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Enhancing Dye-Sensitized Solar Cell Efficiency Using Photosynthetic Pigments from *Navicula* sp. TAD

Ivonne Telussa[1,*], Mirella Fonda Maahury[1], Eka Rahmat Mahayani Anthonia Putera Lilipaly[2], Threbelin Anacovic Lawdrian Latuihamallo[1]

[1]Department of Chemistry, Faculty of Science and Technology, Pattimura University, Jl. Ir. M. Putuhena, Poka Campus, Pattimura University, 97233, Maluku, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Ambon Polytechnic, Ir. M. Putuhena, Ambon 97233, Maluku, Indonesia

ABSTRACT

Microalgae *Navicula* sp. TAD is a microscopic plant that has the potential to serve as an alternative source of pigments, requiring relatively short cultivation time, making it suitable for use as a sensitizer in dye-sensitized solar cells. This research aimed to isolate, characterize, and identify the photosynthetic pigments of *Navicula* sp. TAD, and subsequently test its photoelectric capability as a sensitizer material in solar cells. The study involved cultivating *Navicula* sp. TAD cells to obtain biomass, isolating pigments from dry biomass, purifying pigments using column chromatography techniques, characterizing pigments by scanning visible light absorption patterns, and fabricating solar cells with TiO_2 paste, followed by testing the photoelectric capabilities of the solar cells. From the research, pigments such as β-carotene, chlorophyll a, xanthophyll, and chlorophyll c were obtained, with chlorophyll a and carotenoid contents of 29.9698 μg/mL and 18.4255 μg/mL, respectively. Solar cells sensitized with photosynthetic pigments showed the best photoelectric performance with crude pigment extract at a concentration of 30×10^3 ppm, yielding Short-circuit current density (I_{SC}) 1.93×10^{-5} A; open-circuit voltage (V_{OC}) 0.0465 V; fill factor (FF).58; and efficiency (η) 8.33×10^{-2} %. Meanwhile, variations in pigment concentration of chlorophyll and xanthophyll at a ratio of 0:100 yielded I_{SC} 9.96×10^{-5} A; V_{OC} 0.1004 V; FF 0.45; and η 7.24×10^{-1} %.

Keywords: dye-sensitized, efficiency, *Naviculla sp.* TAD, photosynthetic pigment, solar cell.

1. INTRODUCTION

The potential for solar energy in Indonesia is immense, with an average solar radiation intensity of 4.8 kWh/m²/day. Indonesia's geographical location along the Equator provides high solar intensity throughout the year. Thus, the development of solar energy utilization in Indonesia is of great importance. One promising application of solar energy is in solar cells, which have become a subject of research and development by numerous researchers worldwide [1].

Solar cells are semiconductor devices that can convert sunlight into electric charges. Sunlight consists of photons, which are directly transformed into electrical energy. Silicon-based solar cells were first developed by Chapin et al. [2] at Bell Laboratories, achieving an initial efficiency of 6%, which quickly increased to 10% [3]. Solar cells have continued to evolve to meet the increasing demand for electricity, one of which involves using synthetic dyes as light-sensitive materials or Dye-Sensitized Solar Cells (DSSC). Research by Hug et al. [4] demonstrated that a synthetic dye based on ruthenium complex N719 achieved an efficiency of 10.6%. Meanwhile, research by Chien and Hsu [5] reported a lower efficiency of 1.4% using anthocyanins derived from red cabbage.

*Corresponding author:
E-mail: ivon_telussa@ymail.com (Ivonne Telussa)

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Although synthetic dyes used in DSSCs have higher efficiency, their utilization has some drawbacks, such as high production costs, complex synthesis processes, the presence of heavy metals, and potential environmental contamination [6]. Therefore, the development of natural pigment-based sensitizers has become an attractive alternative. Natural pigments can be found in fruits and vegetables, which are not only readily available and environmentally friendly but also more economical. However, the cultivation of fruits and vegetables requires a relatively long time, prompting the search for more efficient natural pigment sources.

