

Optical Characterization of a 1:1 Combined Mango (*Mangifera indica*) and Moringa (*Moringa oleifera*) Leaf-Derived Natural Dye for Potential Dye-Sensitized Solar Cell Applications

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Received: October 05, 2026; Manuscript No: JMPM-26-4163; Editor Assigned: October 07, 2026; PreQc No: JMPM-26-4163 (PQ); Reviewed: October 23, 2026; Revised: October 27, 2026; Accepted: October 31, 2026; Published: November 25, 2026

Citation: Ibrahim IA, Umar HM, Zarewa IB, Aamir M, Saleh HA, Lawan NA, et al (2026). Optical Characterization of a 1:1 Combined Mango (*Mangifera indica*) and Moringa (*Moringa oleifera*) Leaf-Derived Natural Dye for Potential Dye-Sensitized Solar Cell Applications. J. Math. Phys. Mech. Vol.1 Iss.1, November (2026), pp:454-462.

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ABSTRACT

Natural dye-sensitized solar cells (DSSCs) offer a low cost and environmentally benign alternative to synthetic Ru-based sensitizers. However, most studies to date have concentrated on individual plant sources. This study reports the optical characterization of a 1:1 combined mango (*Mangifera indica*) and moringa (*Moringa oleifera*) leaf extract, prepared by cold maceration in acidified ethanol, as a candidate DSSC sensitizer. UV-visible absorption spectroscopy showed a primary absorption maximum (λ_{max}) at 650 nm and a secondary maximum at 450 nm, suggesting broad absorption of visible light in both the near-UV/blue and red regions of the spectrum. The optical band gap of 2.28 eV was obtained from Tauc plot analysis of the absorption edge, and this value is in the range of successful natural-dye sensitizers reported previously in the literature. These results suggest that device-level testing is the next step and that the combined extract has interesting optical properties for possible DSSC applications.

Keywords: Mango leaf extract; Moringa leaf extract; Natural dye; UV-Visible spectroscopy; Dye-sensitized solar cells (DSSCs)

INTRODUCTION

The ever-expanding demand for sustainable energy supply has attracted the attention of the academic and industrial research community to the development of low-cost Photovoltaic technologies. In particular, dye-sensitized solar cells (DSSCs) are investigated in this regard as efficient alternatives to conventional solar cells due to their desirable eco-friendly and economic characteristics, ease of fabrication and opportunities for optical properties molecular design to optimize [1]. Dye-sensitized solar cells (DSSCs) have been introduced as a potential new type of solar cells with low cost, easy manufacture and high efficiency, when compared to the traditional silicon-based ones. Besides their economic advantages they are also receiving attention due to the possibility of reducing environmental problems arising in energy generation. DSSCs, for example, have a much smaller carbon footprint than normal solar cells, and the construction process does not use toxic materials, thereby decreasing the possibility of harming the environment. Additionally, DSSCs can be modularized and installed into other buildings, thus not requiring extra land usage [2].

There are several well-documented disadvantages associated with the long-term use of synthetic ruthenium-polypyridyl complexes as sensitizers, despite their highest efficiencies compared to any other sensitizers to date. Ruthenium is a rare and expensive metal, complexation into dye molecules involves multiple-step synthesis under controlled conditions, and complexation and decomplexation processes create environmental and toxicity concerns throughout the lifetime of production and usage of the dye [3]. The restrictions have spurred a large number of studies on the possibility of using natural and plant-based pigments as sensitizer alternatives, which are cheaper, biodegradable, and easy to prepare compared to synthetic ones.

In particular, leaves of plants are good candidates for a source of natural chromophores, as they typically possess multiple classes of pigments at the same time. Such pigments are chlorophylls, carotenoids, anthocyanins, and tannins, which absorb light in various parts of the visible spectrum, the only common part of which is that they have different conjugated molecular arrangements. Various classes of pigments being present in a single leaf extract, in addition to the combined use of extracts from different leaf sources for enhancing the spectral coverage of the extract-made dyes, has made the dyes produced from leaves a promising region of research, though generally, dyes made from leaves are lagging behind the synthetic dyes in terms of raw conversion efficiency [3-4].

