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Study of the Photo-Electric Behavior of *Spinacea pleracea* using the T.E-Model of Chlorophyll Pigment

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Abstract

Objective: To Study the photo-electric behavior of *Spinacea pleracea* by using the T.E-model of chlorophyll pigment. **Methods/Statistical Analysis:** The technic and method employed consisted on modeling the chlorophyll as an electrical circuit, to make a statistical analysis of electric conductance process of S. *pleracea* in light and in darkness by evaluating, the statistical average and statistical autocorrelation function, and make a temporal analysis by evaluating, the temporal average and temporal autocorrelation function. **Finding:** The electric conductance of *Spinacea pleracea* leaf plant increases when one passes from darkness to light; the spectral density of power (DSP) of the electric conductance process G(ω,t) under darkness is up to the DSP of the signal when *S. pleracea* is under light for the whole value of the reduced normalized frequency; the process is non-statistics in the broad sense (SSL) and non ergotic. The resemblance of the flow charge evaluated by autocorrelation functions for different values of the shift parameter is higher in light than in darkness. **Application/Improvements:** This study provided an additional tool to have an idea about the state of reactional center of photosystem II, knowing that the fluorescence emission testifies the loss of energy during the transfer of excitation to the reactional centers. In the same way, the electric conductance testifies the transfer of electrons released from the special chlorophyll 'a' of the reactional center to the photosynthetic channel.

Keywords: Chlorophyll, Ergotic, Spectral Density of Power (DSP), *Spinacea pleracea*, Statistics in the Broad Sense (SSL)

1. Introduction

The *Spinacea pleracea* (spinach) is cultivated for its gustatory and nutritional qualities, it is regarded as being a super-food. A daily spinach amount can potentially prevent the insanity and the cognitive fall by improving the cerebral blood surge[1]. Electric model is usually used for studying organic matter[2], that is why, knowing that the electric sensibility of *S. pleracea* leaf plant under light is due to chlorophyll pigment, we have used the T.E-model of chlorophyll pigment[3-5]. Our main concern is to study the photo-electrical behavior of *S. pleracea* leaf plant using the T.E-model, by evaluating the statistical average, the statistical autocorrelation function, the temporal average and temporal autocorrelation function. The rest of the paper is therefore presented as follows: the description of the model, the presentation of the materials used to obtain the data, the analytical methods of those data, the discussion of obtained results, and at the end we have some concluded remarks of the paper.

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2. Model

The model is made up of two parallel branch circuits where R represents the extra chlorophyll space resistance, R' represents intra chlorophyll space resistance; C represents chlorophyll capacitance and U the potential difference on the terminals of the circuit (Figure 1).

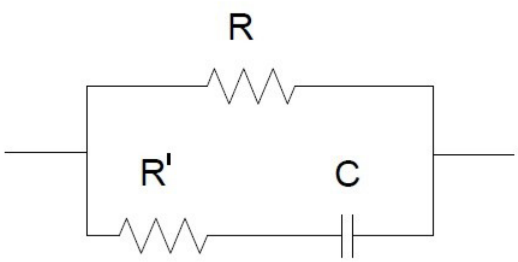

Figure 1. Electrical model of crude chlorophyll solution. R is the extra chlorophyll space resistance, R' is the intra chlorophyll space resistance, C is the capacitance of the pigments, U is the potential difference on the terminals of the circuit.

The impedance of this circuit is expressed as follows:

3. Materials and Methods

At 36°C, in front of a 1000W/m^2 light source, *S. pleracea* was successively in darkness during the first 10 seconds and lighted during the other 10 seconds. During the passage from the darkness state to the lighted state, a short pause was observed to avoid the electrical transition value. The electric parameters were measured starting from the electric assembly represented on Figure 2. The digital multi-meter smart "UT71.A" was programmed to detect automatically the extra chlorophyll space resistance (at zero frequency). All the values measured by the multi-meter were instantly transferred to a laptop to be analyzed. The data were analyzed using software such as XLSTAT and Matlab.

4. Methods of Analysis

4.1 Spectral Density of Power (DSP)

The spectral density of power $\Upsilon_G(\nu)$ of G(t) signal is expressed as:

$$\Upsilon_G(\nu) = |\bar{G}(\nu)^2| \quad (1)$$

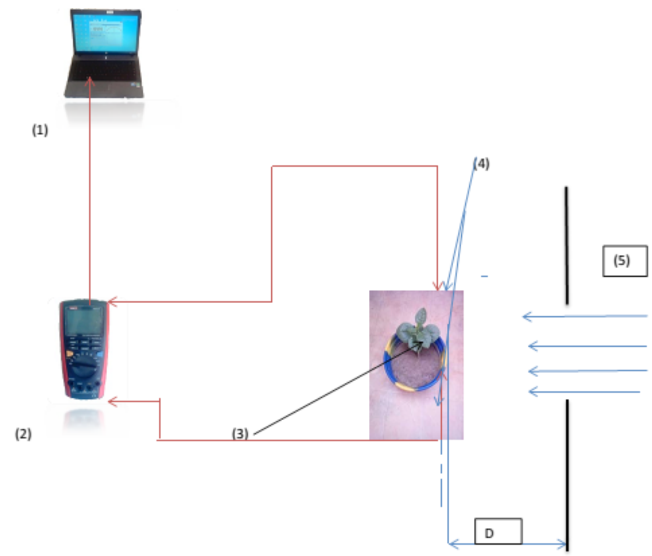

Figure 2. Variation of extra chlorophyll space resistance according to the intensity of the light and time. 1 - Laptop; 2 - multi-meter; 3 - *Spinacea pleracea* leaf plant ; 4 - electrodes; 5 - source of light; D is the distance between the source of light and *Spinacea pleracea* leaf plant.

