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RESEARCH ARTICLE

ESTIMATED PHOTOSYNTHETIC ACTIVITY FROM ITS PASSIVE ELECTRICAL PROPERTIES

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ABSTRACT

Methods such as chlorophyll fluorescence, the amount of O_2 emitted or the amount of CO_2 assimilated are commonly used to estimate the photosynthetic activity of plants, but none of these methods shows us directly the electrical activity that occurs during photosynthesis. The purpose of this study is to show that the photosynthetic activity can be obtained from the behavior of the electrical resistance of extra chlorophyll space. The model used in this study is that of Cole. It appears from our analysis that there is a distinct relationship between the behavior of the extra chlorophyll space resistance and the amount of O_2 emitted or the amount of CO_2 assimilated according to the intensity of the light; while the amount of O_2 emitted or the amount of CO_2 assimilated increases according to the intensity of the light up to a certain threshold, the extra chlorophyll space resistance decreases according to the intensity of white, blue, yellow and red light until it reaches a certain threshold. However, the green light is found to be inactive.

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INTRODUCTION

According to Dr. Mae-Wan Ho, solar energy is by far the most abundant renewable energy resource with zero carbon emissions, and artificial photosynthesis could be the most effective energy storage method and energy availability. Indeed, a method of storing solar energy which has already been invented by nature is photosynthesis, which uses sunlight to split or separate the water, releasing oxygen, on the one hand, and hydrogen which fixes carbon dioxide in the carbohydrates thus creating a biomass. One approach of storing solar energy is artificial photosynthesis, which attempts to replicate and enhance the natural process, to obtain hydrogen fuel used in fuel cells and this is done through the photo-electrochemical separation of water into hydrogen and oxygen (reverse of a fuel cell where the hydrogen and oxygen recombine to form water, releasing the energy which is stored in hydrogen). However, the reproduction and improvement of natural processes such as photosynthesis require a great deal of research. However, the methods generally used to study photosynthesis are:

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The study of biomass (Aleya and et Devaux, 1985) and the measurement of the fluorescence of chlorophyll (Cole and Curtis, 1950), (Loustau *et al*., 1999). All these methods seem limited when we look at the electrical activity that occurs in a chlorophyll solution. Several scientists nowadays use electrical, electric and electronic properties like dielectric behaviors, ac electrical conductivity, to characterize or to differentiate inorganic matter (Kumi *et al*., 2014; Melagiriyappa *et al*., 2014; Tamer *et al*., 2014; Monika *et al*., 2001; Université Mohammed V-Agdal, 2006). The purpose of this study is to show, from the model of Cole (Aleya and et Devaux, 1989) that the variation of extra chlorophyll space resistance in terms of light intensity, helps us understand the photosynthetic activity as well as the assimilation of CO2 or O2 that is released.

MATERIALS AND METHODS

These experiments were conducted at the Laboratory of Biophysics of the University of Yaoundé I and were replicated seven times under the same conditions at a temperature of (20◦C ± 2◦C).

Sampling and preparation

Our chlorophyll solution was obtained from 20g of carica papaya leaves; properly ground in a mortar with 50 ml of acetone solution (Hong-Wen *et al*., 2010) and then filtered through a filter paper and funnel. 30ml solution of crude chlorophyll was obtained and introduced into an 8.5 cm diameter dish.

Cole's model was used for the variation of the extra chlorophyll space resistance according to the intensity of the light. In fact the solution of crude chlorophyll was assumed to being particles of crude chlorophyll in the acetone. Two spaces were considered: the first one is called extra chlorophyll space and the second, an intra-chlorophyll space (see Fig.1). The model is made up of two-branch parallel circuit where R represents the extra chlorophyll space resistance, R' is intra chlorophyll space resistance, and C the chlorophyll capacitance (Fig.2). The impedance of this circuit is expressed as follows:

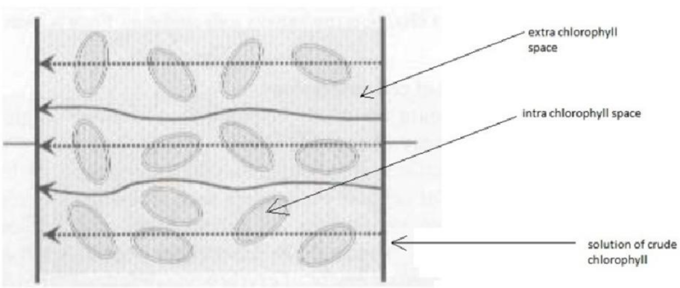

Figure 1. Low and high frequency current paths in solution of crude chlorophyll. The dashed line represents current path of high frequency, the solid line represents current path of low frequency

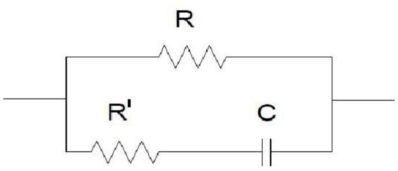

Figure 2. Electrical model of crude chlorophyll solution. R is the extra chlorophyll space resistance, R' is the intra chlorophyll space resistance, C is the capacitance of the pigments, U is the potential difference on the terminals of the circuit

$$Z = \frac{R + R'R(R+R')(C\omega)^2 - jCR^2\omega}{1+[C\omega(R+R')]^2} \qquad \ldots\ldots\ldots\ldots(1)$$

Where $j = \sqrt{-1}$, $\omega = 2\pi f$

At zero frequency, i.e. $\omega = 0$;

$$Z = R \qquad \ldots\ldots\ldots(2)$$

At infinite frequency, i.e. $\omega = \infty$;

$$Z = \frac{RR'}{R+R'} \qquad \ldots\ldots\ldots(3)$$

Where $j = \sqrt{-1}$, $\omega = 2\pi f$

Let us consider the function of distribution of electrical energy Ψ (Eλ) defined by:

$$\frac{nhc\Phi PSII}{\lambda} \quad \text{for } \lambda \in I \qquad \ldots\ldots(4)$$

and

$$0 \quad \text{for } \lambda \in J \qquad \ldots..(5)$$

where I is the unit of active photosynthetic wavelengths, J the unit of non-active photosynthetic wavelengths, n the number of incidental photon, c the velocity of light, h the Planck constant and ΦPSII the quantum yield. By definition, quantum yield is the ratio between the number of emitted O2 molecules and the number of absorbed photons. Owing to the fact that, the number of emitted O2 molecules increases linearly with the quantity of electrons which are released according to the following equation:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

The quantum yield can be expressed by:

$$\phi_{PSII} = \frac{|q|U}{nh\upsilon} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Where nhυ is the energy brought by active photosynthetic light, and |q|U the corresponding electrical energy. υ is the frequency of active photosynthetic light; U the potential difference on the terminals of the circuit of Figure 2. The equation (7) gives:

$$U = \frac{nhc\phi_{PSII}}{\lambda|q|} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

by using the mesh constituted by the tension U, the extra chlorophyll space resistance R, and the mesh constituted by the tension U, the intra chlorophyll space resistance R' and the chlorophyll capacitance C, we have the following linear differential equations:

$$R\frac{dq_e}{dt} = U \qquad \ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$R'\frac{dq_i}{dt} + \frac{q_i}{C} = U \qquad \ldots\ldots\ldots\ldots..(10)$$

The solutions of these two linear differential equations are respectively expressed by:

$$q_e = \frac{U}{R}t \qquad \ldots\ldots\ldots\ldots..(11)$$

$$q_i = q_o(1 - exp - \frac{t}{\tau}) \qquad \ldots\ldots\ldots\ldots..(12)$$

where qi, qe are respectively the quantity of electricity in intra and extra chlorophyll space;

$$q_0 = \frac{nh\upsilon\phi_{PSII}}{|q|} \qquad \ldots\ldots\ldots\ldots(13)$$

$$\tau = CR' \quad \ldots\ldots\ldots\ldots\ldots (14)$$

In the presence of non-active photosynthetic light, or in darkness, the function of distribution of electrical energy Ψ (Eλ) = 0 i.e. U = 0