The leaves of mangos (*Mangifera indica*) contain abundant phytochemicals like phenolic acids, flavonoids, anthocyanins, mangiferin, carotenoids, and tocopherols [5]. UV/Vis absorption characteristics of mango leaf extract and chemicals responsible for this characteristic are stated. Therefore, mango leaf extracts have been screened as a natural sensitizer for dye-sensitized solar cells (DSSCs), and absorption in the 400-600 nm region has been reported [6]. But the absorption of these could be variable due to the different phytochemical composition of mango cultivars [7].

Moringa (*Moringa oleifera*) leaves have a unique but complementary phytochemical profile with large amounts of chlorophylls, carotenoids, flavonoids and phenolic compounds [8]. Absorption of anthocyanin and tannin-rich mango leaf extract overlapped with absorption of carotenoid and chlorophyll fractions suggesting that a synergistic effect of all three factors would be possible in a wider spectral region of absorption than would be possible from either the mango leaf extract or the chlorophyll alone. A complementary-absorption based justification is in agreement with prior works on natural-dye DSSCs, where specific natural dye systems were designed with definite and measurable changes in the absorption behavior of natural dyes by intentionally combining or mixing the individual dyes [9].

Although plant-to-plant color combinations have been done before, the combination of mango and moringa leaf extracts in a defined and controlled ratio has not been investigated specifically for optical characterization. The mango extract and moringa extract have been investigated separately or together in other applications, like the synthesis of nanoparticles, but there is no systematic investigation regarding the absorption behavior, optical band gap, and Urbach energy of mango + moringa extract 1:1 in the literature, to the best of the author's knowledge. The existence of unpublished, regionally indexed, or non-English-language work reporting a similar combination is not precluded, and the novelty claim made herein should therefore be interpreted as being based on the literature search carried out for the purposes of this thesis and not as an absolute claim to priority.

The dye-sensitized solar cells use a dye that absorbs light, which in turn facilitates the transfer of electrons that yield usable energy, but the most usual dyes used for this purpose have a number of practical drawbacks. The metal these sensitizers are based on, ruthenium, is too expensive and not very common to make dyes at any large scale or to use the metal in dyes. It is not simple to convert the raw ruthenium to a usable polypyridyl complex either, as it involves multiple steps of synthesis with highly controlled lab conditions, which increases the cost and demands of the technology that many research laboratories are unable to afford. The compounds are not readily degraded in the environment, and the wastes from their manufacture and elimination are actually toxic. They are not particularly good at absorbing light, either, and they don't absorb a very wide range of the solar spectrum, they absorb only a rather small percentage of the available sunlight. Scarcity, difficult synthesis, environmental persistence, and narrow absorption are not discrete problems but rather are different facets of the problem that is a difficult to use at any reasonable-scale sensitizer.

Natural dyes from plants overcome some of these drawbacks. Natural dyes are extracted from common plants like mango and moringa leaves, which are readily available, they are low cost, non-toxic, and biodegradable and can be made by relatively simple extraction procedures that do not require special synthesis equipment. The properties render natural dyes a potential and eco-friendly method of dyeing, especially in areas where synthetic dyes are not readily available.

The results showed that the absorption and DSSCs performance of the dyes extracted by Soxhlet and ultrasonic extraction techniques from *Rhamnus tinctoria* seeds, *Rubia fruticosa* fruits, and *Pinus pinea* bark were different, indicating that the dye performance is not limited to the plant material alone [10]. The properties of the dye can also be affected by the extraction process. Comparable results have been reported for less common plants investigated for their potential as visible-light sensitizers, such as *Carissa spinarum*, *Iresine herbstii* and *Ipomea purpurea* [11]. The effectiveness of extracts of *Vernonia amygdalina*, *Goeppertia macrosepala* and *Cnestis ferruginea* were also found to be dependent on the plant species and extraction solvents. This suggests that the selection of the plant source, solvent, and extraction technique could all affect the appropriateness of a natural dye for a DSSC application [12]. The performance of plant pigments has also been found to be different when compared with other biological pigments. In fact, it was found that pomegranate and hibiscus dyes had better performance than the microbial pigment prodigiosin [13]. In addition, it has been observed that the optical band gap values of dye change depending on the type of pigment used in the dye when dye reflectance is measured on Degussa P25 photoanodes [14]. Table 1 summarizes the key findings of related literature.