Microalgae are microscopic plant organisms (3-30 µm) that thrive in various aquatic environments, including freshwater and marine waters, and they have the potential to serve as alternative sources of photosynthetic pigments. Studies have utilized microalgae pigment extracts, such as Scenedesmus obliquus, which yielded an efficiency of 0.064%, β-carotene from *Chlorella* sp. with an efficiency of 0.022%, phycocyanin from *Spirulina* sp. at 0.04%, and chlorophyll from Chlorella vulgaris with an efficiency of 0.9% [7–9]. In addition, Telussa et al. [10] investigated pigments from *Navicula* sp., which achieved efficiencies of 6.150×10^{-3} %, 3.482×10^{-3} %, and 4.117×10^{-3} %, respectively. Microalgae offer advantages, including ease of cultivation, rapid growth, and low land requirements, making them non-competitive with terrestrial crops [11].

Microalgal communities are widely distributed across Maluku waters, including Teluk Ambon Dalam (TAD), which hosts microalgae from the class Bacillariophyceae. Some species of Bacillariophyceae, such as *Navicula* sp., are endemic to Teluk Ambon, making them a potential source for photosynthetic pigments [12]. The pigments identified in *Navicula* sp. include β-carotene, chlorophyll a and c, and xanthophyll, which play vital roles in photosynthesis processes. Moreover, these pigments protect cells from high-intensity sunlight [13–15].

Therefore, microalgae *Navicula* sp. From Teluk Ambon Dalam (TAD) deserve exploration as a source of photosynthetic pigments to enhance the efficiency of Dye-Sensitized Solar Cells (DSSC). This study aims to examine the effects of pigment concentrations from *Navicula* sp. On DSSC efficiency.

2. RESEARCH METHODS

2.1. Cultivation and Harvesting of *Navicula* sp. TAD

Navicula sp. TAD was cultured in a modified medium at an initial density of 5×10^{-5} cells mL^{-1} in a simple, room-temperature photobioreactor. Cultures were maintained under 5,000-lux illumination with a 12:12 h light–dark cycle, salinity of 28 ppt, pH 8.2–8.5, and continuous aeration with ambient air bubbles for nine days. The photobioreactor consisted of a transparent glass bottle (height 24 cm, outer diameter 17 cm) with a working volume of 2 L. Cell growth was monitored by light microscopy. After cultivation, cells were harvested by sedimentation followed by filtration through nylon cloth. Wet biomass was quantified on an analytical balance, then dried in a refrigerator until fully dry and re-weighed to determine dry biomass

2.2. Extraction and Purification of Chlorophyll and Xanthophyll Pigments

Five grams of biomass were macerated on ice with 40 mL acetone for 2 h, then centrifuged at 5,000 rpm for 10 min to collect the supernatant. The extract was purified by column chromatography using silica gel 60 as the stationary phase and an n-hexane:acetone:ethyl acetate (7:2:1, v/v/v) mobile phase [13]. A 2 mL aliquot of the crude pigment was loaded onto a silica gel 60 column pre-equilibrated with acetone:ethyl acetate, and eluted at 1 mL min^{-1}. Fractions containing chlorophylls and xanthophylls were collected for subsequent identification and characterization.

The crude pigment extract from *Navicula* sp. TAD microalgae, chlorophyll fractions, and xanthophyll fractions obtained from purification were qualitatively characterized using UV-Vis spectrophotometry. Crude pigment extract, chlorophyll, and xanthophyll were measured at wavelengths between 300 – 700 nm. Quantitative analysis of xanthophyll and chlorophyll pigment contents was performed. The absorbance of the crude pigment solution from *Navicula* sp. TAD was measured using UV-Vis spectrophotometry. Pigment content in *Navicula* sp. TAD was quantified spectrophotometrically at the characteristic absorption wavelengths of chlorophylls and xanthophylls. Filtrate absorbance was recorded at 470, 645, and 662 nm. Concentrations of chlorophyll a and total xanthophylls were then calculated using the Lichtenthaler equations [16].

2.3. Preparation of Photosynthetic Pigments Adsorbed on TiO_2 Electrodes

The solar cells were fabricated using crude pigment extract as well as isolated chlorophyll and xanthophyll as sensitizers. Indium tin oxide (ITO) glass substrates (1.25 × 1.25 cm) were used. Before deposition, the ITO was cleaned with a commercial glass cleaner and sequentially rinsed with acetone, deionized water, and ethanol, followed by 20 min of sonication, a thorough rinse, and oven drying at 60 °C. TiO_2 paste was prepared by dispersing 0.5 g TiO_2 powder in 10 mL of 96% ethanol and heating at 100 °C for 30 min. Nanocrystalline TiO_2 films were formed by coating the paste onto ITO and annealing at 300 °C for 10 min. To load the photosynthetic pigments, the TiO_2-coated ITO slides were immersed in the pigment solutions for 1 h and then allowed to dry at room temperature.

