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The application of fresh water algae to produce electricity in saline water media

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***Abstract*: Currently, there is an increased need for renewable energy resources to combat the rapid depletion of fossil fuels. Bio-photovoltaic (BPV) cells represent an environmentally friendly means of electricity generation from photosynthetic organisms such as algae. However, the applicability of scaling up BPVs to fit larger operations has been a challenge. This research presents a novel, simple and cost-effective chamber-less BPV that can be easily applied on a large-scale. The research also examined the effects of electrode spacing, height of the cell and water salinity on the performance of the BPV.**

Chlorella Vulgaris alga was cultured using UST medium, and was allowed to form a biofilm on a stainless steel anode. The chamber-less design consisted of three parallel and transparent acrylic plates (10 cm x 20 cm) positioned one on top of the other; a base, a middle plate holding the anodic biofilm and a top plate with a 4cm x 5cm opening in which a graphite air cathode settled. Light could reach the biofilm on the middle plate through the transparent top plate. The three plates were supported together by two acrylic rods, which allowed easy adjustment of electrode spacing and cell height. Current intensity was measured under different cathode-anode spacing distances, heights and salinities.

The BPV device produced maximum outputs at a spacing, height and salinity of 2 cm, 15 cm and 20000 TDS respectively. The highest power produced from the device was 0.12 W/m2. Spacing negatively correlated with power output (R=- 0.556) while height and salinity correlated positively (R=0.938, R=0.793 respectively). A salinity of 40000 TDS, however, caused a reduction in electric current after 15 minutes, which indicates that Chlorella Vulgaris malfunctions at higher salinities.

The low-cost, easy-maintenance, chamber-less design of this BPV qualifies it for large scale practice. Additionally ,increased power outputs at greater heights and salinities highlights its potential use in brackish waters or deep ponds.

***Index Terms*: Bioelectricity, bio-photovoltaic action, Algae activity, saline water applications..**

I. INTRODUCTION

The rapid worldwide population grows this threat to the availability of sufficient energy resources across the globe. Nonrenewable energy resources such as fossil fuels are gradually being depleted, in addition to being a source of pollution[1]. Solving the anticipated energy shortage as well as pollution reduction is currently the interest of researchers who are in the field of clean, cheap and applicable energy generation methods.

One such promising field of investigation is the use of microorganisms in harnessing electricity ,a technique that involves combining the microorganisms together with a substrate in a biological battery called microbial fuel cell (MFC)[2].An MFC, in its basic form, consists of two chambers separated with an ion exchange membrane; anodic and cathodic. In the anodic chamber, through the microorganisms respiratory processes, electrons are released, and water is split into hydrogen and oxygen. The electrons are transferred to the anode, while the hydrogen ions pass through the membrane to reach the cathode. Electricity is generated when electrons travel from the anode to the cathode via an external electric circuit to combine with hydrogen ions and oxygen to form water[3].

MFCs, however, have to continuously be provided with the ‘fuel’ needed for the microbe metabolism[4],a drawback that was overcome by modifying the MFC into a Bio-photovoltaic (BPV) cell; which uses photosynthetic microbes such as algae that require sunlight rather than organic matter for energy production[5]. Electricity production from MFCs and BPVs required the presence of mediator compounds for easy electron transfer from the microbe to the receiver anode [6]. Mediators, however, proved to be unfeasible and toxic[7]and were thus replaced by biofilms, which involve attachment of microbial cells on a surface in the form of communities[8].The biofilm acts as an electron donor directly to the anode without the need of mediators for electron transfer. Studies demonstrated that using biofilms in BPVs showed enhancement in the total energy output [9, 10, 11].

A crucial aspect of the BPV is the anodic material. Bombelli et al. used different materials for the anode including indium tin oxide (ITO), stainless steel (SS) and carbon-based materials .ITO showed the best power output followed by SS[9], which makes SS an attractive large-scale solution as an anode, given its price and availability compared to ITO.

Many other factors can affect the power output, for instance, cathode anode spacing was found to impact the electric outcome in MFCs [12, 13]. Also, the height or distance of the cell from the water bed might or might not affect the power output. It would be worth knowing whether BPVs could be scaled up and positioned in deep waters. Another potential influence is the salinity of the water surrounding the device.