Table 1 Summarizes the finding of related literature

Authors	Focus	Key Finding
Alinejad, 2023 [15]	Saffron-sensitized DSSCs with PVA-based gel polymer electrolytes	Electrolyte composition significantly affects natural-dye DSSC stability and performance alongside dye choice
Mahmoud, 2025 [16]	Triphenylamine-based dyes as DSSC co-sensitizers	Co-sensitization with molecularly engineered dyes improved photovoltaic performance over single dyes
Khammee, 2023 [17]	Inthanin bok leaf extract as DSSC light-harvesting dye	Leaf-derived dye functioned effectively as a light-harvesting unit in DSSC assembly
Lana et al, 2025 [18]	Microalgae and plant dyes for TiO ₂ -based DSSCs	Band gaps ranged 1.67–2.87 eV; combining two dye sources produced a synergistic efficiency increase
Sarto, 2025 [19]	Grape skin extract on Ag-decorated TiO ₂ nanotube photoanodes	Tauc plot analysis gave TiO ₂ nanotube band gaps of 3.00–3.20 eV, with confirmed dye adsorption via Raman spectroscopy
<i>Present study</i>	Optical characterization of 1:1 mango-moringa leaf extract for DSSC application	Dual absorption peaks at 650 nm and 450 nm, results support candidacy as a DSSC sensitizer, pending device-level testing.

The focus of studying natural dye-sensitized solar cells (DSSCs) has largely concentrated on the optical properties of individual plant extracts such as their absorption spectra, optical band gap, and Urbach energy. Research on dye mixtures has also revealed that different amounts of the pigment's composition in the various extracts can increase the amount of light absorbed by the mixture. Mango (*Mangifera indica*) and moringa (*Moringa oleifera*) leaves are among the light-absorbing compounds, which are easily available and cheaper to acquire and can be used as natural dyes. The mango leaves have phenolic and flavonoid compounds, and moringa leaves have chlorophylls and carotenoids. The optical properties of a 1:1 mixture of mango & moringa leaf extracts, however, have not been extensively studied. Data about the absorption spectra, optical band gap of this specific combination is still somewhat scarce. Hence, in this study the optical properties of a 1:1 mango-moringa leaf extract are investigated, and its application as a natural dye sensitizer for DSSC is examined. The specific objectives are outlined as follows: (i) To prepare Mango and Moringa leaf extract using cold maceration (ii) To prepare a combined Mango and Moringa at a controlled 1:1 Volume ratio (iii) To determine UV-Visible absorption spectrum of the combine extract (iv) To determine the optical band-gap using Tauc plot (v) To assess the potential suitability of the combine extract dye for Dye-sensitized solar cells based on its optical characteristics.

Experimental

Chemical and Materials

The chemicals and materials used in this study are ethanol, distilled water, Whatman No. 1 filter paper, a funnel, dried moringa and mango leaf powder, a refrigerator, a magnetic stirrer, and an electric blender.

Collection and preparation of *Moringa and Mango leaf*

The moringa leaves and mango leaves were picked from the moringa garden at Mewar University in the morning. For compositional uniformity, only leaves that are uniformly colored and have no physical damage, disease, or discoloration were accepted. The leaves were washed twice with fresh tap water to wash away the dust and bigger surface particles, followed by distilled water to wash any remaining soluble particles, and were shade-dried at room temperature (25–30°C) for 2–5 days. The dried leaves were then powdered in a laboratory blender and stored in the container.

