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Development of Vernonia Amygdalina Photosynthetic Membraneless Electrochemical Cell

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Abstract: *Experimental analyses of Vernonia amygdalina pigment from plant collected in Ilorin, Nigeria, have been carried out using spectrophotometer, 1H nuclear magnetic resonance (400Hz) and X-ray diffractometer. Biological membraneless electrochemical cells were fabricated using ground hydrated chlorophyll containing tissues.*

The cells were assembled by compaction of hydrated pigment housed in an air-tight 6.5 cm^3 cylindrical container, with similar electrodes of copper material. Experimental results showed that the visible part of the electromagnetic spectrum is strongly absorbed at 412 nm and 662 nm by Vernonia amygdalina. The qualitative analysis of the powdered sample of the material showed that the constituents of the sample include Magnesium Carbide (Mg_2C_3), Nitrogen (N_2) and Biuret Hydrate ($C_2H_5N_3O_2H_2O$). In addition to this, chlorophyll a (chl a) and triglyceride were also shown to be major constituents of the pigment. The particle size of the pigment was deduced using X-ray diffractometer to be 2.6 nm, and as such, the processed Vernonia amygdalina pigment is therefore a nano-material for energy conversion by photosynthetic processes.

The copper-copper electrodes photosynthetic cells generated current of about 4 μA and open circuit voltage of about 5 mV. The current generated by copper-zinc electrodes Photosynthetic Electrochemical Cell (PEC) ranged between 0.2 mA and 1.5 mA, while the open circuit voltage ranged between 0.4 V and 0.9 V. The simple preparation technique adopted, using widely available and low cost natural material showed that a biological photosynthetic electrochemical cell is feasible and promising.

Keywords: Photosynthetic electrochemical cell, Vernonia amygdalina, Chlorophyll, Oxidative degradation

1. INTRODUCTION

Dye Sensitized Solar Cell (DSSC) mimics photosynthesis [1], an attribute which distinguishes it from other PV devices. It was of interest to investigate the properties of photosynthetic material (*Vernonia amygdalina*) and its application in energy generation. A large scale photosynthetic electrochemical cell production using photosynthetic material will serve as a renewable source of energy. This is believed to be environmentally friendly and cheap.

Photosynthetic electrochemical cells are distinct from, but related to, bio-fuel cells that use biocatalysts ranging from microorganism to enzymes, to catabolise bio-substrates such as glucose into electricity. The Photosynthetic electrochemical cell generates electrical power, in essence, by harnessing electrons from the photosystems in plants (isolated or intact) during the process of photosynthesis [2]. With this concept micro-electromechanical system (MEMS) photosynthetic electrochemical cell (PSEC) have also been developed. The PSEC has potential application as a power source for microscale and micromechanical system mobile devices, such as remote distributed sensors and autonomous robots [3]. PSECs have been demonstrated previously using live culture of blue-green algae (cynobacterium *Anabaena variabilis*), and subcellular organelles known as thylakoids. Both of which are able to generate about 0.5 volts open circuit voltage, results comparable to many biological electrochemical cells. Electrical output from cynobacterium *Anabaena variabilis* with the use of redox mediator

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Hydroquinone (HNQ) has been measured in both light and dark conditions, implying that PSEC generates electricity from both photosynthesis and catabolism of endogenous carbohydrates in the light and from catabolism alone in the dark respectively.

Photosynthetic organism such as plants and certain bacteria capture solar energy from the sun to power the splitting of water (H_2O), releasing electrons that reduce CO_2 to produce carbohydrate (CH_2O). Sunlight is the only form of energy which adds to the total energy supply of the earth and drives not only the weather and geochemical events, but also the biological cycles [4]. The energy of visible light is sufficient to cause changes in the energy states of the valency electrons of many molecules and can be used by living organisms to effect the transition from a low to a high energy state.

The initial light catalytic photosynthetic reaction is as given below:

$$2H_2O + Light + chlorophyll \rightarrow O_2 + 4H^+ + 4e^- \text{ (Anodic)} \quad (1)$$

Water (H_2O) is oxidized [4] releasing electron which are siphoned by the anode electrode. The electron coming in through the cathode electrode combine with the proton to form water as later shown in equation (4). Photosynthesis efficiently converts solar to electrical energy, which then drives a series of chemical reactions [5]. ATP (Adenosine triphosphate) from photo-phosphorylation and NADPH (Nicotinamide adenine dinucleotide phosphate) from photoreduction are synthesized when photons are captured in the antenna complexes of photosystem I and II by chlorophyll. When chlorophyll '*a*' molecule at a photosystem's reaction centre absorbs energy, an electron is excited and transferred to an electron-acceptor ($NADP^+$) molecule through a process called photo-induced charge transfer. These electrons are shuffled through an electron transport chain that initially functions to generate chemiosmotic potential across the membrane so called Z - scheme.