By using the mesh constituted by the tension U, the extra chlorophyll space resistance R, the Intra- chlorophyll space resistance R' and the chlorophyll capacitance C, we have the following linear differential equation:

$$\frac{dq}{dt} + \frac{q}{R_T\,C} = 0 \quad \ldots\ldots\ldots. (15)$$

The solution of this linear differential equation is expressed by:

$$q = q_o exp - \frac{t}{\tau'} \quad \ldots\ldots\ldots(16)$$

Where

$$\tau' = R_T C, R_T = R + R', q_0 = \frac{nh\upsilon\phi_{PSII}\,C}{|q|} \quad \ldots\ldots\ldots\ldots(17)$$

Measurement of electrical parameters

The digital multi-meter smart"UT71.A" was programmed to detected automatically the extra chlorophyll space resistance for each light intensity (at zero frequency). Indeed the light intensity was varied between 0 and 16000W/m2, using the variation of the halogen lamp position; and for each intensity, the average measure of 25 resistances raised for 25 seconds was calculated (Fig.3). An IR filters were used to reduce art factual heating effects in the specimen. All the values measured by the multi-meter were automatically transferred to a laptop to be analyzed. Self-adhesive electro cardiology electrodes were used to capture the electrical signal from the solution of crude chlorophyll, (Waldhoff *et al*., 2002). The data were analyzed using software such as XLSTAT and Sine qua non software.

RESULTS AND DISCUSSION

Different measurements were made, and the behaviors of resistances were obtained from the variation of different lights intensity colors. For each case, we plot the variation of the extra chlorophyll resistance R versus the light intensity I.

Experiment 1: whit white light According to Figure 4 the resistance decreases due to the intensity of the light and it varies from 669.556kΩ for an intensity of 0 W/m^2 to 103.4812kΩ for intensity 16000W/m^2; it decreases rapidly for intensities between 0 and 1777.8 W/m^2 and slows afterwards.

Experiment 2: with blue light (wavelength: 470 nm)

The same experiment is now carried out with blue light. According to Figure 5 the resistance decreases due to the intensity of the light and it varies from 0.757M Ω for an intensity of 0 W/m^2 to 0. 419M Ω for intensity 16000W/m2; it decreases rapidly for intensities between 0 and 4000 W/m2 and slows afterwards.

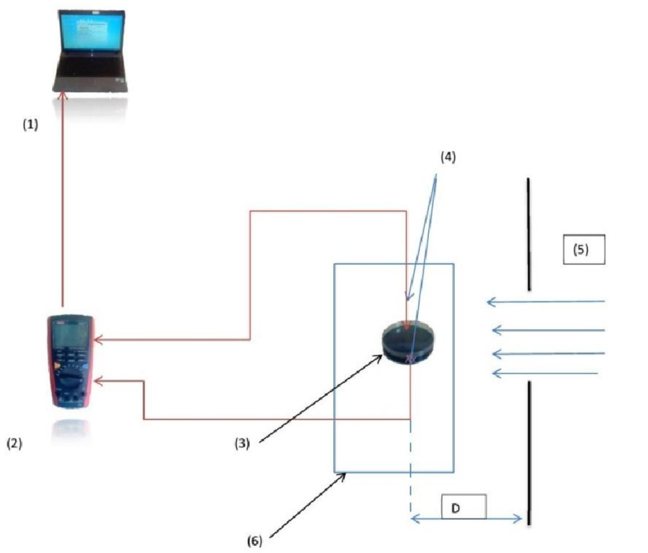

Figure 3. Variation of extra chlorophyll space resistance according to the intensity of the light. 1 - Laptop; 2 - multi-meter; 3 - petri-dish; 4 - electrodes; 5 - source of light; 6 - curve; D is the distance between the source of light and the petri-dish

Experiment 3: with yellow light (wavelength: 580 nm)

The same experiment is now carried out with yellow light. It is therefore found that, the resistance firstly increase from 0. 903M Ω to 0.943M Ω; and then decreases because of the intensity of the light; and it varies from 0, 943M Ω for an intensity of 250 W/m^2 to 0.549M Ω for intensity 16000W/m^2; it decreases rapidly for intensities between 250 and 4000 W/m2 and slows afterwards. (See Fig.6)

