

# Electricity Generation from *Spirulina* in a Two-Chamber Photosynthetic Power Cell: Effects of Electrode Pairing, Sunlight Exposure, and Bicarbonate Supplementation on Open-Circuit Voltage

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Publication Date: 2026/10/05

**Abstract:** Micro photosynthetic power cells ( $\mu$ PSCs) harvest electrons from the photosynthetic and respiratory metabolism of photosynthetic microorganisms and are being explored as low-cost, low-power renewable energy sources. This study examined the use of the cyanobacterium *Spirulina* as the anodic substrate of a low-cost, beaker-scale, two-chamber photosynthetic power cell built on the  $\mu$ PSC concept, and quantified how electrode pairing, sunlight exposure, and sodium bicarbonate ( $\text{NaHCO}_3$ ) supplementation affect its open-circuit voltage (OCV). The anode chamber contained 250 mL of *Spirulina* suspension ( $27.1 \text{ g L}^{-1}$ ) and the cathode chamber contained 250 mL of water, connected by a salt bridge. Three anode–cathode pairs (Zn–C, Zn–Cu, and Mg–Cu) were tested under three sequential conditions: indoor baseline, direct sunlight (substrate temperature  $33\text{--}38^\circ\text{C}$ ), and direct sunlight with  $2 \text{ g NaHCO}_3$  added to the anolyte. OCV was recorded every minute for 10 min. Electrode pairing was the dominant factor: at baseline, mean OCVs were  $0.973 \pm 0.006 \text{ V}$  (Zn–C),  $0.860 \pm 0.009 \text{ V}$  (Zn–Cu), and  $1.375 \pm 0.008 \text{ V}$  (Mg–Cu). Sunlight raised the Mg–Cu OCV by 15.5% (to  $1.588 \pm 0.044 \text{ V}$ ) and the Zn–Cu OCV by 2.8%, with no detectable change for Zn–C. Adding  $\text{NaHCO}_3$  under sunlight further increased OCV for all pairs (2.9–7.1%) and stabilised the Mg–Cu output; the highest mean OCV was  $1.701 \pm 0.010 \text{ V}$  (Mg–Cu, sunlight +  $\text{NaHCO}_3$ ). Because sacrificial metal anodes and an uncontrolled temperature rise contribute to the measured voltage, the biological share of the signal cannot yet be isolated. Abiotic controls, polarisation measurements, and controlled irradiance are therefore required in follow-up work. The results show that the system is a simple, inexpensive platform for studying photosynthesis-driven bioelectrochemistry in school laboratories.

**Keywords:** Biophotovoltaics; Cyanobacteria; Micro Photosynthetic Power Cell; Open-Circuit Voltage; Renewable Energy; *Spirulina*.

**How to Cite:** Doni Nurdiansyah; Rizky Ariakusuma (2026) Electricity Generation from *Spirulina* in a Two-Chamber Photosynthetic Power Cell: Effects of Electrode Pairing, Sunlight Exposure, and Bicarbonate Supplementation on Open-Circuit Voltage. *International Journal of Innovative Science and Research Technology*, 11(9), 2739–2746. <https://doi.org/10.38124/ijisrt/26sep1396>

## I. INTRODUCTION

The global energy system has been under strain since the post-pandemic recovery, when demand rebounded faster than fossil-fuel supply and prices of oil, gas, and electricity rose sharply; the disruption intensified in 2022 as geopolitical conflict reshaped gas flows to Europe (International Energy Agency [IEA], 2023). One consequence was a renewed

reliance on coal, whose global consumption rose by 1.2% in 2022 and surpassed 8 billion tonnes for the first time (IEA, 2022). Coal-fired generation releases carbon dioxide ( $\text{CO}_2$ ) together with sulphur oxides ( $\text{SO}_2$ ,  $\text{SO}_3$ ), nitrogen oxides ( $\text{NO}_x$ ), particulate matter, and mercury (Baig & Yousaf, 2017). These pressures reinforce the need for renewable energy technologies that are clean, low-cost, and deployable at small scales.

Bioelectrochemical systems convert the chemical energy of microbial metabolism into electricity by coupling biological oxidation at an anode to a reduction reaction at a cathode (Logan et al., 2006). When the biocatalyst is a photosynthetic organism, light becomes the primary energy input and the device is often described as a photosynthetic microbial fuel cell or biophotovoltaic system (Rosenbaum et al., 2010; McCormick et al., 2015; Tschörtner et al., 2019). Oxygenic photosynthesis splits water, generating electrons and protons that pass through the photosynthetic electron-transport chain; a fraction of these reducing equivalents, together with those released by respiration of stored carbohydrate in the dark, can be exported to an external electrode (Bombelli et al., 2011; McCormick et al., 2015). Such devices can therefore deliver power in both light and dark periods, and a cyanobacterial biophotovoltaic cell has been shown to power a microprocessor continuously for over six months (Bombelli et al., 2022). Decoupling charge storage from power delivery has also been proposed to raise the power density of these systems (Saar et al., 2018).