Light energy is converted to chemical energy in form of ATP and NADPH. Both are then utilized as an energy source for the light-independent reactions. Given a supply of these compounds the chemical reactions of photosynthesis may proceed without light and thus called dark reactions [4]. The reactions that generate the ATP and NADPH used in carbon fixation are directly dependent on light energy, thus called the light reactions of photosynthesis. The enzymatic catalytic dark reactions of photosynthesis are indirectly dependent on light energy. The reaction utilizes the supplies of ATP ($C_{10}H_{16}N_5O_{13}P_3$) and NADPH ($C_{21}H_{29}N_7O_{17}P_3$) generated for the conversion of carbon dioxide and water into carbohydrates (namely glyceraldehydes -3- phosphate (G3P)) as shown below in equation (2). The carbohydrate products in the dark reaction of the photosynthesis system can also be oxidized, pathways which are duplicated in anodes of bio-electrochemical fuel cells [6].

$$\begin{aligned} &3CO_2 + 6NADPH + 6H^+ + 9ATP + 5H_2O \\ &\rightarrow [C_2H_3O_2 - CH_2OPO_3^{2-} + 2H^+] + 6NADP^+ \\ &\quad + 9ADP + 8[HOPO_3^{2-} + 2H^+] \end{aligned} \quad (2)$$

$[C_2H_3O_2 - CH_2OPO_3^{2-} + 2H^+]$ and $[HOPO_3^{2-} + 2H^+]$ are glyceraldehydes - 3 - phosphate (G3P)and inorganic phosphate (Pi) respectively.

The various biochemical reactions involved in photosynthesis have been grouped into two stages. First, the light-driven linear flow of electrons and hydrogen through membrane-bound multi-protein complexes leads to the reduction of the ferredoxin/thioredoxin system and in addition to the production of the highly energized metabolites ATP and NADPH. In turn these products are necessary for the second step, that is, the energy-consuming reductive conversion of carbon dioxide into carbohydrates, which are used for starch synthesis in the light. These latter reactions follow a cyclic sequence, referred to as the Calvin cycle. This activity depends on complex dissociation, controlled by the ratio of NADPH to NADP, which is directly linked to the light-driven electron flux in the thylakoid membranes [7]. Thus by reduction and oxidation reaction a natural chemical fuel is produced with stored energy from which electrical power can be generated. The electron produced flows in the system and are captured by the anode electrode due to their affinity for the electron and transfers them out of the cell. The electron coming in through the cathode electrode also combine with the proton to form water as shown in equation (4).

During enzymatic reduction of carbon dioxide to carbohydrate, the biological electron carrier (NADPH) is oxidized and becomes $NADP^+$. The resulting carbohydrate product is oxidized as shown below in equation (3):

Oxidative Pentose Phosphate Pathway:

$$\begin{aligned} &6Glucose - 6 - Phosphate + 12NADP^+ + 6H_2O \rightarrow \\ &6Ribulose - 5Phosphate + 6CO_2 + 12NADPH + 12H^+ \end{aligned} \quad (3)$$

(Anodic)

A representation showing energy transfer in the processes. During photosynthesis, electrons are shuttled in the diffusional electron carriers NADPH, or along a series of thylakoid-membrane-bound enzyme complexes of the electron transport chain. These electrons (and protons) are siphoned from their normal photosynthetic duties either from NADPH or the transport chain by redox electron mediator molecules that have diffused into the bacterial cells. The reduced (electron and proton carrying) mediators make their way back by diffusion out of the material and eventually donate the electrons to the anode [8]. Current is also derived from electrons generated from oxidative degradation of carbohydrate stored in the photosynthetic material as a result of dark reaction [9]. The cathodic reaction equation (4) is as indicated below:

$$4H^+ + O_2 + 4e^- \rightarrow 2H_2O \quad \text{(Cathodic)} \quad (4)$$

Previous studies suggested that a photosynthetic electrochemical cell functions like a microbial fuel cell in the dark. Catabolic metabolism persists in the photosynthetic electrochemical cell in the dark, consuming complex nutrient molecules such as glucose already produced internally when light was present. In the dark, the photosynthetic electrochemical cell yielded as much as 500 mV open circuit voltage, an output level that was actually sustained over an hour period. Based on these studies, it seems that the duration of the electrical output generated in the dark was longer than that generated in the light [8]. It is hypothesized that the insertion of micro/nano electrodes proximal to the electron transport chain housed in the photosynthetic membranes would help reveal fundamental mechanism associated with electrochemical reactions inside the cell [10].