2.4. Photovoltaic Characterization of DSSC

The photovoltaic devices were assessed for light harvesting and current generation. Illumination was provided by a Sol 3A solar simulator (AM 1.5) set to 1 Sun (1,000 mW cm^{-2}; ~94,000 lux), with the light source positioned 1 m from the cell. Output from the cells was recorded using a Keithley 2400 digital multimeter under defined voltage steps, maintaining the 1 m source–device distance throughout. Power-conversion efficiency was calculated according to Equation (1).

$$\eta = \frac{V_{oc}\ x\ I_{sc}\ x\ FF}{P_{in}} \times 100\% \quad (1)$$

Where:

- Jsc represents the short-circuit current density (mA cm^{-2}),
- Voc is the open-circuit voltage (V),
- Pin refers to the incoming light intensity (W cm^{-2}), and
- FF is the fill factor, calculated as shown in Equation (2):

$$FF\ (\%) = \frac{V_{mpp}\ x\ I_{mpp}}{V_{oc}\ x\ I_{sc}} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. Cultivation of *Navicula* sp. TAD

Navicula sp. TAD was cultivated in a streamlined, modified medium designed to maximize cell growth and biomass production. The medium was intentionally simple, supplemented with nitrate, silicate, iron, and phosphate. Cultures were inoculated at 5×10^{-5} cells mL^{-1} and maintained for nine days under 5,000 lux illumination, a 12:12 h light–dark cycle, salinity of 28 ppt, and gentle aeration. During cultivation, the culture progressively darkened and became denser; this color shift reflected increasing cell abundance and higher biomass yield (Figure 1a). Cell morphology was assessed by light microscopy, which showed the *Navicula* sp. TAD cells as oval and yellow in appearance (Figure 1b).

The harvesting of *Navicula* sp. TAD cells were carried out on the 9th day, with a darker culture color indicating a higher number of cells. Harvesting was done using sedimentation and filtration techniques (Figure 2(a-b)). The sedimentation process lasted for 30 minutes and was followed by the separation of biomass from the growth medium through filtration. Filtration of

Navicula sp. TAD cells were easier due to the relatively large cell size. From 2.5 liters of *Navicula* sp. TAD cell culture, wet biomass weighing 7.6547±0.03 g was obtained (Figure 2(c)), and dry biomass was obtained weighing 1.0314±0.01 g (Figure 2(d)). The results indicate that the biomass contains 13.47% water. A lower water content generally leads to a more efficient harvesting process.

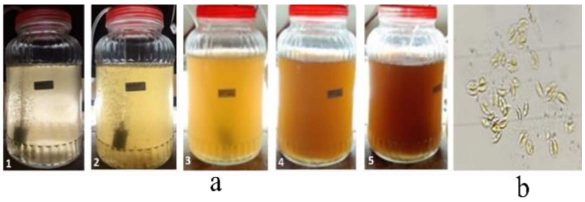

Figure 1. Cultivation of *Navicula* sp. TAD (a) Cultivation over 10 days (1. Day 0; 2. Day 2; 3. Day 4; 4. Day 6; 5. Day 9) and (b) Cell observation under a microscope.

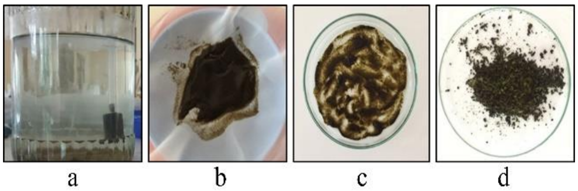

Figure 2. Biomass harvesting process of *Navicula* sp. TAD: (a) Sedimentation process, (b) Filtration process, (c) Wet biomass, (d) Dry biomass.

3.2. Extraction and Purification of Photosynthetic Pigments from *Navicula* sp. TAD

The crude pigment extract of *Navicula* sp. TAD is the result of pigment extraction from dry biomass dissolved in an acetone solvent. The extraction process begins with cell disruption using mechanical methods. The purpose of cell disruption is to allow the photosynthetic pigments located within the thylakoid membrane to be extracted from the cells. The extraction process is carried out using maceration for 5 hours with acetone in an ice bath. The obtained pigment extract has a green color, indicating the presence of chlorophyll pigments. The result of the photosynthetic pigment isolation yielded a value of 1.939% with chlorophyll and carotenoid pigment content of 29.9698 µg/mL and 18.4255 µg/mL, respectively (Table 1).

