



Influence of Ethanol on the Spectral Properties of Natural Dyes from Microalgae: Implications for Dye-Sensitized Solar Cell Performance

¹Lana G. M., ²Adenigba V. O., ³Oyetunji E. O., ⁴Adegboyega O., ⁵Oyewole O. J.,
⁶Bello I. T. and ⁷Adedokun O.

^{1,6}Department of Pure and Applied Physics, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

²Department of Science Laboratory Technology, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

³Department of Physical Science, University of Texas at El Paso, Texas, USA.

⁴Department of Physical Science Education, Emmanuel Alayande University of Education, Oyo, Nigeria.

⁵Department of Physics and Astronomy, The University of Southern Mississippi, Hattiesburg, MS, USA.

⁷Nanotechnology Research Group (NANO+), Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

¹lanagbemigamatthias@gmail.com, ²moadesiyan@lautech.edu.ng, ³Oyetunjiemmanuel8@outlook.com,

⁴oadeboyega@eacoed.edu.ng, ⁵olayinka.oyewole@usm.edu ⁶itbello@lautech.edu.ng

⁷oadedokun@lautech.edu.ng

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Corresponding Author:

oadedokun@lautech.edu.ng, +2347031195750

ABSTRACT

*The increasing need for renewable energy sources that are both sustainable and less costly has spurred growing research into natural dyes as eco-friendly sensitizers for dye-sensitized solar cells (DSSCs). This study entails the extraction and UV-vis and FTIR spectroscopy studies of natural pigments derived from *Chlamydomonas starrii* and *Coelastrella* sp. focusing on solvent selection and thermal treatment. Ethanol proved much better than ethyl acetate and had the most remarkable effects on retaining functional groups, especially hydroxyl (O-H) and carbonyl (C=O), which would be important in terms of dye adsorption for improved photon absorption and electron injection. Spectroscopic analyses indicated that the ethanol-extracted dyes, especially non-heated and moderately heated ones, would enable a broad absorption of light within the visible spectrum. These findings hence have demonstrated that natural dyes extracted with ethanol were better than those extracted with ethyl acetate, which makes ethanol a more efficient, scalable, and greener solvent for the extraction of natural dyes compared to ethyl acetate. Future research is to focus on mixed solvent systems and stabilization techniques to improve dye performance even further. This will therefore be the greatest scion towards high-efficiency DSSCs while further supporting the global transition efforts toward sustainable energy technologies.*

INTRODUCTION

The global demand for sustainable, clean, and renewable energy is steadily rising. This presents a significant challenge for humanity, aligning with the United Nations' Sustainable Development Goal 7. The burning of fossil fuels, including coal, oil, and natural gas, releases carbon dioxide into the atmosphere. These fossil fuel emissions are a major contributor to climate change. Minimizing reliance on fossil fuels and reducing carbon emissions has

become crucial, and putting more resources into encouraging the use of solar energy is vital because solar energy is abundant, readily available, non-polluting and therefore perfect for large scale clean energy production (Jaiswal *et al.*, 2022). Among the available technologies using solar energy, Dye-Sensitized Solar Cells (DSSCs) are found to be among the cheapest and simplest to produce (Sasikumar *et al.*, 2024). DSSCs function based on the principle of utilizing a dye to enhance the solar

cell's ability to capture sunlight and convert it into electrical energy. In the presence of sunlight, dye absorbs the photon whereby one or more of its electrons are raised to an excited state leading to the formation of electron-hole pairs. Thereafter, the induced excitation of the electron leads to the conduction process whereby the electron is filled in the conduction band of the thin layer of titanium dioxide (TiO₂) which is immersed in the dye (Sasikumar et al., 2024). The light-to-electric conversion efficiency of DSSC is to a great extent dependent on the dye's light absorption characteristics in the visible range and the dye's adsorption onto the surface of the semiconductor, or the effect the dye's absorption characteristics have on the injection of electrons in operation (Onah and Lethole, 2024).

In most cases and up to the present time, ruthenium-based synthetic dyes have been used primarily as the dye sensitizers in the DSSCs. These dyes have of course very wide range of absorption spectra and are stable. However, there are several drawbacks (Fetouh et al., 2024). Ruthenium is a rare metal and the process of synthesizing dye is very complicated and expensive. As a result, alternatives that are affordable and accessible have been sorted out with a rapid rise. Natural pigment extracts are a good substitute for synthetic dyes (Rahman et al., 2023). Extracting natural dyes for use in DSSCs presents significant challenges, particularly in achieving high pigment purity and stability. Natural dyes are often derived from plant, microbial, or algal sources, which contain a mixture of pigments, proteins, and other impurities (Alamu et al., 2024; Montagni et al., 2024; Tropea et al., 2024).