In this research, optical, qualitative and structural property of the chlorophyll pigment were investigated. In addition *Vernonia amygdalina* photosynthetic membraneless electrochemical cell (PSEC) without a mediator were developed using a cost effective, environ-

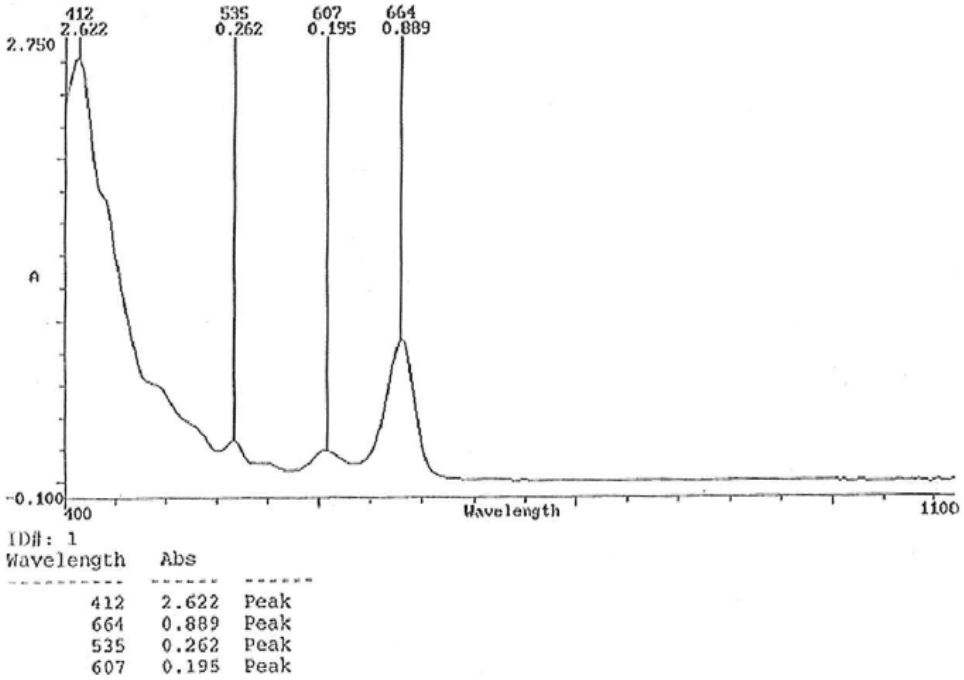

Figure 1. The visible light ray absorption spectrum for *Vernonia amygdalina.*

mentally friendly and a widely available raw material.

2. EXPERIMENTALS

2.1. Chlorophyll Containing Tissues

Processed photon capturing chlorophyll containing tissue from *Vernonia amygdalina*, have been used in developing membraneless electrochemical cell without a mediator. Chlorophyll – name derived from ancient Greek meaning, chloros: green and phylon: leaf – is a green pigment found in most plants, algae and cyanobacteria. Leaves may contain up to *1g* chlorophyll per square metre of surface area but this varies with species, nutrition and age. Chlorophyll molecules are specifically arranged in and around pigment protein complexes called photosystems, which are embedded in the thylakoid membranes of chloroplasts. In these complexes, chlorophyll serves two primary functions. The first is to absorb light (*i.e.* involves the vast majority of chlorophyll (up to several hundred molecule per photosystem) and secondly to transfer the absorbed light energy by resonance energy transfer to a specific chlorophyll pair in the reaction center of the photosystem. In higher plants, there are two forms of chlorophyll; chlorophyll *a* (*chl a*), a special type which form reaction centres, and chlorophyll *b* (*chl b*), an auxiliary pigment passing excitation to *chl a*.

The chlorophyll containing tissues used in this research is from the leave of *Vernonia amygdalina* (Bitter leaf).

2.2. Electrodes

The electrodes with sufficient electron affinity (copper plates) were chosen to capture electrons generated during photosynthesis. It is hypothesized that insertion of micro/nano electrode proximal to the electron transport chain housed in the photosynthetic membranes would help reveal fundamental mechanisms associated with the electrochemical reaction inside the cell [10]. Copper – Copper same electrodes were therefore used.

The pigment and the electrodes were assembled by compaction in tight contact inside a white plastic 6.5 cm^3 container. It is sealed up in order to prevent loss of water molecule by evaporation which is needed for the oxidative degradation (fermentation) of carbohydrate [11] and [12].

2.3. The Pigment

The green leaves were plucked from the *Vernonia amygdalina* plant, cut into smaller parts and then ground immediately to give naturally hydrated green pigment material. This green paste is the photosynthetic electrochemical system used for the development of the biological cell.

2.4. Absorption Spectra

The absorption spectra were recorded using UV – visible spectrophotometer for wavelength between 400 and 900 nm (visible part of the electromagnetic wave). The principle of operation is such that light from a monochromator is incident on a film of the specimen. The light transmitted through the specimen is received and detected by a photocell whose output is compared with an equivalent signal developed by the incident beam and then fed to a recorder. The wavelength is slowly varied and the fluctuation in absorption is simultaneously recorded.

2.5. Qualitative Analysis

The qualitative analysis of *Vernonia amygdalina* was carried out using a mini X-ray diffractometer. To do this, the ground air dried (at room temperature 30^0C) chlorophyll containing tissue, was placed on a rotating X-ray diffractometer holder and X-ray beam incident to it. Constructive interference results were detected (in form of a diffraction pattern), as well as the sample intensities at various rotation angles were recorded. The resulting phase diagrams were then compared with the data already stored on an XRD database, and the constituents of the sample were subsequently identified through matching.