Preparation of Moringa Leaf Extract

The extraction of moringa leaf extract was performed using Cold maceration method using the method in the published literature. To maintain the pigment compounds, moringa leaf dye has been extracted using a cold maceration process. 5 g of the ground moringa leaf powder were placed in a beaker, which had 90 mL of ethanol to which 0.5 mL of hydrochloric acid (HCl) had been added. The mixture was stirred magnetically at room temperature for 1 hour. It was then transferred to a conical flask and covered with aluminum foil to prevent solvent loss and exposure to light and allowed to macerate for 24 hours. The extract was filtered through Whatman No. 1 filter paper, and the filtrate was kept in an amber bottle at 4 °C till further use.

Preparation of Mango Leaf Extract

The mango leaf extract was prepared following the method outlined below: The mango (*Mangifera indica*) leaf dye was prepared the same way. 5 g of ground mango leaf powder were weighed in a beaker, and 90 mL of ethanol with 0.5 mL of HCl was added. This

was stirred at room temperature for 1 hour without heating and then transferred into a conical flask, covered with aluminum foil and left to macerate for 24 hours. The extract was first filtered through Whatman No. 1 filter paper, and the filtrate was kept in an amber bottle at 4 °C for subsequent use.

Preparation of the Combined Extract

The combined mango-moringa dye was prepared from the two stock extracts in Sections 2.3 and 2.4 in a ratio of 1:1 by volume. 1 mL of mango extract was measured and mixed with 1 mL of moringa extract in a clean sample vial and then diluted with 1 mL of ethanol, the same extraction solvent, to bring the total volume to 3 mL. The mixture was homogenized and then measured spectrophotometrically using UV-visible spectroscopy.

UV-Visible Spectroscopic Analysis

The mango extract, moringa extract and mango-moringa extract (1:1) were analyzed by optical absorption measurement using a double beam UV-Visible spectrophotometer. Here the light from the source is divided into two beams, one of which passes through the sample and the other through the blank, at the same time. This enables the instrument to compensate for drift in intensity of the lamp and absorbance of the solvent throughout the scan, resulting in more stable readings than a single-beam system. The sample volume of 3 mL was placed in a quartz cuvette having a path length of 1 cm, for each reading. A blank was made with ethanol as the solvent. All extracts were scanned between 250–800nm and the absorbance was measured at intervals of 50nm.

The absorbance at each wavelength is proportional to the amount of absorbing material, following the Beer-Lambert Law, which states the absorbance of the sample is proportional to concentration of the absorbing material and the path length of the light through the medium:

$$A = \epsilon cl \dots\dots \text{eq (1)}$$

The absorbance is denoted by A and the molar extinction coefficient of the pigment is denoted by ϵ , the concentration of the extract is denoted by c, and the optical path length of the cuvette used is denoted by l (which is 1 cm in this study).

The absorbance data was used to determine the optical band gap of each extract, by applying the Tauc relation:

$$(\alpha h\nu)^n = A(h\nu - E_g) \dots\dots \text{eq (2)}$$

The formula is given as: $\alpha = A(h\nu/E_g)^n$ where α is the absorption coefficient, h is Planck's constant, ν is the frequency of incident radiation, A is a constant and the exponent n is set by the nature of the electronic transition ($n = 2$ for a direct allowed transition, $n = 1/2$ for an indirect allowed transition, and $n = 3/2$ and $n = 1/3$ for the corresponding forbidden transitions). The absorbing species in the extract are discrete, conjugated organic pigments (chlorophylls, carotenoids, flavonoids, and anthocyanins), whose visible bands arise from localized $\pi \rightarrow \pi^*$ transitions between molecular orbitals and not from band-to-band transitions involving a change in crystal momentum. A direct allowed transition ($n = 2$) was therefore adopted, as is commonly done for natural-dye extracts in the DSSC literature. The value obtained in this way is an apparent optical energy gap and should not be read as the band gap of a crystalline semiconductor. Band gap (E_g) was obtained by extrapolating the linear portion of the Tauc plot to $(\alpha h\nu)^n = 0$. The absorption coefficient was estimated as $\alpha = 2.303A/l$, and the uncertainty in E_g was taken from the standard error of the extrapolated intercept of the linear fit.