In recent years, researchers have increasingly explored the use of microbes as sources of natural dyes for DSSCs. This innovative approach leverages the ability of microorganisms to produce bio-pigments with remarkable optical properties

suitable for photovoltaic applications. A notable study by Orona-Navar et al. (2020) investigated the potential of *Scenedesmus obliquus*, a microalga, to generate natural pigments that could act as efficient photosensitizers in DSSCs (Orona-Navar et al., 2020). Similarly, Hernandez-Velasco et al. (2020) assessed the photoelectric performance of DSSCs incorporating the prodigiosin pigment, a vibrant red compound derived from the bacterium *Serratia marcescens*. These studies highlight the promising role of microbial pigments in enhancing the sustainability and performance of solar energy devices (Hernández-Velasco et al., 2020). Vinaayak and colleagues (2022), also developed natural dye-sensitized solar cells (N-DSSCs) using pigments extracted from *Cladophora columbiana* (a green alga) (Vinaayak et al., 2022).

This study looks into the usage of various natural pigment sources as dye sensitizers for DSSCs namely extracts from microorganisms such as *Chlamydomonas starrii* and *Coelastrella sp.* The *Coelastrella sp.* is a genus of green algae in the family *Scenedesmaceae*, classified under the subfamily *Coelastroideae* (Nayana et al., 2022). The genus is characterized by solitary or clustered cells that are spherical, ellipsoidal, or lemon-shaped, enclosed in a hyaline or brownish cell wall with 4 to 40 longitudinal striations, visible primarily under scanning electron microscopy (SEM). Internally, each cell contains a single nucleus, a parietal chloroplast with a pyrenoid, and numerous conspicuous vacuoles (Beaulier et al., 2024; Nayana et al., 2022; Thepsuthammarat et al., 2023). The *Chlamydomonas starrii* is a unicellular green alga belonging to the genus *Chlamydomonas* and is characterized by its distinct morphology and ecological adaptations. Cells are generally ovoid to spherical and are noticed with a single cup-shaped chloroplast, which may contain one or more

pyrenoids for carbon fixation and starch storage (Innami *et al.*, 2022).

We evaluated the performance of ethanol and ethyl acetate solvents in extracting natural dyes from *Chlamydomonas starii* and *Coelastrella sp.* FTIR analyses were done for both ethanol and ethyl acetate extracts. Because tests showed excellent results with ethanol, UV-Vis spectroscopy was done only for the ethanol extracts. Further, heat treatment was studied to improve the performance of extracted dye concerning its application in DSSCs. This is a pilot study on the extraction and characterization of natural dyes from microalgae and plants using spectroscopic techniques.

EXPERIMENTAL

Materials

Cultures of *Chlamydomonas starii* (represented as CS) and *Coelastrella sp.* (represented as CO) were cultivated using Blue Green II (BGII) in the Department of Science Laboratory Technology (SLT) laboratory at Ladoke Akintola University of Technology. The cultures were maintained under natural light in the laboratory and the flasks were subjected to manual agitation of 10 minutes at an average of three times daily to enhance biomass growth and prevent photo-inhibition of cells (Adenigba *et al.*, 2020). Absolute ethanol (>99%) and ethyl acetate (>99.5%) were used without further purification unless otherwise stated.

Preparation of natural dye extract

After about 28 days of biomass production of CS and CO, the cells were harvested using a centrifuge at 4000 rpm for 20 minutes. The obtained pellet of each alga was washed and dried in a hot air oven at 60 °C to obtain a dried biomass which was used for extraction of dye. The dried biomass of the two microbes was hard-pounded separately using a mortar and pestle for easy extraction of the active

substances. For extraction, 100 ml of ethanol and ethyl acetate were used separately as solvents, allowing for comparison between the two solvents. The ground microbe's biomass was placed in the respective solvents and extraction was done using two different methods. The first method involved soaking the biomass in the ethanol without heating for 24 hours while the second method of extraction was carried out in a water bath at 60 °C for 1 hour. This process made it possible to extract all natural dyes in comparable conditions which ensures the quality of pigment and extraction efficiency assessment of the various sources of natural dyes could be done with ease (Alamu *et al.*, 2021). At the end of the extraction, the solutions were filtered clean using Whatman filter paper to separate the dye from the biomass, the dye of the two microbes was stored in bottles for further analysis.