Experiment 4: with red light (wavelength: 650 nm)

The same experiment is now carried out with red light. According to Figure 7 the resistance firstly increase from 4.54232 to 5.60088; and then decreases according to the intensity of the light; and it varies from 5, 60088M Ω for an intensity of 326.6 W/m^2 to 5.061M Ω for intensity 16000W/m^2; it decreases rapidly for intensities between 326.6 and 4000 W/m2 and slows afterwards.

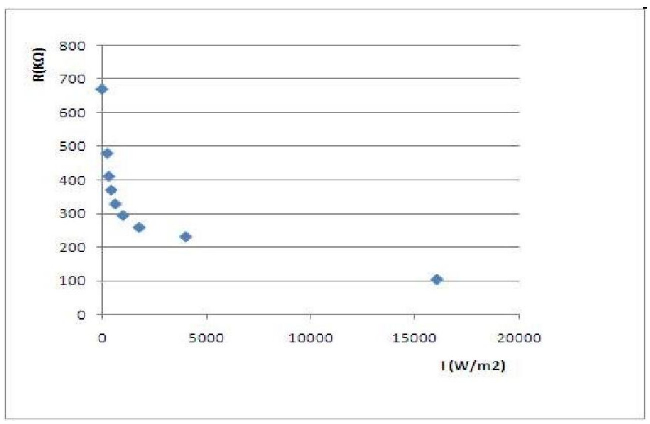

Figure 4. Variation of extra chlorophyll space resistance according to the intensity of the white light. The resistance decreases due to the intensity of the light and it varies from 669.556kΩ for an intensity of 0 W/m2 to 103.4812kΩ for intensity 16000W/m2; it decreases rapidly for intensities between 0 and 1777.8 W/m^2 and slows afterwards

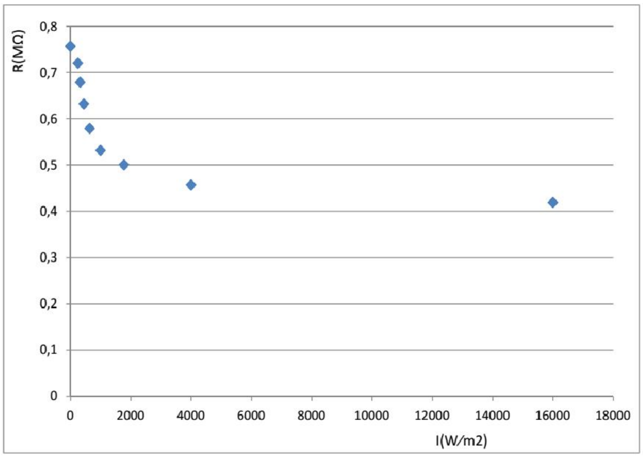

Figure 5. Variation of extra chlorophyll space resistance according to the intensity of the blue light. The resistance decreases due to the intensity of the light and it varies from 0.757M Ω for an intensity of 0 W/m^2 to 0, 419M Ω for intensity 16000W/m^2; it decreases rapidly for intensities between 0 and 4000 W/m2 and slows afterwards

Experiment 5: with green light (wavelength: 520 nm)

The same experiment is now carried out with green light. The green light is now used and comparisons are made. Contrarily to Figures 4,5,6,7 the resistance according to figure 8 increases only from 9.836M Ω for an intensity of 0 W/m2 to 14.256M Ω for intensity 16000W/m^2; it increases rapidly for intensities between 0 and 4000 W/m^2 and slows after wards.