A 400 Hz proton-Nuclear Magnetic Resonance (NMR) was also used to examine the pigment. The resonance is a phenomenon which occurs when the nuclei of certain atoms are immersed in a static magnetic field and exposed to a second oscillating magnetic field. The proton possess a property called spin, which will cause the nucleus to produce an NMR signal. NMR spectroscopy is the use of NMR phenomenon to study physical, chemical and biological properties of matter.

2.6. Assembling of the Cell

The ground chlorophyll containing material was used as the base in the container; the copper plate put on it and covered up with the

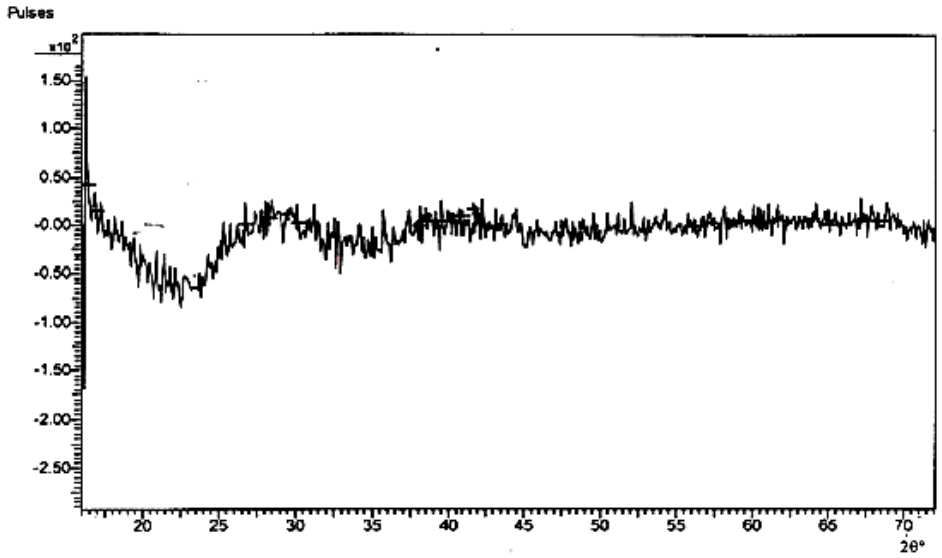

Figure 2. XRD spectrum of *Vernonia amygdalina* showing the diffraction at 2θ values.

green pigment material. Copper plate was put on top of the pigment and covered up again with the green pigment. The plastic container was filled up and closed air tight, leaving the probes linking the electrodes out as positive and negative terminal of the electrochemical cell. This is similar to organic photovoltaic (PV) devices which comprises donor and acceptor semi-conducting regions sandwiched between conducting electrodes. In PV cells, separated free electrons and holes diffuse out towards the metal electrodes, completing the energy transduction process [5].

2.7. Electrical measurements

Open circuit voltage (volts (or V)) and current (mA) for *Vernonia amygdalina* electrochemical cells made using copper plates as both the positive electrode and negative electrode, were measured using a sensitive multimeter. The same measurement was done repeatedly for Vernonia amygdalina electrochemical cells with copper and zinc plates as positive and negative electrodes respectively.

3. RESULTS AND DISCUSSION

3.1. Absorption spectral analysis for Vernonia amygdalina

It is known that the visible part of electromagnetic radiation from the sun is absorbed by plants to cause transition from low energy to a high energy state of many molecules [13] and [4]. In order to investigate the variation of absorption with respect to the wavelength for *Vernonia amygdalina,* the green sample extracted by pressure from hydrated ground chlorophyll containing tissues was examined using a UV visible spectrophotometer.

Figure1 shows the variation in absorbance for wavelength 400 nm to 750 nm. It is observed that the visible part of the electromagnetic spectrum is absorbed by *Vernonia amygdalina* strongly at wavelengths 412nm and 664nm, which corresponds to the blue and red region of the electromagnetic wave. There is a remarkable reflection between 480 and 600 nm which is the green region of the visible radiation. And as a result of these absorbencies, the light it reflects and transmits appears green. The high absorbencies of the visible blue and red light and reflection of visible green light as recorded by [4] were also confirmed in this study. This shows that the pigment is a good solar absorbing material in the visible region of electromagnetic spectrum.

3.2. Chemical analysis of Vernonia amygdalina

X-ray diffractometer analysis showed that Nitrogen (N_2), Magnesium carbide (Mg_2C_3) and biuret hydrate ($C_2H_5N_3O_2H_2O$) are present in the photosynthetic material. Figure 2 illustrates the generated XRD diffraction pattern of *Vernonia amygdalina.* The particle size is obtained from the full width at half maximum (FWHMs) of the diffraction peaks in Table 1. The FWHMs (β) can be expressed as a linear combination of the contributions from the strain (ε) and particle size (L) through the following relation:

$$(\beta \cos \theta) / \lambda = 1/L + (\varepsilon \sin \theta) / \lambda \quad (5)$$

