating hybrid solar cell designs.

4 Conclusion

The photochemical performance of DSSCs with *F. benjamina* based natural dye extract has been studied extensively. The effects of three different extraction solvents on the cell's performance have been carefully analyzed. The pigment analysis of the extracted dye revealed that the carotenoid-to-chlorophyll concentration ratio plays a crucial role in the light harvestability of the natural dye. Photochemical studies have revealed that methanol has shown high performance compared to other solvents with an efficiency of 0.198% and Current Density of 0.0447 mA/cm^2, Maximum Power Density of 0.0113 μW/cm^2, Fill Factor (FF) of 31.72% and open-circuit voltage of 0.0616 V. Methanol has acted as anti-aggregation agent for dye molecules which enhanced the overall efficiency of the DSSC. In summary, methanol as a solvent has performed better than ethanol and ethanol has performed better than dd-water.

Acknowledgments

The authors express their gratitude to the School of Renewable Energy and the Energy Research Center at Maejo University, Chiang Mai, Thailand, as well as the Program in Biotechnology, for providing the research funding and necessary facilities to successfully conduct this experimental study.

Conflict of Interest Declaration

The authors assert that there are no conflicts or personal affiliations that might be construed as impacting the outcomes shared in this research.

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