Characterization

The optical absorbance spectra were recorded using a double-beam UV-Vis-IR spectrophotometer (ASUV-6300PC) equipment with the spectrum series of wavelengths 200–800 nm. The structural properties of the dye were studied by Fourier transform infrared spectroscopy (Thermo Scientific™ Nicolet™ iS5 FTIR spectrometer).

RESULTS AND DISCUSSION

FTIR Analysis

Table 1 summarizes the FTIR results for the functional groups and their corresponding wave numbers for each sample under heated and non-heated conditions. The FTIR spectra of *Chlamydomonas starii* as shown in Figure 1 reveal significant differences in functional group distributions under varying solvent and thermal treatments, which influence its suitability as a dye in DSSCs. These samples have been prepared with either ethanol (E) or ethyl acetate (A) as solvents

with further heat (H) and no heat (NH) processing. The analysis supports the fact that structural alterations are necessary to realize optimum photon absorption and electron injection in DSSCs. Meanwhile, profuse peaks were found at 3636.84 cm^{-1} and 3425.27 cm^{-1} showing intense O–H

stretching vibrations due to hydroxyl grouping of CS-ANH (solvent ethyl acetate, not-heated) (Dai *et al.*, 2023). The pointy peak at 1642.07 cm^{-1} is likely due to C=O stretching from either carboxylic acids or amides (Saito *et al.*, 2022).

Table 1. FTIR Analysis of Functional Groups and Wave Numbers for Natural Dye Extracts under Heated and Non-Heated Conditions.

Sample	Solvent	Condition	Wave Number (cm^{-1})	Functional Group
<i>Chlamydomonas starii</i>	Ethanol	Non-heated	3698, 3471.12, 1642.4, 2924, 1037.6	O-H, C=O, C-H, C-O
		Heated	4015.56, 2115.72	O-H, C≡N, C-O, C-H
	Ethyl Acetate	Non-heated	3636.84, 3425.27, 1642.07	O-H, C=O
		Heated	3427.34, 2176.79, 1637.33	O-H, C≡C, C=O
<i>Coelastrella sp</i>	Ethanol	Non-heated	3680.69, 1632.23, 1045.84	O-H, C=O, C-O
		Heated	3704.15, 1632.23	O-H, C=O
	Ethyl Acetate	Non-heated	3719.78, 1710.42, 1045.84	O-H, C=O, C-O
		Heated	3766.69, 1804.24, 1436.77	O-H, C=O, C–C