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Some MFC studies have reported augmentation of power output with increased salt concentrations [14, 15], while others noted a reduced output with any addition of salts [16].No previous work though has studied the effect of such factors on the performance of BPVs.
In the past couple of years, several studies aimed at enhancing the electric output from BPVs through the use of intricate devices and techniques including micro fluidics, Nano-scaling and bacterial/algal genetic modification [17, 18, 19, 20]. These studies have succeeded in generating considerable amounts of electricity on the laboratory scale and have been pivotal for the evolution of BPVs. However, to the authors knowledge, there are no engineering suggestions for a large scale, cost-effective design have been presented. This study describes a novel simple mediator-less, membrane-less and chamber-less BPV design which offers a scalable solution capable of producing a significant electric output. Furthermore, the study compares between various determinants of electric output in BPVs including anode-cathode spacing, height of the cell and salinity of the water, in an attempt of optimizing these features.

II. MATERIALS AND METHODS

A. Algal Culture

In this study, the green algae, Chlorella Vulgaris was cultured to be used in biofilm formation for the BPV. BG11 the expensive medium is the most widely used culture medium in studies involving Chlorella Vulgaris [10, 21, 22]. A study proved the success of UST medium the cheap medium that costs nearly 1/100 of the cost of BG11, with Scenedesmus Obliquus [23].
So, In this study a comparison between the two culture medium attempted to ensure that the cheap medium will not affect the efficiency of the Chlorella Vulgaris algae activity. The chemical constituents of the two media types are shown in Table (1). 1.20 liters of Chlorella Vulgaris solution containing 0.67 million cells/ml (counted by hemo-cyto-meter) were added to 6-litre batches of each medium and left for seven days under nearly 4000 lux and continuous mixing[23].

Table 1 Chemical Constituents of Used Media Types.

BG11		UST	
Chemical	Gram / 500 ml	Chemical	Gram / 100 L
$NaNO_3$	75	Urea	50
K2HPO4.3H2O	2	Super phosphate	25
Na2CO3	1	Trace elements	5
MgSO4.7H2O	3.75		
CaCl2.2H2O	1.8		
EDTA-Na2	0.05		
Ammonium ferric citrate green	0.3		
Citric acid	0.3		
H3BO3	2.86		
MnCl2.4H2O	1.81		
ZnSO4.7H2O	0.22		
Na2MoO4.2H2O	0.39		
CuSO4.5H2O	0.08		
Co(NO3)2.6H2O	2.6		

B. Biofilm Formation

To form biofilms with an even homogenous attachment, one liter of algae solution with a cell density of 10 million cells per ml (counted using hemocyto-meter) were added to 0.5litre of media and left to settle, attach and colonize on a10 x 20 cm SS sheet (anode) for eight days while replacing media after four days. **Figure 1**shows biofilms during the settling process.

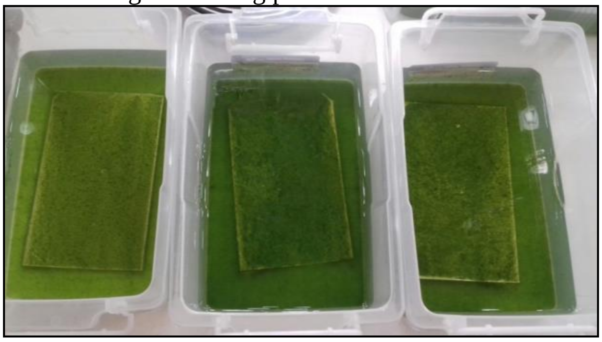

Figure 1Biofilm formation

C. Bpv design

The proposed BPV design consisted of three parallel acrylic plates measuring10cm x 20cm, positioned one on top of the other and supported together with two acrylic rods (**Figure 2**).The bottom one acted as a base for the device, the middle one held the anodic-biofilm, and the top one contained a 4cm x 5cm opening in which the graphite cathode settled. The rest of the top acrylic plate was transparent to allow the light to reach the biofilm underneath on the middle plate. The acrylic plates holding the anode and cathode can be moved along the acrylic rods to adjust the spacing and the height.