Figure 3 is the plot of βcosθ/λ versus sinθ/λ. The reciprocal of intercept on the βcosθ/λ axis gives the average particle size as approximately 2.6 nm. Hence *Vernonia amygdalina* pigment being

Table 1. Diffraction angles, Intensities and the Full Width at Half Maximum (FWHMs) of the diffraction peaks

2θ°	d	Iint	Imax	Irei	Icorr	FWHM
16.45	5.38700	331	42.3	12.5	17.3	0.10488
16.92	5.23922	783	15.8	29.5	40.0	0.66405
26.78	3.32836	279	15.3	10.5	10.7	0.25254
28.32	3.15165	2651	22.1	100.0	100.0	1.6664
29.51	3.02681	378	13.4	14.3	14.0	0.39154
30.14	2.96483	90	5.8	3.4	3.3	0.21494
37.99	2.36840	0	0.8	0.0	0.0	0.0072001
38.51	2.33741	180	4.3	6.8	6.2	0.56896
39.69	2.27071	209	4.6	7.9	7.1	0.61639
40.99	2.20192	700	9.7	26.4	23.7	0.98697
41.66	2.16792	105	17.4	4.0	3.5	0.081847
43.47	2.08164	274	9.2	10.3	9.1	0.40017
56.25	1.63527	32	1.9	1.2	1.0	0.2263
57.47	1.60358	85	3.3	3.2	2.7	0.33982
59.33	1.55765	62	3.1	2.3	2.0	0.26694
60.25	1.53592	46	2.5	1.7	1.5	0.25025
60.75	1.52463	18	3.5	0.7	0.6	0.069671

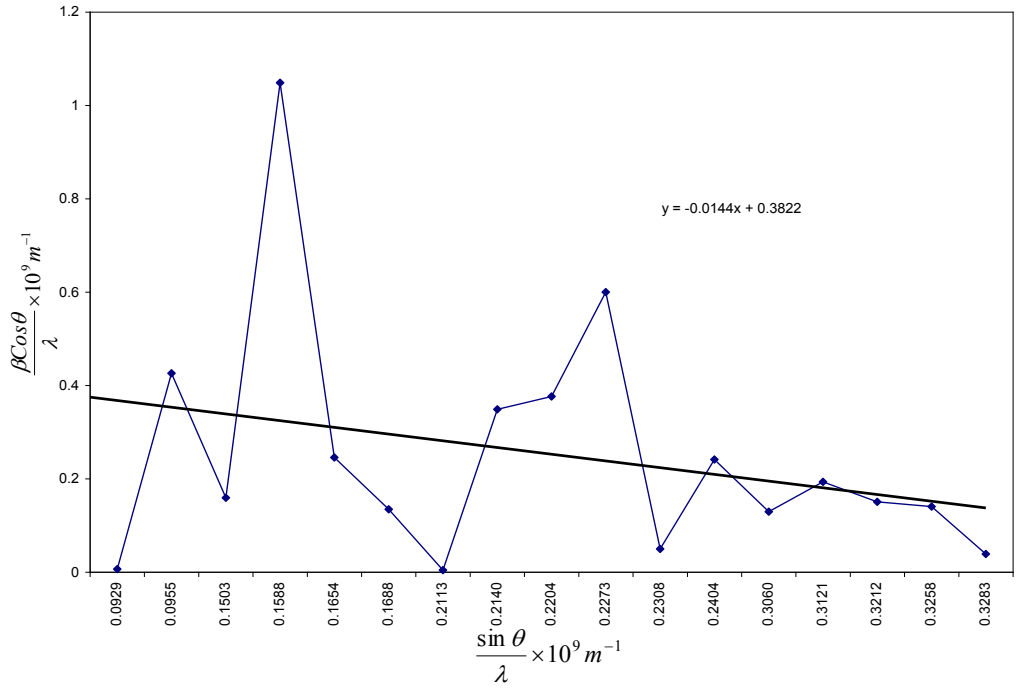

Figure 3. Plot between (βcosθ)/λ versus (sinθ)/λ for *Vernonia amygdalina*.