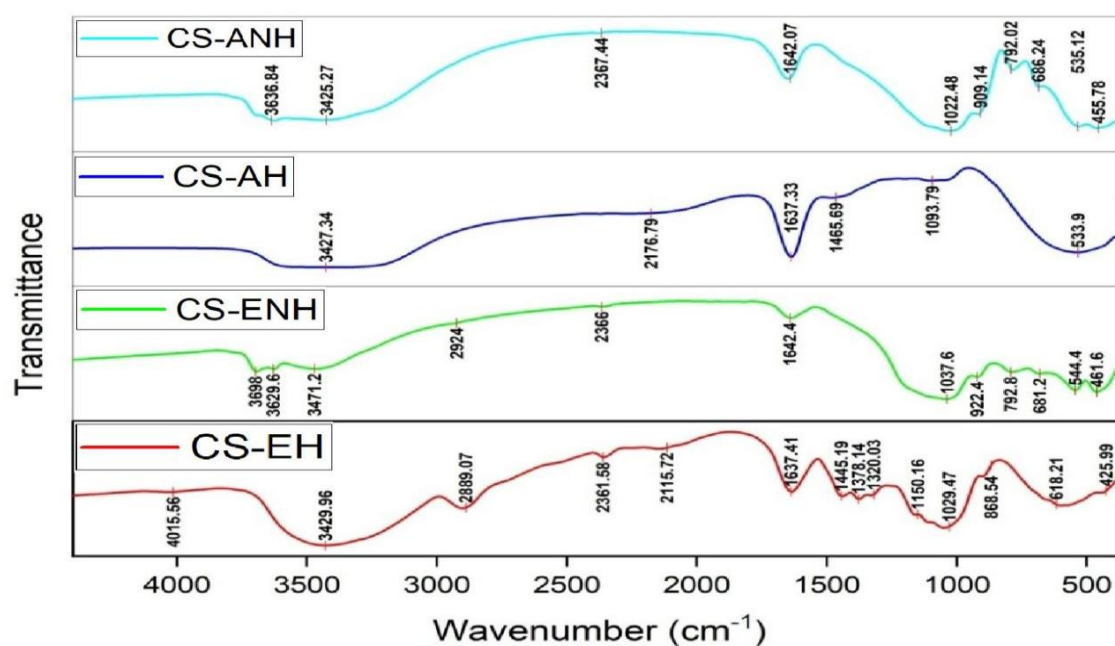
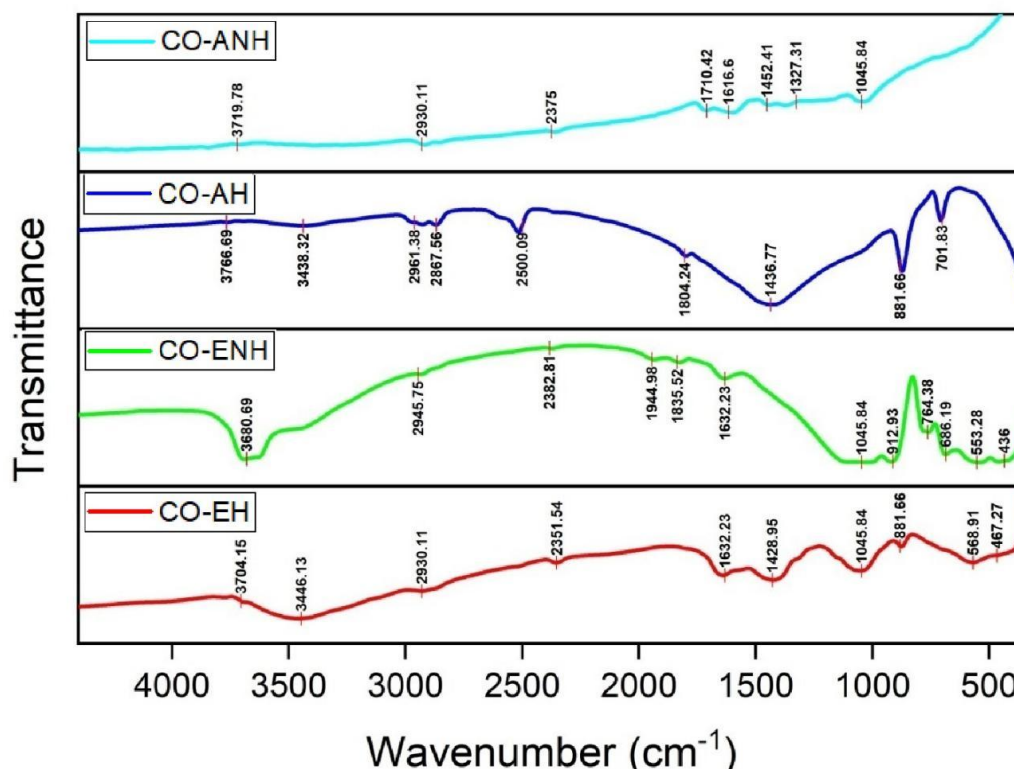


Figure 1: FTIR spectra of *Chlamydomonas starii*

Figure 2: FTIR spectra of *Coelastrella* sp

Such functional groups can also indicate chlorophyll and carotenoid pigments, which are important for photon absorption. However, the low absorption in most other areas could limit the photon capture efficiency. CS-AH (ethyl acetate solvent, heated) exhibits a broad O-H stretching peak at 3427.34 cm^{-1} with two additional peaks at 2176.79 cm^{-1} and 1637.33 cm^{-1} , which are due to the alkyne and carbonyl functionalities respectively. The pigments present here are probably chlorophyll and carotenoids, but due to heating, could have resulted to either reduced potency or activation and their overall performance would thus be compromised in DSSCs. The CS-ENH (ethanol solvent, not-heated) spectrum shows sharp O-H stretching peaks at 3698 cm^{-1} and 3471.12 cm^{-1} , in addition to a clear C=O stretching peak at 1642.4 cm^{-1} (Dai *et al.*, 2023).