The micro photosynthetic power cell ( $\mu$ PSC) is a miniaturised implementation of this principle in which an anode chamber containing photosynthetic microorganisms is separated from a cathode chamber by a proton-exchange medium (Shahparnia et al., 2015).  $\mu$ PSCs have been proposed as competitors to photovoltaic cells for low- and ultra-low-power applications such as Internet-of-Things sensors (Tanneru et al., 2019a, 2019b), and arraying of individual cells has raised power densities to the order of  $10^3 \text{ mW m}^{-2}$  (Kuruvinashetti & Packirisamy, 2022). Nevertheless, the technology remains at an early stage and is limited by low power density, high material cost, and short operational lifetimes (Tanneru et al., 2019a).

*Spirulina* (*Arthrospira*) is a filamentous, non-heterocystous cyanobacterium that grows in warm, alkaline, carbonate-rich waters, with optimal growth at pH of about 9.5–9.8 and temperatures of roughly 30–35 °C (Vonshak, 1997; Ali & Saleh, 2012). It is cultivated at large scale for food and feed, is inexpensive and widely available, and is therefore an attractive biocatalyst for low-cost bioelectrochemical devices. Previous work with *S. platensis* in membrane-less photosynthetic microbial fuel cells reported OCVs of 0.39–0.49 V and power densities of up to  $10 \text{ mW m}^{-2}$  (Fu et al., 2009; Lin et al., 2013). Because the photosynthetic rate depends on light and on the supply of inorganic carbon, and because the cell voltage depends strongly on the electrode materials, these three factors are natural levers for improving the performance of simple *Spirulina*-based cells. Their combined effect, however, has rarely been examined in low-cost configurations that can be built with standard school-laboratory equipment.

This study therefore aimed to (a) construct a two-chamber photosynthetic power cell that uses *Spirulina* as the anodic substrate, (b) quantify the OCV produced with three anode–cathode pairs, and (c) examine how two factors that influence photosynthesis—sunlight exposure and bicarbonate ( $\text{CO}_2$ ) supplementation—change the OCV of the cell.

## II. MATERIALS AND METHODS

### ➤ Study Design and Setting

A quantitative, laboratory-based experimental design was used. The study was conducted in the Physics Laboratory of SMA Taruna Bakti, Bandung, Indonesia, between March and September 2024, covering literature review, preparation of materials, electrical data collection, and reporting. The independent variables were (i) the anode–cathode electrode pair, (ii) exposure of the cell to direct sunlight, indexed by the substrate temperature, and (iii) the addition of sodium bicarbonate ( $\text{NaHCO}_3$ ) to the anolyte. The dependent variable was the open-circuit voltage (OCV) of the cell.

### ➤ Materials

The substrate was a *Spirulina* suspension. Other materials were tap water (catholyte),  $\text{NaHCO}_3$ , a salt bridge, glass beakers, a digital multimeter, a digital balance, a thermometer, external connecting wires, and zinc (Zn), magnesium (Mg), copper (Cu), and carbon (C) electrodes.

The biomass concentration of the suspension was estimated gravimetrically as:

$$M = [(m - v) / v] \times 1000$$

Where  $M$  is the biomass concentration ( $\text{g L}^{-1}$ ),  $m$  is the total mass of the suspension (g), and  $v$  is its volume (mL); the expression assumes a density of  $1 \text{ g mL}^{-1}$  for the aqueous phase. The suspension used in all experiments had a concentration of  $27.1 \text{ g L}^{-1}$ .

### ➤ Cell Construction

The cell followed the two-chamber architecture of a  $\mu$ PSC, implemented at beaker scale in the form of a galvanic (voltaic) cell (Figure 1). The anode chamber contained 250 mL of *Spirulina* suspension, and the cathode chamber contained 250 mL of water, which served as the electron-accepting catholyte. The two chambers were connected by a salt bridge that maintained electroneutrality and allowed ion migration between them. Metals with a strong tendency to oxidise according to the electrochemical series (Zn and Mg) were used as anodes, and more noble or inert materials (C and Cu) were used as cathodes (Bratsch, 1989). The electrodes were connected through a digital multimeter without an external load, so that the measured quantity was the OCV.