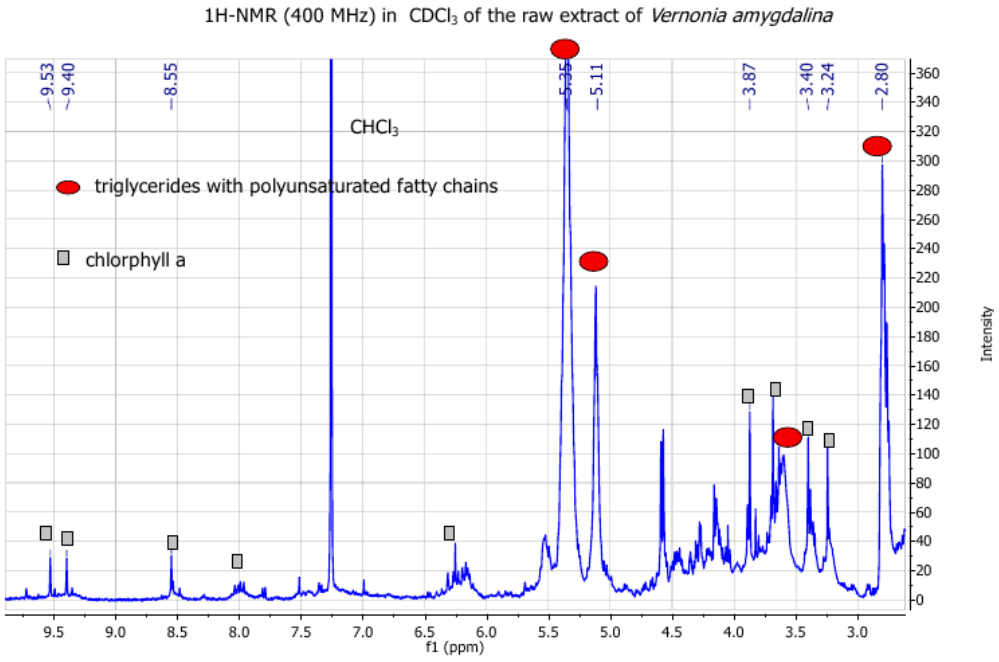

Figure 4. A proton NMR spectrum of raw extract of *Vernonia amygdalina*

used is a nano material for solar energy conversion to electricity.

3.3. Proton-Nuclear magnetic resonance (NMR) signal

Further qualitative analysis was carried out using 1H-NMR (400Hz), for extracts of *Vernonia amygdalina* in chloroform. The results showed the constituents of the hydrated ground pigment to be *chl a (chlorophyll a)* and triglycerides with polyunsaturated fatty chains as illustrated in Figure 4. Each group of signals actually corresponds to protons in a different part of the molecule. The presence of chlorophyll confirms the dark reaction photosynthetic process to take place in the isolated system. This photosynthetic process results in the formation of carbohydrates, needed as fuel for oxidative fermentational flow of energy.

The triglycerides also revealed as part of the pigment have been reported to be a major component of biodiesel (a new biological fuel derived from photosynthetic materials) from which clean energy can be obtained and its production helping to combat the increasing concentration of carbon dioxide in the atmosphere [14].

3.4. Electrical Measurements

An electrochemical cell works by different electrodes in an electrolyte. This research is focussed on revealing the electron transport chain energy, generated by partly light catalytic photosynthesis and mainly enzymatic dark–reaction photosynthesis, initiated by solar energy. The energy generated for same electrode cells (Fig. 5 and 6) is therefore exclusive of the contribution of difference in the electrodes used.

However, when different electrodes were used, the effect of the difference in the electrodes resulted into a higher open circuit voltage and short circuit current (Fig. 7 and 8), than only biologically generated energy from reduction of carbon dioxide and oxidative degradation of the carbohydrate obtained during the dark reaction

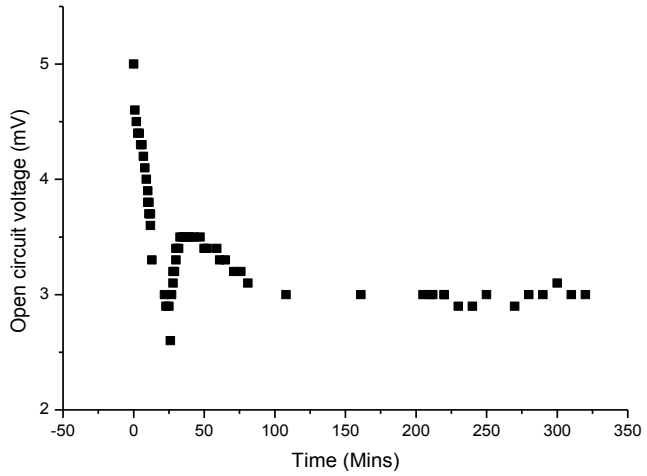

Figure 5. Open circuit voltage vs. Time for Cu-Cu electrodes *Vernonia amygdalina* cell.

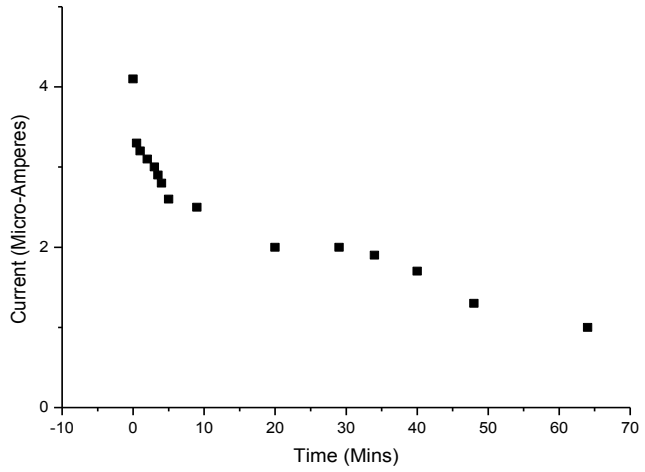

Figure 6. Current vs. Time for Cu-Cu electrodes single *Vernonia amygdalina* cell.

processes in addition to light catalytic photosynthetic generated energy.