The presence of CH stretching at 2924 cm^{-1} and C-O stretching at 1037.6 cm^{-1} gave underlining evidence for enriched hydroxyl and carbonyl groups. These are indicative of greater amounts of both chlorophyll and carotenoids, owing to the

highly effective nature of the solvent in extracting these pigments and concentration enhancement by heating (Bekele and Sintayehu, 2022). The sharp peaks and structural stability make CS-ENH the most effective candidate for DSSC applications, as these pigments play a crucial role in photon absorption and electron injection. CS-EH (ethanol solvent, heated) shows a broader O-H stretching region at 4015.56 cm^{-1} and a nitrite ($\text{C}\equiv\text{N}$) peak at 2115.72 cm^{-1} , along with prominent C-O and C-H stretching peaks. While such functional groups are indicative of chlorophyll and carotenoids, the broadness of the O-H peak and lack of heating has led to an active pigment concentration that is less than that of heat samples, thus lowering the efficiency of this sample (Vatankhah *et al.*, 2023).

The FTIR spectra of *Coelastrella* sp. as displayed in Figure 2 under different solvent and thermal treatments show the functional groups present in the samples, influencing their potential as DSSCs. The CO samples were drawn from ethanol (E) and ethyl acetate (A) solvents, further classified as heat (H)

and non-heat-treated (NH). Spectra functional groups characterize some pigments like chlorophyll and carotenoids, as the most important for both photon absorption and electron injection in DSSCs. Typical for CO-ANH (ethyl acetate solvent, not heated) is the spectrum: at 3719.78 cm^{-1} , there is a broad O-H stretching peak, at 1710.42 cm^{-1} , a strong C=O stretching peak, and fairly well-separated C-O stretching at 1045.84 cm^{-1} (Bekele and Sintayehu, 2022).

Such features are indicative of the presence of chlorophyll and carotenoids that promote light absorption. However, their presence in other regions as weaker peaks indicates a reduced concentration of active pigments compared to the other samples. CO-AH (ethyl acetate solvent, heated) exhibits sharp O-H stretching at 3766.69 cm^{-1} and prominent peaks at 1804.24 cm^{-1} and 1436.77 cm^{-1} , corresponding to C=O and aromatic C-C stretching, respectively (Badawy et al., 2024). While these functional groups confirm the presence of pigments like carotenoids, the presence of heating may result in a less organized molecular structure, reducing the efficiency of electron injection in DSSCs. CO-ENH (ethanol solvent, non-heated) displays well-defined O-H stretching at 3680.69 cm^{-1} , C=O stretching at 1632.23 cm^{-1} , and C-O stretching at 1045.84 cm^{-1} (Badawy et al., 2024).

The presence of sharp peaks suggests a higher concentration of chlorophyll and carotenoids (Bekele and Sintayehu, 2022). Ethanol is particularly effective in extracting these pigments, and the heating process stabilizes their molecular structures, making CO-ENH a strong candidate for DSSC applications due to enhanced light absorption and strong dye-TiO₂ binding. CO-EH (ethanol solvent, heated) shows a broader O-H stretching region at 3704.15 cm^{-1} and prominent C=O stretching at 1632.23 cm^{-1} , similar to CO-ENH.

UV – Vis Spectra

UV-Vis spectroscopy was not performed for ethyl acetate extracts due to their inferior results in pigment extraction and functional group preservation, making them less suitable for further analysis. Instead, UV-Vis spectroscopy was exclusively conducted for ethanol extracts, which demonstrated superior performance in retaining critical pigments and functional groups. The UV-Vis spectra for *Chlamydomonas starii* extracts shown in Figure 3 reveal significant absorption peaks in the visible region, indicating the possible presence of light-absorbing pigments adequate for DSSCs. They both presented.

major absorption peaks; CS-H (heated) 400-450 nm and CS-NH (non-heated) 650-700 nm, into the primary range. The peak of 400-450 nm indicates absorption of carotenoids and chlorophyll a, whereas that close to 700 nm is typical of chlorophyll b (Alhorani et al., 2022). These pigments excel in photosynthetic light harvesting and hold significant promise for DSSC applications by enabling efficient light absorption across a broader spectrum. The spectrum CS-NH is characterized by slightly more absorbance in the 400-450 nm region compared with CS-H which was interpreted to mean that heating probably caused some pigment reduction intensity, presumably through thermal degradation. Absorption in the ranges of 650-700 nm is mostly unaffected implying that chlorophylls are stable when treated in the heat.