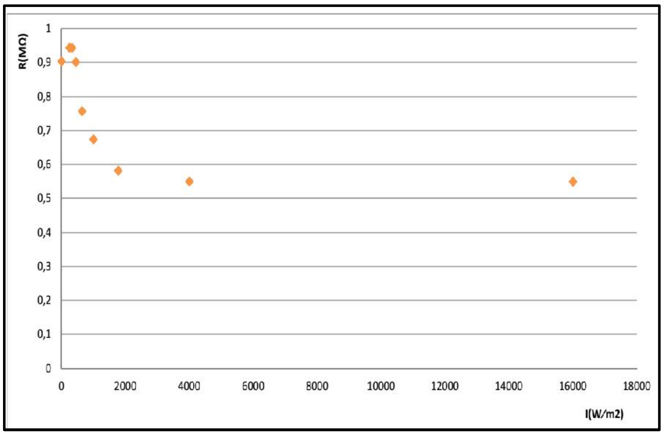

Figure 6. Variation of extra chlorophyll space resistance according to the intensity of the yellow light. The resistance firstly increase from 0.903M Ω to 0.943M Ω; and then decreases because of the intensity of the light; and it varies from 0, 943M Ω for an intensity of 250 W/m^2 to 0.549M Ω for intensity 16000W/m^2; it decreases rapidly for intensities between 250 and 4000 W/m2 and slows afterwards

From all the above results, there is a strong relationship between the measure of electrical parameters and photosynthetic activity. In this framework, in the presence of white, red, blue and yellow light, the general decrease of extra chlorophyll space resistance(R) (Fig.4, 5, 6, and 7) can be explained by the fact that white, blue, yellow and red light are active in the photosynthetic process. In fact photosynthetic pigments units form an antenna that collects the emitted light energy from the lamp; when a pigment captures a photon energy corresponding to its absorption capacity, one of its electrons which come from the doubles conjugates bonds (delocalizes electrons)of tetrapyrrole nucleus, goes to the excited state. This energy can be transmitted in four ways:

- by reissuing in the form of light photon,
- in the form of heat,
- by sending energy by resonance,
- by performing photochemistry,

The fourth way corresponds to the transfer of energy to an electron, and the production by a particular molecule of chlorophyll 'a' and high electron energy in the reaction center according to the equation:

$$\text{Chla} + \text{photon} \rightarrow \text{chla}^* + e^- \qquad \text{…………(18)}$$

The presence of the charge carriers in the extra chlorophyll space will result in increased conductivity that is to say reducing the extra chlorophyll space resistance, which confirms the work of Sellers (1985) who studied the relationship between stomata conductance of the leaves and the light intensity and showed that the conductivity of maize leaves increases as a function of the light intensity, that is to say that the electrical resistance decreases as a function of the light intensity.

In Fgure 8, the fact that the green light does not create the same variation of the behavior of the curve like white, red, blue and yellow light (Fig. 4, 5, 6, 7) can be explains by the fact that the absorption spectra of a crude chlorophyll is null for green light; this imply that there is no a release of charge carriers in the extra chlorophyll space.

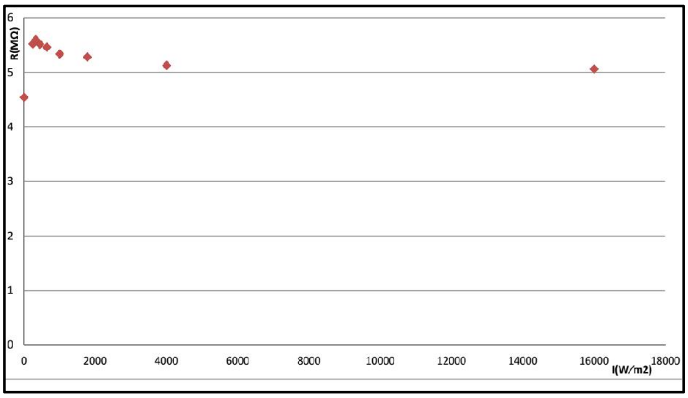

Figure 7. Variation of extra chlorophyll space resistance according to the intensity of the red light. The resistance firstly increase from 4.54232 to 5.60088; and then decreases due to the intensity of the light; and it varies from 5. 60088M Ω for an intensity of 326.6 W/m^2 to 5.061M Ω for intensity 16000W/m^2; it decreases rapidly for intensities between 326.6 and 4000 W/m2 and slows afterwards

The study of photosynthetic intensity is usually estimated by the amount of O2 released or the amount of CO2 assimilated depending on the light intensity (Mallick and Mohn, 2003), (Aleya and et Devaux, 1989) it's from these studies that; the intensity of photosynthesis initially low for low luminance increases rapidly, in proportion to the light intensity:

photosynthesis depends directly on energy received from light because it corresponds to its conversion into chemical energy.