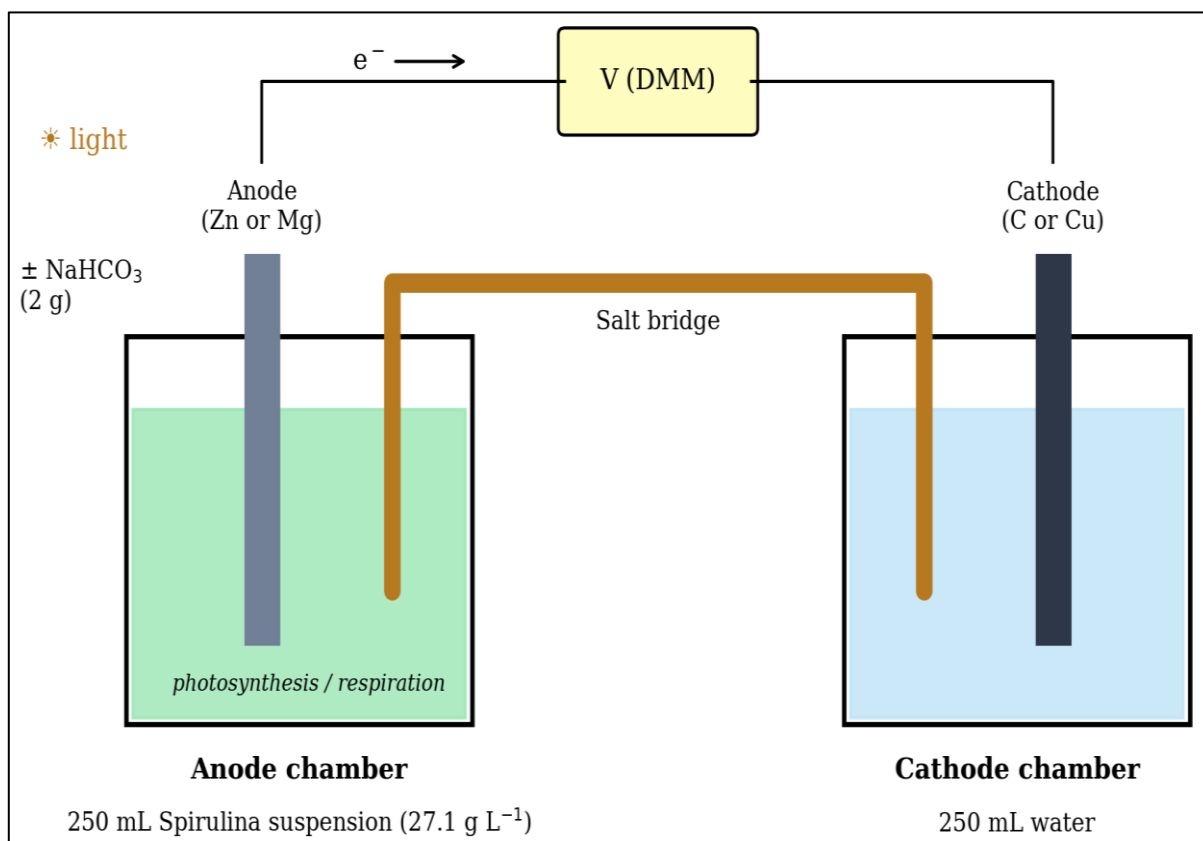


Fig 1 Schematic of the two-chamber photosynthetic power cell. The anode chamber holds the *Spirulina* suspension and a Zn or Mg anode; the cathode chamber holds water and a C or Cu cathode. The chambers are joined by a salt bridge, and the open-circuit voltage is read with a digital multimeter (DMM).

#### ➤ Experimental Conditions

Three electrode pairs were tested: Zn anode–C cathode (Zn–C), Zn anode–Cu cathode (Zn–Cu), and Mg anode–Cu cathode (Mg–Cu). Each pair was measured under three sequential conditions (Table 1). In the baseline condition, the cell was operated indoors in the laboratory. In the sunlight condition, the cell was moved to a location exposed to direct sunlight to increase the light available for photosynthesis;

because irradiance could not be measured directly, the substrate temperature was recorded with a thermometer as an indirect indicator of solar exposure. In the sunlight + NaHCO<sub>3</sub> condition, 2 g of NaHCO<sub>3</sub> ( $\approx 8 \text{ g L}^{-1}$ ) was added to the anolyte of the sun-exposed cell to raise the concentration of dissolved inorganic carbon (CO<sub>2</sub>/HCO<sub>3</sub><sup>−</sup>) available for photosynthesis.