Table 1. Photosynthetic pigment content in the microalgae *Navicula* sp. TAD.

Pigment Types	Content (µg/mL)
Chlorophyll.	29.9698
Carotenoid	18.4255

The photosynthetic pigments from *Navicula* sp. TAD were purified by column chromatography using a silica gel matrix and an n-hexane:acetone:ethyl acetate (7:1:2, v/v/v) eluent. Elution at 1 mL min^{-1} produced 130 fractions, which were subsequently profiled by thin-layer chromatography and UV–Vis spectrophotometry (Figure 3).

Carotene-containing fractions showed three absorption maxima at 424, 449, and 474 nm—features consistent with β-carotene (Figure 3a). The chlorophyll a fraction, visually dark green, displayed peaks at 375, 410, and 424 nm (Soret region) and at 527, 570, 611, and 660 nm (Q-band region) (Figure 3c) [10,13]

The xanthophyll fraction, identified by its orange color, displayed absorption peaks typical of xanthophyll at 422, 447, and 470 nm (Figure 3.b). Xanthophyll is a major and abundant pigment in brown microalgae, such as diatoms, which gives them their characteristic brown color. The chlorophyll c fraction showed characteristic absorption peaks at wavelengths of 450, 581, and 629 nm (Figure 3.d) [10,13].