RESULTS AND DISCUSSION

UV-Vis Absorption Spectrum

The 1:1 mango-moringa extract had the highest absorption among the others over the entire range measured (250–800 nm) with peak absorption ($A = 0.9644$) at 650 nm. A second, broader absorption region appeared between 300 and 450 nm, peaking at 450 nm ($A = 0.9061$) and remaining elevated at 350 nm (0.8780) and 400 nm (0.8068). There was also a decrease in absorbance towards baseline in the region of 550-600 nm and again after 650 nm. The extract thus absorbs strongly in two distinct regions of the visible spectrum – blue/near-UV and red – and has weaker absorption in the middle of the spectrum, which makes it more capable of absorbing a wider range of the spectrum than a typical natural dye from a single plant source. The readings at 550, 600 and 750 nm are slightly negative (as low as -0.0022) but are due to baseline drift (not absorbance) and are considered negligible. Figure 1. illustrates UV-Visible absorption spectrum of diluted 1:1 combine moringa (*Moringa oleifera*) and mango (*Magnifera indica*) leaf extracts.

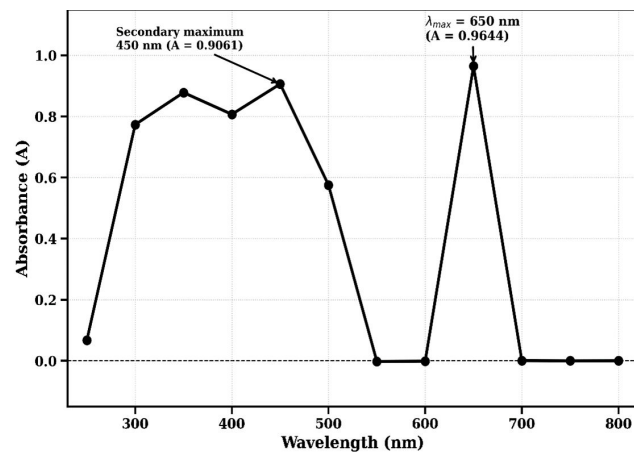


Figure 1: demonstrates UV-Visible absorption spectrum of diluted 1:1 combine moringa (*Moringa oleifera*) and mango (*Magnifera indica*) leaf extracts.

The graph demonstrates absorbance versus wavelength for the 250-800 nm wavelength range that was scanned. They are able to identify two peaks, one broad and rounded, with a maximum at around 450 nm but over a range of approximately 300-500 nm, and the other is quite sharp, with a maximum at 650 nm, the highest point of the curve. The curve of these two dips to almost zero absorbance between 550 and 600 nm and again to nearly zero and beyond 650 nm until the scan ends at 800 nm. With a separation of 50 nm between the recording stations, the slopes of the rising and descending sections have a maximum at 650 nm, the highest point of the curve. The curve of these two dips to almost zero absorbance between 550 and 600 nm and again to nearly zero and beyond 650 nm until the scan ends at 800 nm. With a separation of 50 nm between the recording stations, the slopes of the rising and descending section of the peak at 650 nm are particularly steep.

Optical Band Gap (Tauc Plot Analysis)