Table 1 Experimental Conditions and Electrode Pairs

| Condition                     | Light             | Anolyte additive                                        | Substrate temperature (°C)  | Electrode pairs    |
|-------------------------------|-------------------|---------------------------------------------------------|-----------------------------|--------------------|
| Baseline                      | Indoor laboratory | None                                                    | 26                          | Zn–C, Zn–Cu, Mg–Cu |
| Sunlight                      | Direct sunlight   | None                                                    | Zn–C 38; Zn–Cu 33; Mg–Cu 38 | Zn–C, Zn–Cu, Mg–Cu |
| Sunlight + NaHCO <sub>3</sub> | Direct sunlight   | 2 g NaHCO <sub>3</sub> ( $\approx 8 \text{ g L}^{-1}$ ) | 38 (all pairs)              | Zn–C, Zn–Cu, Mg–Cu |

- **Note.** Anolyte: 250 mL *Spirulina* suspension ( $27.1 \text{ g L}^{-1}$ ); catholyte: 250 mL water. Electrode pairs are written as anode–cathode.

#### ➤ Measurements and Data Analysis

For each electrode pair and condition, the OCV was read once per minute from minute 1 to minute 10 ( $n = 10$  readings per run). Descriptive statistics (mean, standard deviation [SD], minimum, maximum, and coefficient of variation [CV]) were calculated for each run. Temporal drift was estimated as the slope of an ordinary least-squares

regression of OCV on time ( $\text{mV min}^{-1}$ ). To describe the magnitude of the treatment effects, the absolute and relative changes in mean OCV between conditions were computed for each electrode pair, and Welch's *t*-tests with Holm correction for multiple comparisons and Cohen's *d* were calculated. An exploratory two-way analysis of variance (ANOVA) with electrode pair and condition as factors was also performed. Because the ten readings within a run are successive measurements of the same cell rather than independent replicates, these inferential statistics describe within-run consistency and should be interpreted as exploratory. Analyses were carried out in Python (SciPy and statsmodels).

### III. RESULTS

All nine runs produced a stable, measurable OCV throughout the 10-min recording period (Figure 2; raw readings in Supplementary Table S1). Descriptive statistics are summarised in Table 2, and pairwise comparisons

between conditions are given in Table 3. In the exploratory two-way ANOVA, electrode pair ( $F(2, 81) = 14,839.8, p < .001$ ), condition ( $F(2, 81) = 624.6, p < .001$ ), and their interaction ( $F(4, 81) = 261.0, p < .001$ ) were all significant, indicating that the response to the treatments differed among electrode pairs.

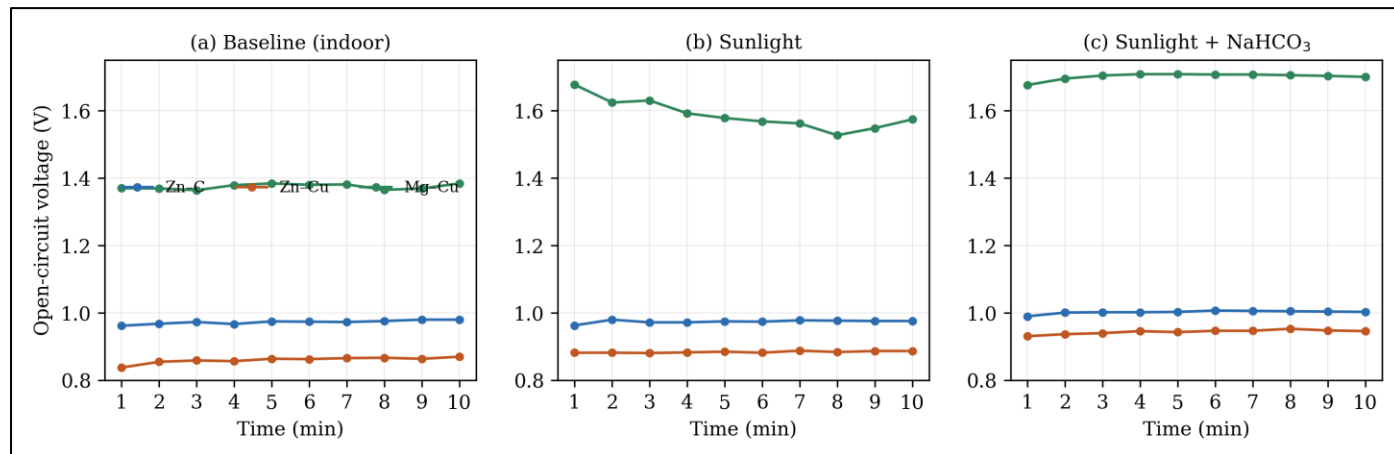


Fig 2 Open-Circuit Voltage of the *Spirulina* Cell Recorded at 1-min Intervals for Three Electrode Pairs (Anode–Cathode) Under (a) Indoor Baseline, (b) Direct Sunlight, and (c) Direct Sunlight with 2 g  $\text{NaHCO}_3$  Added to the Anolyte.