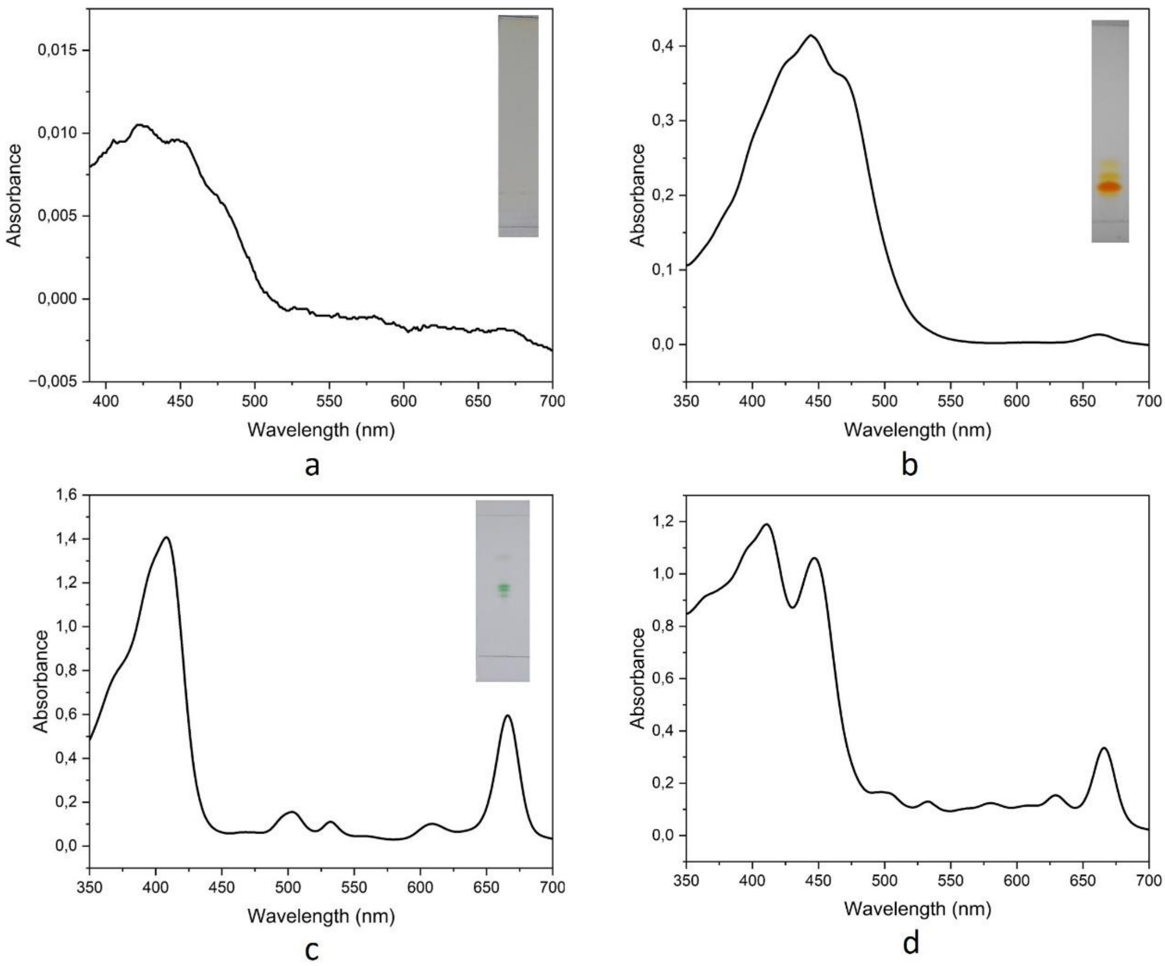

Figure 3. Absorption spectrum of (a) carotene fraction; (b) xanthophyll fraction; (c) chlorophyll a fraction; (d) chlorophyll c fraction.

3.3. Photovoltaic Characterization of DSSC

Dye-sensitized solar cells comprise a photoanode, a counter electrode, an electrolyte, and a sensitizer—in this case, a pigment extract [17,18]. The operating principle is as follows: photons striking the photoanode are absorbed by the pigment (*Navicula* sp. TAD) adsorbed on TiO_2. Photoexcitation promotes electrons that are then injected into the TiO_2 conduction band, with TiO_2 serving as the electron acceptor. These electrons flow through the external circuit to the counter electrode. At the counter electrode, typically carbon-catalyzed, electrons facilitate the reduction of the triiodide species in the electrolyte. The electrolyte subsequently donates electrons back to the oxidized pigment, regenerating the sensitizer to its ground state. This redox cycle sustains continuous operation as long as the electrolyte can support dye regeneration [19–21].

Pigments used as sensitizers comprised crude extracts at 5×10^{-3}, 1×10^{-4}, and 3×10^{-4} ppm, as well as chlorophyll–xanthophyll blends prepared at 0:100, 20:80, 40:60, 80:20, and 100:0 (v/v). The photoanode semiconductor paste was made by dispersing TiO_2 powder in 96% ethanol. After coating the substrate with the TiO_2 paste, the photoanodes were exposed to the pigment solutions; the ensuing color change indicated successful adsorption of the pigments onto the TiO_2 surface.

The photoanode was then connected to the ITO glass coated with carbon as the cathode, using KI/I_2 as the electrolyte solvent. The sensitized solar cell was then tested for its photoelectric capability using a solar simulator. Table 2 shows that with increased crude pigment extract concentration, solar cell efficiency improves, as higher concentrations enhance light absorption. Meanwhile, solar cells with varying chlorophyll and xanthophyll mixtures show increased efficiency as the chlorophyll ratio decreases. The solar cell with the best efficiency for crude extract concentration was obtained at $30×10^3$ ppm, yielding an efficiency (η) of $8.33×10^{-2}$ %, with I_{SC} $1.93×10^{-5}$ A, V_{OC} 0.0465 V, and FF 0.58 (Table 2, Figure 4.a). The best efficiency for chlorophyll and xanthophyll pigment variation was obtained at a ratio of 0:100, yielding an efficiency (η) of $7.24×10^{-1}$ %, with I_{SC} $9.96×10^{-5}$ A, V_{OC} 0.1004 V, and FF 0.45 (Table 2, Figure 4.b).

Table 2. Photoelectric Characteristics of Solar Cells Sensitized by Pigments from *Navicula* sp. TAD.

Type of Pigment	Pigment Concentration	Photoelectric Characteristics of Solar Cells			
		V_{OC} (V)	I_{SC} (A)	FF	η (%)
Crude Extract	$5×10^3$ ppm	0.0029	$1×10^{-7}$	0.97	$4.48×10^{-5}$
	$10×10^3$ ppm	0.0488	$1.04×10^{-5}$	0.41	$3.31×10^{-2}$
	$30×10^3$ ppm	0.0465	$1.93×10^{-5}$	0.58	$8.33×10^{-2}$
Chlorophyll: Xanthophyll Ratio	0:100	0.1004	$9.96×10^{-5}$	0.45	$7.24×10^{-1}$
	20:80	0.0430	$2.15×10^{-5}$	0.78	$1.158×10^{-1}$
	40:60	0.0386	$1.07×10^{-5}$	0.58	$3.86×10^{-2}$
	80:20	0.1388	$1×10^{-7}$	1	$2.2×10^{-2}$
	100:00	0.0511	$2×10^{-7}$	0.71	$1.2×10^{-3}$