The optical band gap was estimated from the Tauc relation $(\alpha h\nu)^2 = A(h\nu - E_g)$, taking $n = 2$ for a direct allowed transition and $\alpha = 2.303A/l$ with $l = 1$ cm. Linear fitting of the $(\alpha h\nu)^2$ versus $h\nu$ plot over the 450-550 nm absorption edge gave $E_g = 2.28$ eV with $R^2 = 0.980$. Because the fit rests on only three points, the standard error of the extrapolated intercept is about ± 0.04 eV; this figure reflects the quality of the fit alone and is not a replicate-based uncertainty. Each spectrum was recorded once, at 50 nm intervals, so no replicate measurements are available, and run-to-run variation in absorbance and in E_g could not be quantified. The coarse wavelength spacing also limits the precision of the edge position, since adjacent points near 2.3-2.8 eV are separated by roughly 0.2-0.3 eV. The value of 2.28 eV should therefore be regarded as a preliminary estimate. Repeated measurements (at least three independent extractions, each scanned in triplicate at a finer wavelength step of 1-5 nm) will be required to report a mean $\pm$ standard deviation. The choice of $n = 2$ follows from the molecular, $\pi \rightarrow \pi^*$ character of the absorbing pigments (Section 2.6), but it was not tested experimentally here. Other exponents would shift the extrapolated value, and with only three points in the edge region the data cannot discriminate between them. A rigorous test would compare the linearity of the $(\alpha h\nu)^n$ plots for $n = 2$ and $n = 1/2$ over a densely sampled edge, together with an Urbach-energy analysis of the absorption tail. The value found here lies within the range of 1.7-2.9 eV reported for natural-dye systems [18]. No band gap is assigned to the 650 nm band because only two measured points lie near this peak (corresponding to about 1.9 eV) and a linear extrapolation is not justified. Figure 2. Presents Tauc plot of diluted 1:1 combined moringa (*Moringa oleifera*) and mango (*Magnifera indica*) leaf extracts.

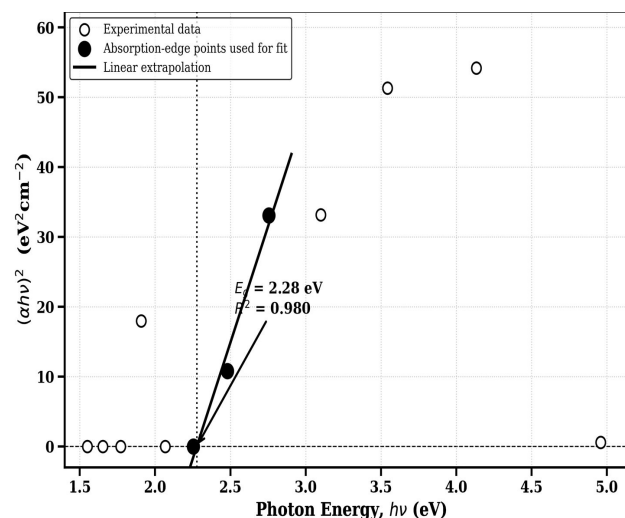


Figure 2: illustrates Tauc plot of diluted 1:1 combine moringa (*Moringa oleifera*) and mango (*Mangifera indica*) leaf extracts.

The variation of $(\alpha h\nu)^2$ with $h\nu$ is indicated in the Figure 2. Some of the data points from the experimental absorbance spectrum are converted to a set of open circles. Three of the points (450, 482, and 524 nm, or 2.26, 2.48, and 2.76 eV) selected from the well-resolved 450-550 nm absorption edge are plotted as filled circles. The solid straight line drawn through these three points and extended to the horizontal axis. This is the crossing point shown at 2.28 eV, called the optical band gap and represented by the vertical dotted line.

Interpretation of the Spectrum

The two absorption bands are typical of conjugated plant pigment $\pi \rightarrow \pi^*$ transitions. The absorption bands of mango leaves in the red and blue region are due to phenolic acids, flavonoids, and anthocyanins [5,8]. The absorption bands of moringa leaves in the blue region are due to chlorophylls, carotenoids, flavonoids, and phenolics. In case of multiple types of pigments absorbing in a similar range, it is only possible to conclude that a certain pigment is one of the abovementioned types but not which type specifically. However, confirmation at the compound level would be necessary (FTIR or HPLC), and that is beyond the scope of this study.

Effect of Combining the Extracts

The overall extract has two absorption peaks in the same two spectral windows as observed for other combined natural dyes, as mentioned in [9]. From this data, it is impossible to draw a quantitative conclusion because, in this study, the mango-only and moringa-only extracts were not scanned independently under the same conditions, so it is not possible to compare the absorption intensity of both extracts or compare the combination with the two extracts separately. The data does not show that the two band structures are synergistic; they are a direct effect of mixing the two extracts.