However, when the light intensity reaches a certain value, the intensity of photosynthesis does not increase, either because of excess energy conversion capacity, or lack of raw material (CO_2). From our results and previous results, there is a clear relationship between the behavior of extra chlorophyll space resistance and the amount of O_2 issued or the amount of CO_2 assimilated according to white, blue, yellow, and red light

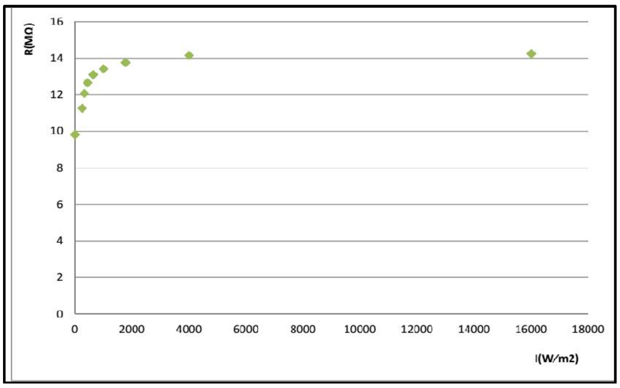

Figure 8. Variation of extra chlorophyll space resistance according to the intensity of the green light. The resistance only increases from 9.836M Ω for an intensity of 0 W/m^2 to 14.256M Ω for intensity 16000W/m^2; it increases rapidly for intensities between 0 and 4000 W/m2 and slows afterwards

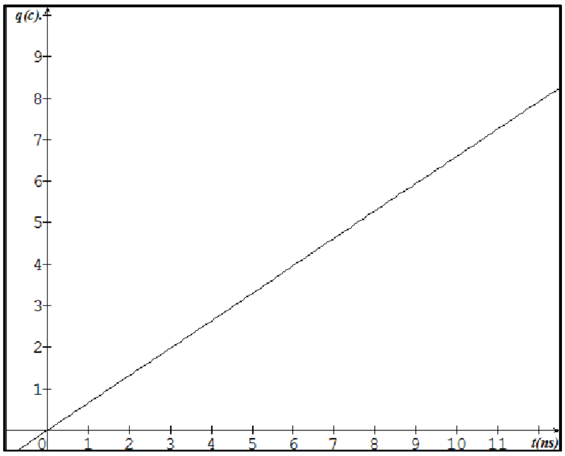

Figure 9. Variation of the quantity of electricity according to time in the presence of active photosynthetic light. The quantity of electricity and the time are respectively gives in coulomb and nano second. The quantity of electricity in extra chlorophyll space increases linearly with time in the presence of active photosynthetic light. n=1000; Ψ_{PSII}= 0.41$M\Omega$; $c = 3 \times 10^8 ms^{-1}$; $h = 6.62 \times 10^{-34}$

The study of photosynthetic intensity is usually estimated by the amount of O_2 released or the amount of CO_2 assimilated depending on the light intensity (Mallick *et al*., 2003; Aleya *et al*., 1989), it's from these studies that; the intensity of photosynthesis initially low for low luminance increases rapidly, in proportion to the light intensity: photosynthesis depends directly on energy received from light because it corresponds to its conversion into chemical energy. However, when the light intensity reaches a certain value, the intensity of photosynthesis does not increase, either because of excess energy conversion capacity, or lack of raw material, in this case (CO_2). From our results and previous results, there is a clear relationship between the behavior of extra chlorophyll space resistance and the amount of O_2 issued or the amount of CO_2 assimilated according to white, blue, yellow, and red light intensity, because, while the amount of O_2 emitted or the amount of CO_2 assimilated increases in function of the light intensity unto a certain threshold, the extra chlorophyll space resistance decreases with the intensity until it reaches a threshold. There is an exception for the green light. These results confirm the work previously carried out by Teuma *et al*., who showed that the photochemical phase with active photosynthetic lights are characterized by a decrease of the extra chlorophyll space resistance. The non-photochemical phase is characterized by an almost constant or increase of the extra chlorophyll space resistance. They also observe a vertical offset at the spectrometric curves of bio-impedance, implying a difference in electrical activity in darkness and active photosynthetic lights respectively. However, the green light is found to be inactive, since the photosynthetic activity is the same as in darkness.