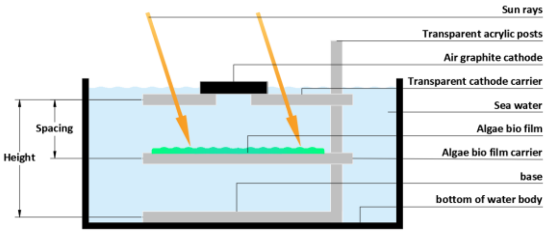

Figure 2BPV structure design side view

D. Power output recording

The BPV device was put in water, so that the water level was at the level of the cathode, but not completely covering it. In other words, the cathode was exposed to air (air cathode). For every liter of water, 10 ml of media were added. A first test was made to verify the electricity output possibility from the new design which was a success with an output of 4 mA. The power output of the biofilm was then tested under different conditions to identify factors which produce the best output. These include height of the cell i.e. the distance between the base acrylic plate and the electrodes (15, 20, 25 and 30 cm), the spacing distance between anode and cathode (1, 2 and 3 cm) and salinity of the water around the biofilm (200, 2000, 8000, 20000 and 40000 TDS).

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The cell testing the height was adjusted at a spacing of 3 cm while the cell investigating the spacing was set at a height of 15 cm, both were inserted in fresh water. Finally, the cell involved with studying the salinity was fixed at a height of 15 cm and a spacing of 3 cm.

Each factor was tested on a different biofilm. However, the different variables within each factor were tried on the same biofilm to make sure that the biofilm cell density is almost the same. The electric output was measured through a resistance of 1.5 kΩfor one hour for each parameter using a multimeter 16Bconnected to a computer device which allows continuous recording of the current produced.

E. Statistical Analysis

Analysis of variance (ANOVA) test was used to compare between the means of recordings in each parameter. Pearson correlation coefficient (R) was used to identify the strength of correlation between variables. P value <0.05 was considered statistically significant. Statistical analysis and graphs were constructed using R version 3.5.3 and R studio version 1.1.383

III. RESULTS

A. Choice of cultural media

BG11 and UST were used to culture algae. The starting cell count in each was 0.67 million cell/ml. After 7 days, under the same light and aeration conditions, the cell culture by BG11 increased 4.5-fold, while UST increased by 8 folds as illustrated in Figure 3. This means that UST as algae cultural media is the best and the study complete with

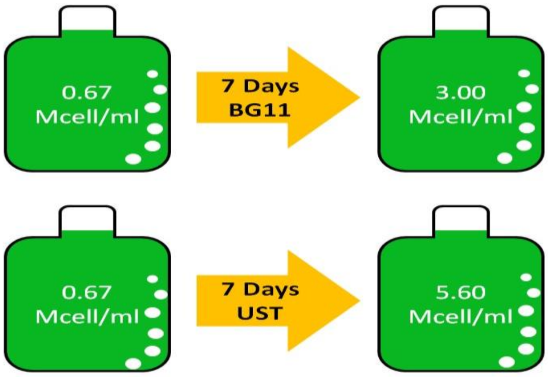

Figure 3 Chlorella Cell Count Following 7 Days with Both Types of Media

B. Electric output

Three biofilms were used to test the electrical current produced. Each biofilm tested a specific parameter. The highest output recorded was 121 mW/m2 at a voltage of 13.5 V/m2and an intensity of 9mA/m2. The three parameters tested were anode-cathode spacing, height of the cell and salinity of water. Electricity output was recorded for a complete hour for each spacing, height and salinity.

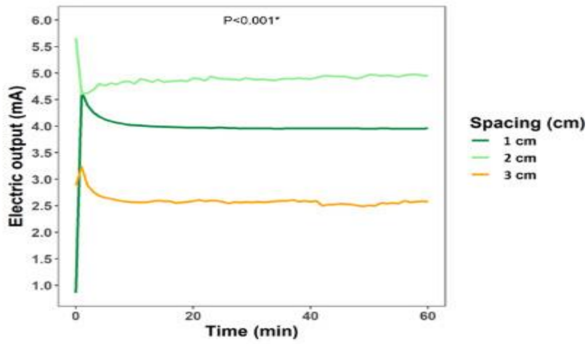

Figure 4-a The electric output power recordings for different spacing distances

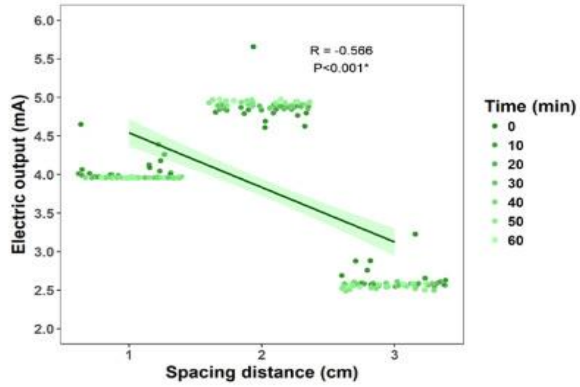

Figure 4- b Correlation Between Spacing and Output Recording

Figure 4-a shows that there was a significant difference between the three spacing distances (P<0.001).The ideal distance between the anode and cathode was 2cm, with an output of 5mA/m2. There was a moderate negative correlation between spacing and power output (R=-0.566, P<0.001 as shown in Figure 4-b.