DSSC Relevance

The broad visible absorption and the apparent optical gap of 2.28 eV fall within the ranges reported for other natural sensitizers, so the extract shows optical features that are compatible with a candidate DSSC dye. The 450 nm and 650 nm bands cover the blue and red regions of the solar spectrum, although absorption is weak between about 550 and 600 nm, where the solar photon flux is high. Optical suitability, however, is only a necessary condition for sensitization. Device performance also depends on the following: adsorption and anchoring of the pigments on TiO_2 (the extract contains no deliberately designed anchoring groups); alignment of the pigment HOMO and LUMO levels with the TiO_2 conduction band edge and the redox potential of the electrolyte; electron-injection efficiency; the rate of charge recombination; and pigment stability. None of these were examined here, and the absorption spectrum was recorded in ethanol solution, not on a dye-loaded TiO_2 film, where band positions and intensities usually change. The comparison with the literature is also only qualitative. Natural-dye DSSCs based on chlorophyll, anthocyanin, or mixed-pigment extracts typically report band gaps of roughly 1.7–2.9 eV and power conversion efficiencies below about 3%, and the present extract cannot be ranked against them until its efficiency is measured. In this study no device was fabricated or tested, so the results are limited to optical characterization and do not demonstrate sensitization performance. Such a claim would require J–V characteristics under standard illumination (AM 1.5G, 100 mW cm⁻²) with the resulting power conversion efficiency, IPCE spectra, and electrochemical impedance spectroscopy to examine charge transport and recombination.

Comparison with Previous Studies

The two-band absorption profile (A at 650 nm and 450 nm) of this study was similar to that of, which added anthocyanin extract at a 1:1 ratio to chlorophyll extract [20]. We added complementary absorption to improve the absorption profile. We found that the anthocyanin of the mangos and the chlorophyll of the moringa were co-chromophores and not absorbing separately. The range of absorbencies for the three pigments was 400-700 nm, which is similar to the range of absorbencies used for the extract in this investigation (300-650 nm) [21]. On the other hand, the acidified ethanol extractant is similar to Erande, 2021 for anthocyanin-rich pomegranate, although the increasing band gap they reported (3.23 eV) is larger than the band gap of this study (2.28 eV), perhaps due to the presence of added pigments (chlorophyll and carotenoid), which tend to shift the absorption edge and hence the band gap to lower energies than an anthocyanin-only system would exhibit [22]. The selection of the solvent will not always be a one-size-fits-all situation. In this study acidified ethanol proved to be a safe solvent for mango's pigment fraction, but this is not necessarily true for moringa plants, distilled water was found to be the best solvent for *Rivina humilis* betalains Aliah, 2023 and methanol for *Annona atemoya* and *Physalis peruviana* [23-24]. The maceration time used in this study was 24 hours, as in the other study done by Kusumawati, 2024, but with a higher sample-to-solvent ratio (1:6), it is possible that this could be one of the reasons for the differences in absorbances between the two studies [21]. As another limitation mentioned in Section 4.2, used in the Tauc plot regression but not applied to these two, it is able to scan with a higher resolution.

FUTURE PERSPECTIVE AND SOCIO-ECONOMIC IMPACT

The results of this study are only a necessary first step towards the device-level evaluation and demonstration, however, natural dye-sensitized solar cells as a new technology class still have to overcome several challenges in order to progress towards industrial-scale