The UV-Vis spectra of *Coelastrella sp.* extract as displayed in Figure 4, reveal distinct absorbance characteristics that highlight their suitability for dye-sensitized solar cells (DSSCs). Both CO-H and CO-NH samples exhibit distinct peaks within the visible spectra of wavelengths roughly between 400-450 nm and 650-700 nm. The pigments, carotenoids and chlorophylls, are important for light

absorption in DSSCs (Loum *et al.*, 2020). However, the CO-NH sample absorbs more than CO-H within these regions, thus suggesting that new pigment or thermal degradation tends to preserve more carotenoids and chlorophyll pigments compared to the former heat extraction.

The broad absorption range of the CO-NH sample is extended by high-energy (blue) and low-energy (red) wavelengths combined, expanding its ability to trap as much sunlight as possible. Its importance is defined by the efficiency with which it can do energy conversion in the DSSCs. Such pigments capture most of the light between the two ends of the wavelength region they cover, with carotenoids contributing significantly to ranges of 400–500 nm and chlorophylls (a and b) accounting for peaks around 430 nm, 670 nm, and 460 nm and 640 nm, respectively. These pigments synergistically optimize the potential for light harvesting over a broad spectrum in the solar spectrum (Chumwangwapee *et al.*, 2023).

Impact of Solvent

The choice of solvent is of utmost importance in the extraction and stability of the natural pigments used as sensitizers in DSSCs. Solvents determine the capability to extract essential pigments and maintain functionality (Ponnambalam *et al.*, 2023). Ethanol emerged as the most efficient solvent because of its polarity and ability to dissolve the various ranges of pigments-from chlorophylls to carotenoids. These pigments are crucial for photon absorption and electron transfer in DSSCs.

Ethanol's strong solvating power ensures efficient extraction of both polar and slightly nonpolar compounds, preserving the integrity of key functional groups such as hydroxyl (O–H) and carbonyl (C=O). Conversely, ethyl acetate produced limited efficacies in pigment extraction because they were viewed to give lower concentrations of

pigment and weaker functional groups as seen with FTIR analysis.

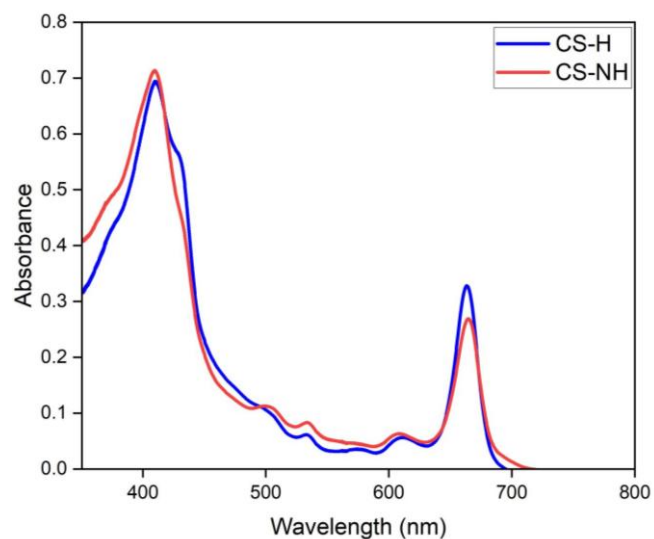


Figure 3: UV-Vis spectra of *Chlamydomonas starii*

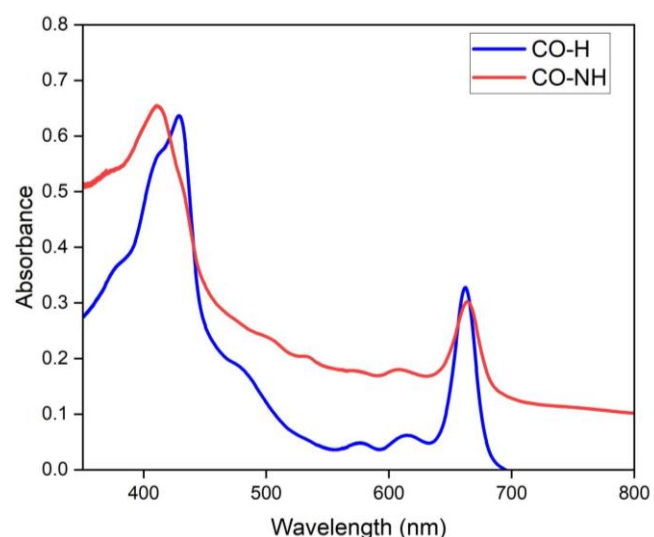


Figure 4: UV-Vis spectra of *Coelastrrella sp*

For instance, when *Chlamydomonas starii* (CS) samples were ethanol-extracted in a non-heated condition, CS-ENH samples had sharp and well-defined peaks that correspond to O–H and C=O stretching vibrations in FTIR spectra such vibrations are necessary for efficient electron injection into the TiO₂ photoanode coupled with strong anchoring of dye. Ethyl acetate-extracted samples, on the other hand (CS-ANH) showed wider and less intense peaks, signaling an incomplete pigment extraction