Table 2 Descriptive Statistics of the Open-Circuit Voltage (V) for Each Electrode Pair and Condition ( $n = 10$  Readings Per Run)

| Condition                   | Electrode pair | Mean $\pm$ SD     | Min–Max     | CV (%) | Drift ( $\text{mV min}^{-1}$ ) |
|-----------------------------|----------------|-------------------|-------------|--------|--------------------------------|
| Baseline                    | Zn–C           | $0.973 \pm 0.006$ | 0.962–0.980 | 0.59   | +1.68                          |
|                             | Zn–Cu          | $0.860 \pm 0.009$ | 0.838–0.870 | 1.06   | +2.53                          |
|                             | Mg–Cu          | $1.375 \pm 0.008$ | 1.364–1.384 | 0.57   | +0.81                          |
| Sunlight                    | Zn–C           | $0.974 \pm 0.005$ | 0.963–0.980 | 0.48   | +0.79                          |
|                             | Zn–Cu          | $0.884 \pm 0.003$ | 0.881–0.888 | 0.28   | +0.65                          |
|                             | Mg–Cu          | $1.588 \pm 0.044$ | 1.527–1.677 | 2.79   | –12.57                         |
| Sunlight + $\text{NaHCO}_3$ | Zn–C           | $1.002 \pm 0.005$ | 0.990–1.007 | 0.47   | +1.02                          |
|                             | Zn–Cu          | $0.944 \pm 0.006$ | 0.931–0.953 | 0.67   | +1.72                          |
|                             | Mg–Cu          | $1.701 \pm 0.010$ | 1.676–1.708 | 0.57   | +1.65                          |

- **Note.** CV = coefficient of variation; drift = slope of the least-squares regression of OCV on time.

#### ➤ Effect of Electrode Pairing

Under baseline conditions the Mg–Cu pair produced the highest OCV ( $1.375 \pm 0.008$  V), followed by Zn–C ( $0.973 \pm 0.006$  V) and Zn–Cu ( $0.860 \pm 0.009$  V). Replacing the Zn anode with Mg (Zn–Cu versus Mg–Cu) raised the OCV by 0.514 V (+59.8%), whereas replacing the C cathode with Cu (Zn–C versus Zn–Cu) lowered it by 0.113 V (–11.6%). The ranking Mg–Cu > Zn–C > Zn–Cu was preserved under all three conditions (Figure 3). The Zn-based cells showed a small upward drift of 1.7–2.5  $\text{mV min}^{-1}$  during the baseline run, while the Mg–Cu cell had no significant drift ( $p = .38$ ).

#### ➤ Effect of Sunlight Exposure

Moving the cells into direct sunlight raised the substrate temperature to 33–38 °C. The effect on OCV depended strongly on the electrode pair (Table 3). The Mg–Cu OCV increased by 0.214 V (+15.5%) to  $1.588 \pm 0.044$  V, the largest

single effect observed, and the Zn–Cu OCV increased by 0.024 V (+2.8%). The Zn–C OCV was essentially unchanged (+0.15%,  $p = .53$ ). Under sunlight, the Mg–Cu cell was also the least stable run: its OCV peaked at 1.677 V in the first minute and then declined at  $-12.6 \text{ mV min}^{-1}$  ( $p = .002$ ) to 1.527 V at minute 8, before partially recovering (CV = 2.79%).

#### ➤ Effect of Bicarbonate Supplementation

Adding 2 g of  $\text{NaHCO}_3$  to the sun-exposed anolyte increased the OCV of every electrode pair: by 0.028 V (+2.9%) for Zn–C, 0.060 V (+6.8%) for Zn–Cu, and 0.113 V (+7.1%) for Mg–Cu (all Holm-adjusted  $p < .001$ ). The combined effect of sunlight and bicarbonate relative to baseline was +3.0% (Zn–C), +9.7% (Zn–Cu), and +23.8% (Mg–Cu). Bicarbonate also stabilised the Mg–Cu output, reducing its CV from 2.79% to 0.57% and removing the downward drift seen under sunlight alone. The highest mean OCV of the study,  $1.701 \pm 0.010$  V, was obtained with the Mg–Cu pair under sunlight with  $\text{NaHCO}_3$ .