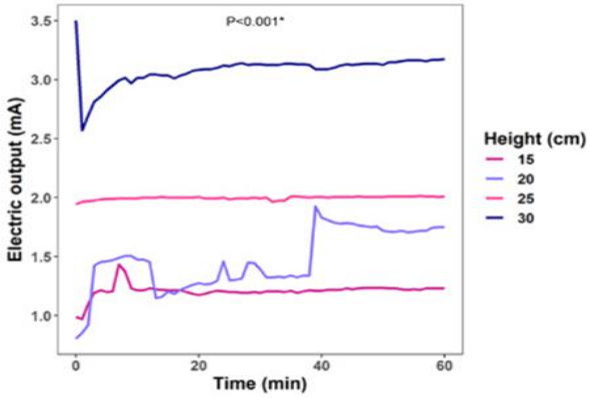

Figure 5-a the Electric Output Power Recordings different heights

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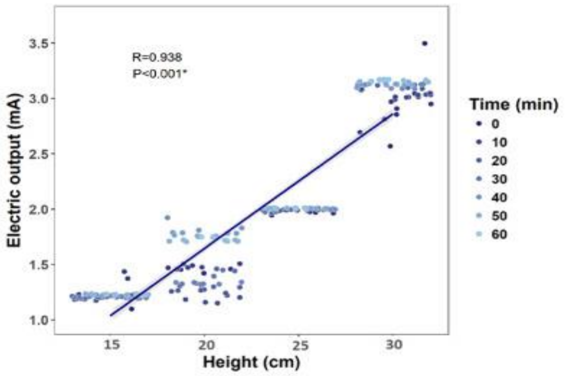

Figure 5- b Correlation between height and output recording

As for height, the means of readings were different between the four different heights (P <0.001). The highest current intensity observed was 3.2 mA/m2 at a height of 30 cm as illustrated in Figure 5-a. The relation between height and electric output, Figure 5-b, showed a strong positive correlation (R=0.938, P<0.001).

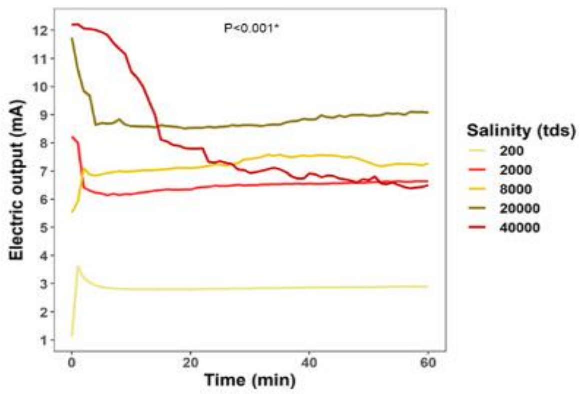

Figure 6-a The electric output power recordings for different salinities

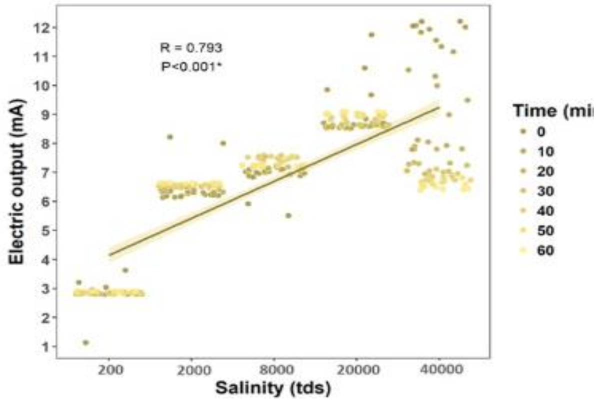

Figure 5- b Correlation between salinity and output recording

IV. DISCUSSION

An engineering approach is introduced in this study to generate electricity using an easy constructed BPV made of cheap and simple materials. The practicality of this suggested design allows it to be used in many various applications and be placed in different water bodies for potentially affordable energy. To achieve a cost-effective power generation ,this research started from the first step; algal growth and culture. Most of the previous studies employed the BG11 medium[10, 21, 22].