3.4.1. Open Circuit Voltage with Time of Vernonia amygdalina Copper–Copper Electrodes Single Cell

The maximum open circuit voltage of 5.0 mV was obtained at the beginning of the measurement (see Fig. 5.) indicates the accumulation of charges on the cu-cu electrodes. This value decreases to 2.6 mV (a decline thought to be due to the consumption of charges on the electrodes; seen at 26 mins), before increasing again very slowly to 3.5 mV (at 40 mins). This slow increase in open circuit voltage is understood to be the biological charge generation period (which is observed to be a slow process). Following this, the attained values fluctuate between 3.0 to 3.5 mV. It is assumed that this fluctuation is dependent on the reaction rates.

3.4.2. Current Generated with Time of Vernonia amygdalina Copper–Copper Electrodes Single Cell

The same electrodes (Cu-Cu electrodes) cell was developed in order to show that the cell system is not just an electrochemical reaction resulting from use of different electrodes with different energy levels. The focus of the study was mainly to assess the biological processes of charge generation and transfer. The electrodes were merely used as a means of electron collection and transfer.

It can be seen from Figure 6 that *Vernonia amygdalina* photosynthetic electrochemical cell with Cu-Cu electrodes is able to generate a current of approximately 4 μA. The current diminishes exponentially with time as the cell is being short-circuited for measurement. This suggests that the rate of generation of energy is a slow process.

3.4.3. Open Circuit Voltage with Time of Vernonia amygdalina Copper-Zinc Electrodes Single Cell

It can be seen from Figure 7 that the OCV values ranged between 0.4 V and 1.0 V, where the average value is found to be 0.8 V. It is observed that the open circuit voltage for each single cell increases within the first 50 h, after which the cells maintains a range of values, although exhibiting instability. The instability observed in the values of the open circuit voltage for each sample might be due to distortion in pigment-electrodes contact and the unstable hydrated nature of the pigment in contact with the electrodes.

3.4.4. Current generated with Time of Vernonia amygdalina Copper-Zinc Electrodes Single Cell

A range of current values between 0.45 and 0.8 mA for all the cell samples for the first 75 h (3 days) was recorded. In Figure 8, the current between 0 to 75 h of the cell is considered to be the current obtained from light catalytic photosynthetic energy transfer, the current generated by the dark reaction photosynthetic process and charges generated from oxidative degradation of carbohydrate formed.

After 75 h of cell production, a general decrease in the current generated is observed up until 180 h. This reduction may be a consequence of changes in biological processes believed to be taking place in the photosynthetic cell system. Additionally, it's quite possible that only dark reaction photosynthetic process as well as gradual charge formation (by oxidative fermentation of carbohydrate) may be taking place during this time frame. The current increases again from 180 h (after cell production) reaching a maximum at 230 h. This increase may perhaps be due to increasing oxidative degradation (or fermentation) of the carbohydrates formed. Following this, an exponential decrease in current with time is observed which could be a result of biologically degradation of the material. In addition, the fluctuation and instability in the current values may well be due to the fact that, the hydrated pigment was not held in tight stable contact with the electrodes; or as a result of distortion from pigment-electrodes contact.

4. CONCLUSION

The concept of generation of current, based on the use of organic and hybrid nano-structured materials is taking the attention of researchers recently. Experimental investigations are on the way to develop environmental friendly low cost materials for the manufacturing of organic solar and bio-electrochemical cells.

Photosynthetic chlorophyll-containing tissues in *Vernonia amygdalina* (Bitter leaf) were processed into a hydrated green pigment

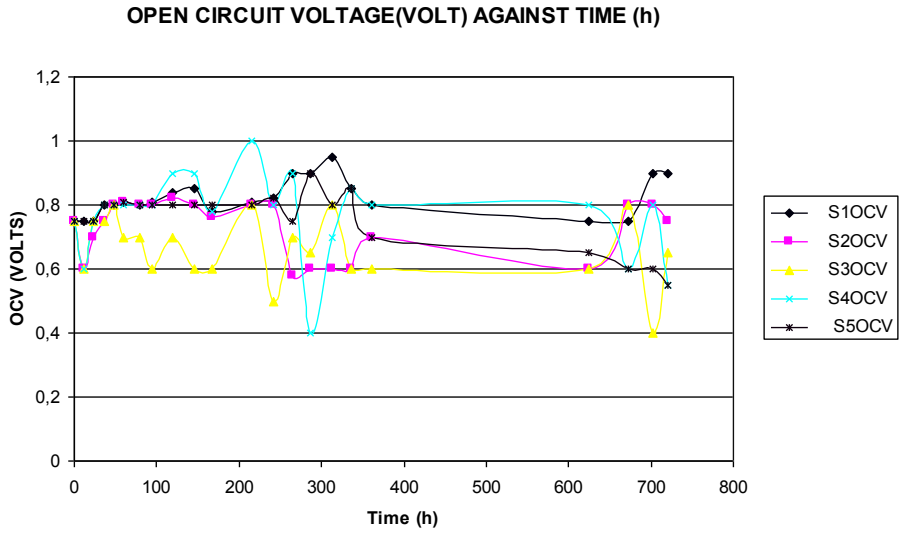

Figure 7. Open circuit voltage vs. Time for Cu-Zn electrode single *Vernonia amygdalina* cells.