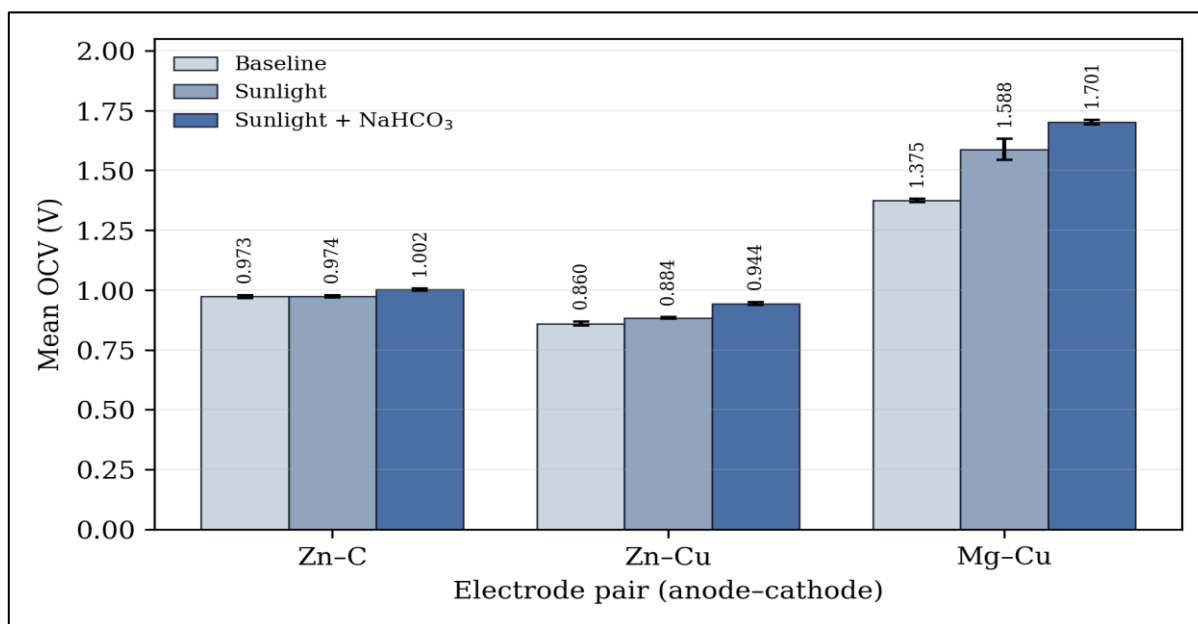


Fig 3 Mean Open-Circuit Voltage ( $\pm$  SD,  $n = 10$  Readings) for Each Electrode Pair Under the Three Conditions.

Table 3 Changes in Mean Open-Circuit Voltage Between Conditions

| Electrode pair | Comparison                                           | $\Delta$ OCV (V) | Change (%) | Welch $t$ | Holm-adjusted $p$ | Cohen's $d$ |
|----------------|------------------------------------------------------|------------------|------------|-----------|-------------------|-------------|
| Zn-C           | Baseline $\rightarrow$ Sunlight                      | +0.002           | +0.15      | 0.64      | .529              | 0.29        |
|                | Sunlight $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.028           | +2.87      | 13.31     | < .001            | 5.95        |
|                | Baseline $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.030           | +3.03      | 12.60     | < .001            | 5.63        |
| Zn-Cu          | Baseline $\rightarrow$ Sunlight                      | +0.024           | +2.77      | 7.98      | < .001            | 3.57        |
|                | Sunlight $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.060           | +6.75      | 27.82     | < .001            | 12.44       |
|                | Baseline $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.084           | +9.71      | 23.87     | < .001            | 10.67       |
| Mg-Cu          | Baseline $\rightarrow$ Sunlight                      | +0.214           | +15.53     | 15.00     | < .001            | 6.71        |
|                | Sunlight $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.113           | +7.13      | 7.89      | < .001            | 3.53        |
|                | Baseline $\rightarrow$ Sunlight + NaHCO <sub>3</sub> | +0.327           | +23.78     | 82.43     | < .001            | 36.86       |

- *Note.* Readings within a run are successive measurements of the same cell; test statistics are therefore exploratory indicators of within-run consistency rather than tests across independent replicate cells.

#### IV. DISCUSSION

##### ➤ Electrode Materials Dominate the Open-Circuit Voltage

The clearest result of this study is that the choice of electrode pair determined the OCV far more than any of the treatments. This is expected for a cell that uses reactive metal anodes. The standard reduction potentials of  $\text{Mg}^{2+}/\text{Mg}$  ( $-2.37$  V) and  $\text{Zn}^{2+}/\text{Zn}$  ( $-0.76$  V) differ by about 1.6 V (Bratsch, 1989), so a Mg anode is expected to deliver a substantially higher cell voltage than a Zn anode against the same cathode, as observed. The measured values were, however, well below the standard cell potentials (e.g., about 2.7 V for  $\text{Mg}/\text{Cu}^{2+}$ ), because the catholyte contained no  $\text{Cu}^{2+}$  and the electrode potentials in such cells are mixed potentials set by metal dissolution at the anode and by oxygen or water reduction at the cathode, and because Mg rapidly forms a partially passivating hydroxide film in water. The higher OCV of Zn-C compared with Zn-Cu suggests that the carbon cathode supported a more positive rest potential for the cathodic reaction than the copper surface, which may have carried an

oxide layer; this interpretation should be tested with separate half-cell measurements against a reference electrode.