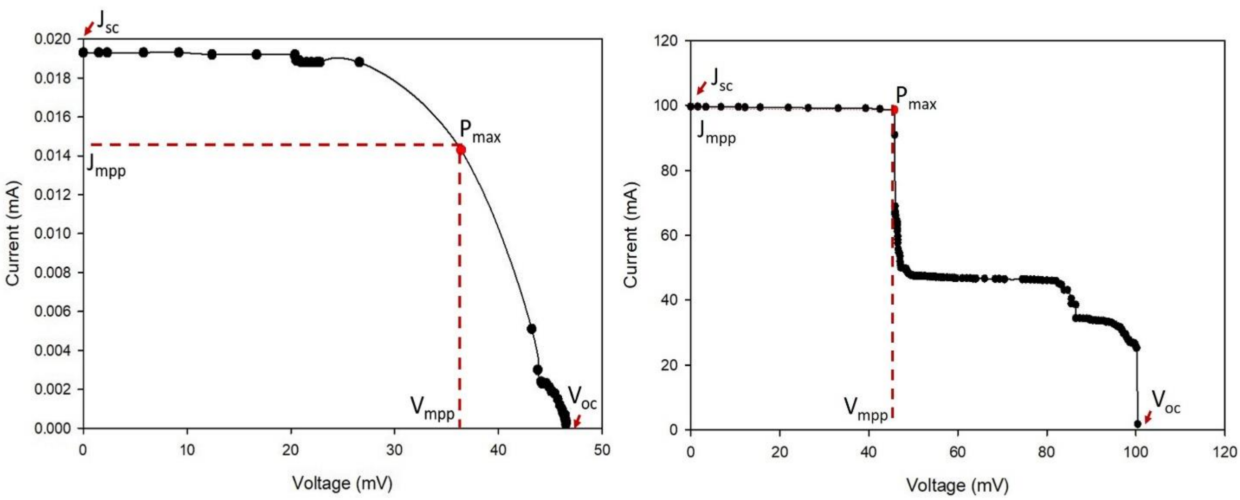

Figure 4. I-V Curve of Solar Cells with Photosynthetic Pigments from *Navicula* sp. TAD; (a) Concentration of Crude Pigment Extract $30×10^3$ ppm, (b) Rasio of Chlorophyll: Xanthophyll 0:100

In previous research, dye-sensitized cells using *Navicula* sp. TAD pigments yielded efficiencies of 6.150×10^{-4}% for crude extract, 3.482×10^{-3}% for chlorophyll, and 4.117×10^{-3}% for xanthophyll [10]. Increasing the crude-extract concentration by ~117-fold enhanced efficiency relative to the prior result; however, incorporating chlorophyll reduced performance. This is consistent with Rossi et al. [22], who reported that spinach chlorophyll did not produce current effectively because it lacks free carboxyl or hydroxyl groups needed to anchor onto TiO_2. Chlorophyll contains two ester linkages on the porphyrin ring, one involving a phytol substituent. Treatment with NaOH promotes base hydrolysis of these bonds, generating two carboxyl groups that enable binding to TiO_2, yielding an average efficiency of ~0.62%. Compared with the findings of Rossi et al. [22] and Telussa et al. [10], the efficiency achieved in this study remains relatively high, indicating that *Navicula* sp. TAD photosynthetic pigments are viable sensitizers for current-generating solar cells.

4. CONCLUSION

The cultivation of *Navicula* sp. TAD yielded a biomass of 7.6547±0.03 g, with chlorophyll a and carotenoid contents of 29.9698 μg/mL and 18.4255 μg/mL, respectively. Solar cells sensitized with photosynthetic pigments achieved the highest efficiency with a crude pigment extract concentration of 30×10^{3} ppm, reaching η 8.33×10^{-2} %. Meanwhile, for variations in the concentration of chlorophyll and xanthophyll pigments with a ratio of 0:100, an efficiency of 7.24×10^{-1} % was obtained.

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