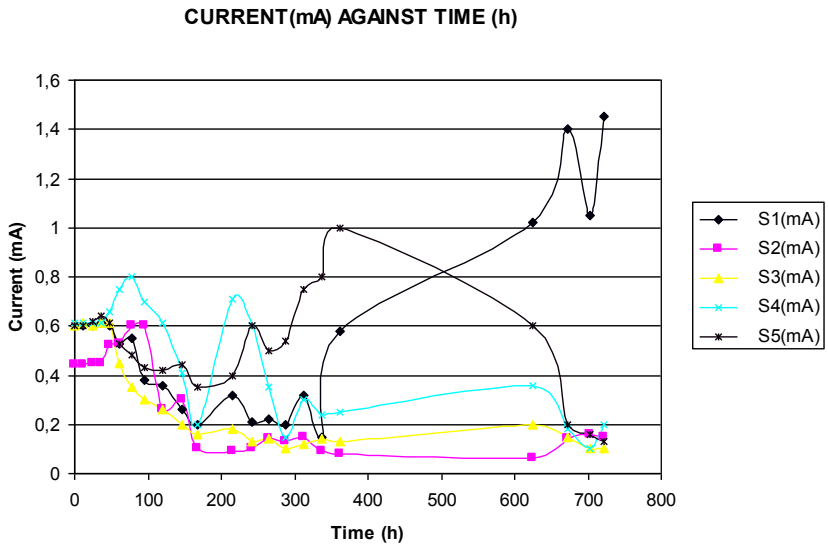

Figure 8. Current generated vs. Time for Cu-Zn electrodes *Vernonia amygdalina* single cells.

material. Optical qualitative and structural analyses of the material were carried out using spectrophotometer, mini-X-ray diffractometer and proton nuclear magnetic resonance (400 Hz). The processed material was then used in the fabrication of *Vernonia amygdalina* photosynthetic memebraneless electrochemical cells. Electrical measurements were taken to know the open circuit voltage and the current generated.

The visible part of electromagnetic spectrum was absorbed by *Vernonia amygdalina* strongly at wavelengths 412 and 664 nm corresponding to the blue and red region the electromagnetic spectrum. A very low absorbance in the green region between 480 nm to 600 nm was detected, an indication that the colour green is being seen.

Qualitative analysis of the air dried ground pigment, showed its constituents to be magnesium carbide (Mg_2C_3), nitrogen (N_2) and biuret hydrate ($C_2H_5N_3O_2H_2O$);. In addition to this, chlorophyll a (*chl a*) and triglyceride were also shown to be major constituents of the pigment. These results underscore the likelihood of ongoing photosynthetic process in the isolated processed *Vernonia amygdalina* tissues; as well as put forward the idea of obtaining biodiesel (whose basic composition is from triglyceride) from the material.

The particle size of the material was deduced using X-ray diffractometer data such as full width at half maximum (FWHMs) of the diffraction peaks and diffraction angles. This was found to be 2.6 nm. And as such, processed *Vernonia amygdalina* pigment used in this study is therefore, a nanomaterial for solar energy conversion by photosynthetic processes.

The chemical structure reviewed showed that the material is a conjugated system with alternating single and double bonds. Single bonds are referred to as σ-bonds and double bonds contain σ- and p-bond. The electrons that constitute the π-bonds are delocalized over the entire molecule.

The essential property which comes out from conjugation is that the π- electrons are much more mobile than the σ electrons. They can jump from site to site between carbon atoms with a low potential energy barrier as compared to the ionization potential. The π-electron system has all the essential electronic features of organic materials: light absorption and emission, charge generation and transport [15]. These properties indicate that the bonding system contributes to the electron transfer in the material.

Photosynthetic Electrochemical cells were fabricated using *Vernonia amygdalina* pigment from plant. The current generated from copper-copper electrodes photosynthetic cells was about 4 μA and open circuit voltage of about 5 mV. The current generated by copper-zinc electrodes Photosynthetic Electrochemical Cell (PEC) ranged between 0.1 mA and 1.5 mA, while the open circuit voltage ranged between 0.4 V and 0.9 V.

The reality of energy generation by photosynthetic process and degradation of photosynthetic product is clearly shown by the copper-copper electrode cell with same potential level.

The innovative technique employed in the cell production, using widely available environmentally friendly and low cost natural material point up the possibility of a biologically derived photosyn-

thetic electrochemical devices for future use. To this end, the investigation has been useful in revealing the photosynthetic architecture being mimicked in dye sensitized solar cells (DSSC), as well as the stages of energy availability in the photosynthetic process.

5. ACKNOWLEDGEMENT

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