An important implication is that, in the present configuration, a large part of the measured voltage is galvanic—that is, it originates from the corrosion of the sacrificial anode rather than from electrons exported by *Spirulina*. Photosynthetic power cells that rely solely on microbial electron transfer typically report OCVs below 1 V (Fu et al., 2009; Lin et al., 2013; Tanneru et al., 2019a). The present results confirm that *Spirulina* can be combined with inexpensive metal electrodes to obtain OCVs above 1.5 V, but they do not by themselves establish how much of that voltage is biological.

##### ➤ Sunlight and Temperature

Sunlight increased the OCV of the Mg-Cu and Zn-Cu cells but not of the Zn-C cell. Light is the energy source of photosynthesis, and more photosynthetic activity is expected to increase the supply of reducing equivalents in the anolyte (McCormick et al., 2015). Direct sunlight, however, also heated the anolyte to 33–38 °C, and temperature affects the kinetics of metal dissolution, the thermodynamics of the electrode reactions, and the conductivity of the electrolyte. The effects of light and heat are therefore confounded in this design. The fact that the largest response occurred with the

most reactive anode (Mg), and that this response was transient—a peak followed by a decline of about 12.6 mV min<sup>-1</sup>—is consistent with a surface process at the Mg electrode, such as heat-accelerated dissolution followed by re-formation of a hydroxide film. It is also notable that Fu et al. (2009) found *S. platensis* photosynthetic fuel cells to produce more power in the dark than in the light, which they attributed to photosynthetic oxygen production and the use of stored reserves in the dark. Because 38 °C is near the upper limit of the optimal growth range of *Spirulina* (Vonshak, 1997), prolonged exposure under these conditions may also stress the culture.

#### ➤ Bicarbonate Supplementation

Adding NaHCO<sub>3</sub> raised the OCV of all three pairs and made the Mg–Cu output markedly more stable. Bicarbonate is the main inorganic carbon source in standard *Spirulina* culture media, and increasing the dissolved inorganic carbon can support higher photosynthetic rates in carbon-limited cultures (Vonshak, 1997). At about 8 g L<sup>-1</sup>, however, NaHCO<sub>3</sub> also changes the ionic strength, conductivity, and pH buffering of the anolyte, which can shift the mixed

potentials of metal electrodes and alter the formation of surface films on Mg and Zn. The observed increase is therefore compatible with both a biological mechanism (more photosynthetic activity) and an electrochemical one (a modified anolyte chemistry). Distinguishing the two requires running the same treatment in a cell-free medium.

#### ➤ Comparison with Previous Studies

Table 4 places the present results alongside published photosynthetic power cells. The OCVs measured here (0.86–1.70 V) are higher than those reported for *Spirulina* cells with inert or noble electrodes (0.39–0.49 V), but the comparison is not like-for-like because of the sacrificial anodes used here. Moreover, OCV alone does not describe the useful output of a cell; the current and power that can be drawn under load, normalised to electrode area, are the standard performance metrics (Logan et al., 2006) and were not measured in this study. The practical value of the present system is that it can be built from inexpensive, readily available components and used to demonstrate and investigate how light, carbon supply, and electrode materials influence a bioelectrochemical cell.

Table 4 Comparison with Selected Photosynthetic Power-Cell Studies

| Study                               | Organism                    | Configuration / electrodes                                            | Reported output                                                       |
|-------------------------------------|-----------------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------|
| Fu et al. (2009)                    | <i>Spirulina platensis</i>  | Membrane-less, mediator-free PMFC                                     | Max OCV 0.39 V (dark);<br>1.64 mW m <sup>-2</sup> (dark)              |
| Lin et al. (2013)                   | <i>S. platensis</i> biofilm | Membrane-less; gold-mesh anode, graphite cathode                      | Max OCV 0.49 V; 10 mW m <sup>-2</sup>                                 |
| Kuruvinashetti & Packirisamy (2022) | Photosynthetic microalgae   | μPSC, single cell and arrays                                          | 413.2 mW m <sup>-2</sup> (single);<br>1914 mW m <sup>-2</sup> (array) |
| This study                          | <i>Spirulina</i> suspension | Two-chamber beaker cell; Zn or Mg anode, C or Cu cathode, salt bridge | Mean OCV 0.860–1.701 V;<br>power not measured                         |

## V. LIMITATIONS AND FUTURE WORK

This exploratory study has several limitations. First, no abiotic control (the same electrodes in cell-free medium, or in medium containing non-viable biomass) was included, so the biological contribution to the OCV could not be separated from the galvanic contribution of the metal anodes. Second, irradiance was not measured and was confounded with temperature, and the baseline temperature was not recorded. Third, the conditions were applied sequentially rather than in random order, so electrode ageing and changes in the culture over time may have contributed to the differences. Fourth, each condition was represented by a single 10-min run of one cell, so the ten readings are not independent replicates. Fifth, only OCV was measured; current, power density, internal resistance, and long-term stability were not characterised. Future work should include abiotic and dark controls, independent replicate cells, measured irradiance with temperature held constant, polarisation and power-density curves using inert electrodes (e.g., carbon felt or graphite) at both anode and cathode, and longer operation over light–dark cycles.