and probably degradation of functional groups. Similarly, for *Coelastrella sp.* (CO), ethanol-extracted samples (CO-ENH) displayed clear and intense peaks in FTIR spectra, particularly for O–H stretching at 3680.69 cm^{-1} and C=O stretching at 1632.23 cm^{-1} . In contrast, ethyl acetate-extracted samples (CO-ANH) exhibited weaker and broader peaks, reflecting the solvent's limitations in maintaining pigment stability and functional group integrity.

UV-Vis results further confirmed that the solvent ethanol was superior. Samples extracted using ethanol from both *Chlamydomonas starii* (CS-ENH) and *Coelastrella sp.* (CO-ENH) showed larger and more intense absorption peaks under visible light (400-700 nm) with absorption spectra corresponding to chlorophylls and carotenoids. For example, clear absorption peaks were found at 400-450 nm and 650-700 nm for CS-ENH, while CO-ENH showed appreciable absorbance within similar ranges, necessary for efficient light harvesting. Peaks were more pronounced in samples extracted with ethanol as compared to those from ethyl acetate. Ethyl acetate-extracted samples (CS-ANH and CO-ANH), on the contrary, had lower and narrower absorption peaks suggesting lower pigment concentrations and lesser light-harvesting efficiency.

The polarity of the solvent is considered significant in pigment extraction and functional group retention. As a result, the use of ethanol has proved successful, as it dissolves most polar compounds, including hydroxyls and carbonyls, as well as breaking hydrogen bonds. It is, therefore, an appropriate solvent for the extraction of chlorophylls and carotenoids, since these pigments play significant roles in photon absorption and electron transfer. Ethyl acetate, being less polar, is not effective at extracting any polar compound. This is also manifested in the total absence of functional

group signals and absorption peaks in UV-Vis spectra of ethyl acetate-extracted samples. Ethyl acetate has a relatively low boiling temperature and, therefore, evaporates quickly during extraction, limiting pigment stability and efficiency.

Effect of Heating

Heating during extraction greatly affected the natural pigments derived from *Chlamydomonas starii* (CS) and *Coelastrella sp.* (CO). It affected the integrity of functional groups and overall pigment quality. Controlled heating broke down cellular structures to release bound pigments and gave passage to improve extraction. The influence of this heating process was analyzed using FTIR and UV-Vis spectroscopy to understand the responses the extracted samples received.

Among the samples extracted using ethanol, the heating-enhanced purification and preservation of functional groups in pigments. The FTIR spectra of CS extracted with ethanol-heated conditions (CS-EH) showed distinctive peaks associated with hydroxyl (O-H) stretching at 4015.56 cm^{-1} and nitrite (C=N) stretching at 2115.72 cm^{-1} . These peaks signify the presence of stable functional groups important for the light absorption and electron injection sections of the DSSC. Similarly, *Coelastrella sp.* (CO) samples derived from ethanol heating (CO-EH) exhibited sharp O-H stretching peaks over 3704.15 cm^{-1} and marked C=O stretching at 1632.23 cm^{-1} , implying that pigment remains stable and extraction is efficient.

In other words, heating reduced the yield of ethyl-acetate-extracted samples. The decrease in peak intensity with broadening was observed for O-H stretching at 3427.34 cm^{-1} and alkyne (C≡C) stretching at 2176.79 cm^{-1} in the case of CS ethyl acetate heated processed materials (CS-AH) samples: that is indicative of damage in important pigments and functional groups, mostly caused by

thermal degradation. The O-H stretching peak of CO ethyl-acetate-heated samples (CO-AH) appeared at 3766.69 cm⁻¹ and had a lighter aromatic C=C stretching peak of 1436.77 cm⁻¹, indicating compromised integrity of pigment.

UV-Vis spectroscopy subsequently underscored the differential heating effects on the two solvents. Ethanol-heated samples like CS-EH and CO-EH bore broader and higher absorption peaks in the visible range (400-700 nm). These peaks are typically characteristic of chlorophyll and carotenoids that actually serve efficient light harvesting in DSSCs. On the contrary, ethyl acetate heated samples such as CS-AH and CO-AH displayed lower absorption peaks, denoting a low concentration of these pigments and the absence of light-harvesting capabilities.