deployment, including achieving efficiencies comparable to synthetic dyes and demonstrating long-term stability of the mango-moringa extract under continuous light exposure before any performance claims relative to synthetic dyes can be made reported by Korir, 2024 [25]. The socio-economic relevance of the research area is further highlighted by the fact that using decentralized solar technology in underserved regions of the world can improve household income, business productivity, and gender equity in rural communities, empirical evidence from the deployment of decentralized solar power systems in Sub-Saharan Africa has shown that wider access to solar-based electricity has a measurable impact on these socio-economic outcomes [26]. In south-west Nigeria specifically, solar home systems have been documented to contribute to the creation and survival of micro-enterprises, and similar effects have been observed in rural Ethiopia, where the use of solar home systems has improved household welfare indicators associated with lighting and productive energy [27-28]. Therefore, using a locally sourced and low-cost sensitizer material, such as the mango-moringa extract examined here, aligns with the broader push for decentralized, affordable solar technology suitable for underserved regions. Another interesting economic aspect of the use of moringa leaves that cannot be overlooked is the fact that moringa is already known to be a multifunctional crop being used to supplement the livelihoods of smallholder farmers throughout Africa and that life cycle assessment (LCA) has indicated its potential as a crop to generate income for small-scale farmers, where the availability of food or economic output from one crop will not be compromised by harvesting as a source of dye [29].

CONCLUSION

The extract of mango leaves was successfully prepared along with the moringa leaves extract at a ratio of 1:1 by the 'cold maceration' method using acidified ethanol, and the preparation was characterized with a UV-visible spectrum. The absorption spectra showed two generally strong absorption regions (peaks) in the visible spectrum, near-UV/blue and red, and weak absorption at 450 nm and a large absorption at 650 nm. The remarkable outcome of the research is that the pigments obtained from the leaves of mango & moringa have a two-band profile, which is wider in the visible spectrum area than a natural dye derived from a single source would be. The well-defined absorption edge was used in the Tauc plot to determine the optical band gap, which was 2.28 eV within the range of other reported effective natural dye sensitizers. The high light absorption and moderate band gap suggest that the characteristics of the light-extracted material are favorable, and further studies of this material to be used in the sensitizer of the DSSC would be desirable.

RECOMMENDATIONS

Stability studies, which detail the optical and chemical stability of the extract under prolonged light exposure and storage, would also be required before commercial durability can be assumed. Additionally, testing other ratios of mango-moringa to determine whether or not the 1:1 ratio provides the best performance would also be of interest. Dye loading studies using an actual TiO₂ photoanode would be required to determine how well the extract adsorbs under real device conditions. However, it is still the case that none of this optical work can answer the question of whether or not the mango-moringa extract is a viable DSSC sensitizer: to answer that question, a device must be fabricated, J-V measurements must be obtained to determine power conversion efficiency, IPCE measurements must be obtained to determine variation of performance with wavelength, and electrochemical characterization, likely including impedance spectroscopy, should be used to evaluate charge transport and recombination once the extract is incorporated into the solar cell.

ACKNOWLEDGMENTS

The authors sincerely acknowledge the Department of Physics, Mewar University, Chittorgarh, Rajasthan, India and North West University, Kano, Nigeria (Maitama Sule University, Kano, Nigeria), for providing the academic and laboratory environment that supported this research. The authors are grateful to colleagues and reviewers whose constructive feedback improved the quality of the manuscript.

FUNDING

No specific funding was received from any public, commercial, or not-for-profit funding agency for this research.

CONFLICT OF INTEREST

The authors declare no conflicts of interest with respect to the research, authorship, or publication of this article.

DATA AVAILABILITY

The datasets generated during the current study are available from the corresponding author upon reasonable request.

CREDIT AUTHOR CONTRIBUTIONS

Ibrahim Abba Ibrahim: Conceptualization, Investigation (nanoparticle synthesis and characterization), Writing – Original Draft.

Hamza Mustapha Umar: Methodology, Validation, Writing – Review & Editing.

Isyaku Bala Zarewa: Writing – Review & Editing and Data Curation

Huzaifa Ali Saleh1: Writing – Review & Editing and Validation.

Mohammad Aamir: Characterization (UV-Vis, FTIR, XRD, SEM instrumentation access and analysis), Software (data processing/plotting), Resources.

Nasir Abdullahi Lawan: Formal Analysis, Visualization.

Yasmeena Maqbool: Supervision, Resources, Final approval of the manuscript.

Ethical Approval

This study did not involve human participants or animals performed by any of the authors. Not applicable

CONSENT TO PUBLISH

'Not applicable'

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