## VI. CONCLUSION

A simple two-chamber photosynthetic power cell using *Spirulina* as the anodic substrate produced stable open-circuit

voltages between 0.86 and 1.70 V. The electrode pair was the dominant factor, with the Mg–Cu pair giving the highest OCV under all conditions. Direct sunlight increased the OCV of the Cu-cathode cells—by 15.5% for Mg–Cu—but also raised the substrate temperature, and adding NaHCO<sub>3</sub> under sunlight further increased and stabilised the output of all pairs, giving a maximum mean OCV of 1.701 V. Because the metal anodes and the temperature rise contribute to these values, the results should be read as the performance of a hybrid galvanic–photosynthetic cell rather than as a direct measure of *Spirulina* electrogenic activity. The system nevertheless provides a low-cost platform for studying photosynthesis-driven bioelectrochemistry, and the controls and measurements identified above offer a clear path towards quantifying the biological share of its output.

## ACKNOWLEDGMENTS

The authors thank SMA Taruna Bakti for providing laboratory facilities and the school principal for approving and supporting this research. This work was prepared as part of the Olimpiade Penelitian Siswa Indonesia (OPSI) 2024.

#### ➤ Author Contributions

- Doni Nurdiansyah: supervision, methodology, formal analysis, writing—review and editing.

- Rizky Ariakusuma: conceptualisation, investigation, data curation, writing—original draft.

➤ *Conflict of Interest*

The authors declare no conflict of interest.

➤ *Funding*

This research received no external funding.

➤ *Data Availability Statement*

All raw open-circuit voltage readings are provided in Supplementary Table S1.

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**SUPPLEMENTARY MATERIAL**

Supplementary Table S1. Raw open-circuit voltage readings (V) recorded at 1-min intervals

| <b>Time (min)</b> | <b>Baseline Zn–C</b> | <b>Baseline Zn–Cu</b> | <b>Baseline Mg–Cu</b> | <b>Sun Zn–C</b> | <b>Sun Zn–Cu</b> | <b>Sun Mg–Cu</b> | <b>Sun+NaHCO<sub>3</sub> Zn–C</b> | <b>Sun+NaHCO<sub>3</sub> Zn–Cu</b> | <b>Sun+NaHCO<sub>3</sub> Mg–Cu</b> |
|-------------------|----------------------|-----------------------|-----------------------|-----------------|------------------|------------------|-----------------------------------|------------------------------------|------------------------------------|
| 1                 | 0.962                | 0.838                 | 1.370                 | 0.963           | 0.882            | 1.677            | 0.990                             | 0.931                              | 1.676                              |
| 2                 | 0.968                | 0.855                 | 1.369                 | 0.980           | 0.882            | 1.624            | 1.001                             | 0.937                              | 1.695                              |
| 3                 | 0.973                | 0.859                 | 1.364                 | 0.972           | 0.881            | 1.630            | 1.002                             | 0.940                              | 1.704                              |
| 4                 | 0.967                | 0.857                 | 1.379                 | 0.972           | 0.883            | 1.592            | 1.002                             | 0.946                              | 1.708                              |
| 5                 | 0.975                | 0.864                 | 1.384                 | 0.975           | 0.885            | 1.578            | 1.003                             | 0.943                              | 1.708                              |
| 6                 | 0.974                | 0.863                 | 1.380                 | 0.974           | 0.882            | 1.568            | 1.007                             | 0.947                              | 1.707                              |
| 7                 | 0.973                | 0.866                 | 1.381                 | 0.978           | 0.888            | 1.562            | 1.006                             | 0.947                              | 1.707                              |
| 8                 | 0.976                | 0.867                 | 1.365                 | 0.977           | 0.884            | 1.527            | 1.005                             | 0.953                              | 1.705                              |
| 9                 | 0.980                | 0.864                 | 1.369                 | 0.976           | 0.887            | 1.548            | 1.004                             | 0.948                              | 1.703                              |
| 10                | 0.980                | 0.870                 | 1.384                 | 0.976           | 0.887            | 1.574            | 1.003                             | 0.946                              | 1.700                              |

- *Note.* Substrate temperature under sunlight: Zn–C 38 °C, Zn–Cu 33 °C, Mg–Cu 38 °C; under sunlight + NaHCO<sub>3</sub>: 38 °C for all pairs.