In this study we attempted to use a much cheaper medium, UST and found, interestingly, that it was more effective than BG11, achieving cellular levels around double those with BG11.It was therefore selected as the medium of choice in this study.

Another economical alternativeappliedin this workwas the electrode material. Quite a few studies utilize platinum or apply a platinum coating on the cathode[5, 21, 24, 25],which is relatively costly. In this study, pure graphite plates were used for the cathode with no sort of metal plating. For the anode, SS foil was adopted, which achieved minimum material usage and low cost. Many BPV studies have used carbon based anodes [26, 27, 28, 29, 30], however, Thorne et al. has found that Chlorella vulgaris cells grown on carbon were irregular in shape and had a disconnected matrix [31] and Baudler et al.proclaimed that carbon was not suitable for large scale applications [32].Pocaznoi et al. compared graphite and SS anodes and showed that the latter had a greater ability for biofilm formation and electricity generation [33]. Tin oxide-associated anodes and titanium dioxide ceramic anodes have provided high electric outputs[5, 21, 31]but have the disadvantage of being far more expensive than SS which limits their use in mass production. In the current design, a small square cathode was positioned above the larger anode, where the light can reach the anode through the transparent acrylic plate holding the cathode. This design easily permits the cathode to obtain oxygen from air. Furthermore, the design allows any excess dissolved oxygen produced from photosynthesis of the algal biofilm to float and reach the lower surface of the cathode [34] providing then an extra source of oxygen for the cathode from the anode side. Very few studies, such as the one by McCormick et al. have the cathode on top [10]. In all cases, all former work required a closed chamber whereas this design is entirely chamber-less, being assembled together using the transparent acrylic structure, which makes it easy for biofilm maintenance and qualifies it for large-scale operations. The effect of several varying parameters on the generated electrical output was studies, namely height of the cell, anode-cathode spacing and salinity. The maximum intensity recorded was 9mA/m2 which was equivalent to a voltage of 13.5 V/m2 and a power of 121 mW/m2. Interestingly, it was observed that the elevation of the cell in the water level had the most pronounced effect on current intensity. In addition, the height of the cell positively correlated with current level.

This was a fortunate finding, as production-level designs are likely be deployed in deeper reservoirs or ponds and thus require greater elevation. Spacing was also found to have a modest effect on current output, with the optimal spacing being 2 cm. This is likely to change with design dimensions, however. Increasing salinity was also associated with higher electrical output, but only up to a salinity of 20000 TDS.At 40000 TDS, the initial increase in electric output was followed later by a marked reduction in output, probably due to arrest of the biological processes secondary to the extreme salt gradient between the intracellular and extracellular compartments.

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This agrees with a study by Church et al. that showed that Chlorella Vulgaris can survive in waters containing a NaCl concentration of up to 45g/L, however the growth rates decreased with increasing salinity[35].

Reduced algal growth at higher salinities reflects poor cellular functioning which will affect other biological processes as well, including photosynthesis and energy production. In spite of this, the salts increase the production of energy through enhancing proton transfer and decreasing internal resistance [14]. In addition, salts reduce the solubility of oxygen in water[36] which, in case of this design, would make oxygen float to the cathode leaving less dissolved oxygen to compete as an electron acceptorwith the anode. It is therefore important to identify the optimum salinity at which the used organism functions best as an electrician.

V. CONCLUSION

Unrestricted power generation may be accomplished using the photosynthetic microorganisms found in nature such as algae. Algae mass production showed to be feasible and practical for many uses including electricity production through BPVs. The goal of this study was to qualify the BPV cell to the large-scale usage.

A novel chamber-less BPV with simple and cheap materials was designed in this study which cans produce9mA/m2of electric current with 13.5 V/m2. The cost, simplicity and accessibility of this BPV cell entitle it for large scale practice.

Moreover, increasing the height and the salinity proved to have positive impacts on power output which makes this design an attractive choice for brackish and seawater use in power generation.

The electricity production by this methodology could be applied for water and wastewater plants depends on algae activity in its treatment.

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