The results, therefore, indicate the selection of solvent in heat-assisted extraction. When heating increases the efficacy of ethanol as a solvent, thereby allowing its improved pigment purity and functional group stability, it negatively affects ethyl acetate-extracted samples because of the poorer heat thermal stability of the solvent. The results point out the need for well-optimized heating conditions and indeed solvent selection for efficient extraction and preservation of naturally-occurring pigments for application purposes in DSSCs.

Implications for DSSC Performance

The performance of DSSCs is highly dependent on the stability of functional groups within natural dyes and their ability to efficiently absorb light (Sabarikrishwaran *et al.*, 2023). Functional groups such as hydroxyl (O-H), carbonyl (C=O), and conjugated double bonds are critical for facilitating photon absorption, electron transfer, and effective dye anchoring onto the photoanode surface, typically TiO₂. The preservation of these functional groups directly correlates with enhanced light

absorption and, consequently, improved DSSC efficiency (Mahajan *et al.*, 2024).

Stable functional groups thus guarantee an efficient exit of electrons from the dye to the TiO₂ photoanode conduction band. FTIR analysis of the ethanol-extracted dyes in this study showed that the O-H and C=O groups of such samples, particularly under non-heated extraction (e.g. CS-ENH), had good integrity. Such functional groups very much show the ability of the dye to bond tightly with TiO₂ and hence allow the transferring of electrons without much recombination loss improvement in overall photocurrent (Halala *et al.*, 2024).

Likewise, the efficiency of light absorption can be dynamically related to the stability of functional groups. As per the UV-Vis spectroscopy results, it is well established that dyes with intact functional groups showed higher and wider absorption peaks in the visible region, mainly in the range of 400-450 nm (carotenoids) and 650-700 nm (chlorophylls). For instance, it was observed that non-heated ethanol-extracted dyes had a higher absorption than heated or ethyl acetate acid-extracted dyes. Superior absorption resulted in more efficient capture of light and translated to a better light-to-electricity conversion process in DSSC (Zhou *et al.*, 2021).

Degradation of functional groups, on the contrary, adversely affects DSSC performance. Extracted samples by ethyl acetate acid, especially with heating, manifested comparatively weak FTIR peaks of critical groups and lower absorbances in UV-Vis spectrometry. The degradation limits the anchoring of dyes onto the surface of TiO₂, which reduces their efficiency in electron injection. Therefore, those dyes, which were extracted in ethyl acetate acid, acted as poor sensitizers, which highlighted the crucial point that solvent choice and extraction conditions should be optimized to ensure stability with the functional groups.

Solvent and thermal treatment selection may also be very important in considering the functional group stability and their absorption efficiency. Ethanol-extracted dyes showed better retention of functional groups under light absorption overall conditions than non-heated extractions-only extractions and therefore are better for DSSC use. The stability of functional groups means that the dye will still be effective over time, enhancing the durability and operating life of the DSSC. On the other hand, it shows the unstable nature of ethyl acetate extracted dyes under heat; thus, it may need careful optimization to conform to performance in the DSSC.

CONCLUSION

This study highlights the viability of natural dyes as eco-friendly alternatives to synthetic sensitizers in DSSCs. The pigments derived from *Chlamydomonas starii* and *Coelastrella sp.* proved themselves about their stability of functional groups and effective light absorption. Ethanol appeared to be an excellent solvent with high extraction performance while not depriving hydroxyl (O-H) and carbonyl (C=O) functional groups. Extraction without heating or mild heating (e.g., 60°C for 1 hour) was found to provide a balance between pigment stability and purity while very high temperatures or the use of unstable solvents like ethyl acetate resulted in degradation. To further enhance performance, extraction should be carried out in the dark. Future research should involve mixed solvents as well as advanced techniques for stabilization like encapsulation or co-sensitization. This shows the need for the optimization of solvents and thermal treatments on the grounds of efficiency, durability, and scalability toward the global pursuit of energy technologies that are truly sustainable and renewable. This is a pilot study on the extraction and characterization of natural dyes from microalgae and plants using spectroscopic techniques. The

follow-up study on performance evaluation of the potential of natural dyes from Microalgae and Plants for high efficiency in TiO₂-based dye-sensitized solar cells will be published soonest.

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