Figure 9 is the curve of equation (10). According to figure 9, the quantity of electricity in extra chlorophyll space increases linearly with time in the presence of active photosynthetic light. This result is in agreement with the previous results, where in light the amount of O_2 emitted increases with time.

Figure 10 is the curve of equation (15) which represents the quantity of electricity that is released during the transitional period between lighting by an active photosynthetic light and non-active photosynthetic light or darkness. According to figure 10 the quantity of electricity in extra chlorophyll space decreases exponentially from $q_o$to zero during a short time of 34,8ns. This result is also in agreement with the curve representing the variation of the concentration of H_3O^+ of thylakoid in suspension which are successively exposed to darkness and light.

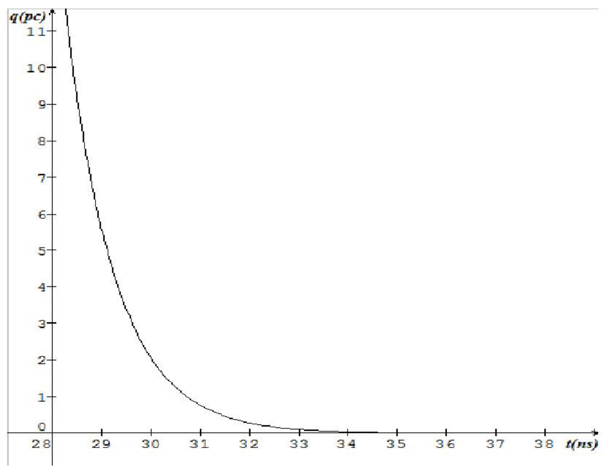

Figure 10. variation of the quantity of electricity according to time during the transitional period enters lighting by active photosynthetic light and the extension of this light. The quantity of electricity and the time are respectively gives in pico coulomb and nano second. The quantity of electricity in extra chlorophyll space decreases exponentially from $q_o$to zero during a short time of 34,8ns. n=1000; Ψ_{PSII} = 0, 4; λ = 4, 70 × $10^{-9}m$; $R = 1M\ \Omega$; $R' = 0.5M\ \Omega$; $c = 3 \times 10^8 ms^{-1}$; $h = 6, 62 \times 10^{-34}$; $C = 10 \times 10^{-9}$*coulomb*

Conclusion

The purpose of this study was to demonstrate that the photosynthetic activity can be obtained from the behavior of the electrical resistance of extra chlorophyll space. The model used in this study is that of Cole. This analysis shows that there is a distinct relationship between the behavior of the extra chlorophyll space resistance and the amount of O_2 emitted or the amount of CO_2 assimilated according to the intensity of the light; while the amount of O_2 emitted or the amount of CO_2 assimilated increases according to the intensity of the light up to a certain threshold, the extra chlorophyll space resistance decreases according to the intensity of white, blue, yellow and red light until it reaches a certain threshold. However, the green light is found to be inactive. It is clear that, from all the above results, this method give us more direct information about the electrical behaviors of chlorophyll pigment than fluorescence for example, where we need first to determine parameters like: primary fluorescence (F0), maximal fluorescence (Fm), variable fluorescence (Fv) (Loustau *et al*., 1999), the photochemical quantic yield (ΦP SII) of the photosystem II, and the assimilation quantic yield of CO_2 (ΦCO_2) before having an information about the electrical behavior of chlorophyll pigment. It is also observed from our studies that the theoretical curves obtained from our model are in agreement with many other results.

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