Where $\bar{G}(\nu) = \sum_{n=1}^{N} G(n) e^{-j2\pi n\nu}$; $G(n) = \frac{1}{R(n)}$ (2)

$\bar{G}(\nu)$ is the discrete time Fourier transformation of the electric conductance G(t) signal; N the number of G(t) sample; ν is the normalized reduced frequency; $\nu \in [0;1[$.

The spectral density $\Upsilon_G(\nu)$ was evaluated firstly when the *S. pleracea* was in darkness during the first 10 seconds and secondly when the plant was lighted during other 10 seconds. The resulting evaluations of the spectral density $\Upsilon_G(\nu)$ were each time plotted when the plant was in darkness and lighted.

4.2 Stochastic Process Analysis

Since the measure value of G(t) is unpredictable whether in darkness or in light, we define a probabilized space (Ω,@,P), where $\Omega = \{\omega_1, \omega_2\}$ is the universe space, @=p(Ω) the entireparts of Ω and P the probability of the plan be either in darkness or in light.

We define the random variable ω which takes values:

$\omega = \omega_1 = 1$, when the solution is in light and,

$\omega = \omega_2 = -1$, when the solution is in darkness.

We consider that P is equiprobable on Ω, since the *S. pleracea* leaf plant was 10s in light and 10 other seconds in darkness; so we have:

$P = \frac{10}{20} = 0.5$ i.e

$P(\omega=\omega_1=1)= P(\omega=\omega_2= -1) = 0.5$

We also define E as the whole possible states of the process, and E_1, E_2 as:

$E = \bigcup_{i=1}^{2} E_i$,

where E_1 and E_2 are respectively the whole possible state of the process in light and in darkness.

T represents the whole discrete time.

We now define the electric conductance process G(ω,t) as:

$$G:\ \Omega \times T \rightarrow E$$
$$(\omega, t) \rightarrow G(\omega, t)$$

Where $G(\omega,t) = G_t(\omega) = \begin{cases} E1 \ if\ \omega = \omega 1, \forall t \in T \\ E2\ \ if\ \ \omega = \omega 2, \ \ \forall t \in T \end{cases}$

$T = \{1,2,3,4,5,6,7,8,9,10\}$; $g_{i,j}$ is the j^{em} element of Ei ;

$i \in \{1,2\};\ \ j \in \{1,2,3,4,5,6,7,8,9,10\};$

Let us suppose: $\hat{g}_{m,n}$ the m×n matrix of extra-chlorophyll space resistance, and $g_{i,j}$ one of its element; with m=2, n=10. We then have:

$\hat{g}_{m,m} = (g_{i,j}) 1 \le i \le m \le j \le n$ with

$$(g_{i,j}) = G(\omega = \omega_i, t = j) \qquad (3)$$

4.3 Statistical Properties

-Average : $M_R(t) = \sum_{i=1}^{2} G_t(\omega_i) \times P(\omega = \omega_i)$ i.e (4)

$$M_R(t=j) = \sum_{i=1}^{2} g_{i,j} \times P(\omega = \omega_i) \text{ i.e}$$
$$M_R(t=j) = \frac{1}{2}(g_{1,j} + g_{2,j}) \qquad (5)$$

- Autocorrelation Function:

$$\tau_G(t=i, t=i+k) = \sum_{i=1}^{2}\sum_{l=1}^{2} g_{i,j} \times g_{l+k,j} \times P(\omega=\omega_i, \omega=\omega_l) \qquad (6)$$

Where:

$P(\omega = \omega_i, \omega = \omega_l) = 0 \ \ for\ i \neq l$, because the leaf plant can't be in the darkness and in light at the same time, and $P(\omega = \omega_i, \omega = \omega_l) = \frac{1}{4}$, because of the independence of the *S. pleracea* in light and in darkness; $k \in N$.

Considering the above assumption, we then have:

$$\tau_G(t=i, t=i+k) = \frac{1}{4}(g_{1,j} \times g_{2+k,j} + g_{2,j} \times g_{1+k,j}) \qquad (7)$$

4.4 Temporal Properties

- Temporal Average

$$\mu_G(\omega = \omega_i) = \frac{1}{N}\left(\sum_{j=1}^{10} g_{i,j}\right) \qquad (8)$$

- Temporal Autocorrelation Function

$$\mu_{GG}(\omega = \omega_i) = \frac{1}{N}\left(\sum_{j=1}^{10} g_{i,j} \times g_{i,j+k}\right) \qquad (9)$$

5. Results and Discussion

Different measurements were made at zero frequency, and the value obtained was the extra-chlorophyll space resistance, and the electric conductance was obtained according to the equation 2. The electric conductance is obtained according to the light intensity and time.

We plotted the variation of electric conductance G(t) versus time successively in darkness and in 1000W/m^2 light intensity; evaluated and plotted the parameters of the process G(ω,t):

- the spectral density of power $\Upsilon_G(\nu)$,
- the statistical average,
- the statistical autocorrelation function,
- the temporal average,
- the temporal autocorrelation function.

The conductance of *S. pleracea* increases when passing from darkness to light. The average value for the first the 10 seconds is 1.3531 µS in darkness and 1.5619 µS in light (Figure 3).

Let us consider that the 11^{th} second corresponds to the 1^{rst} second of *S. pleracea* leaf plant under light, the 12^{th} second corresponds to the 2^{nd} second of *S. pleracea* leaf plant under light, and the 13^{th} second corresponds to the 3^{rd} second of *S. pleracea* leaf plant under light and so on. We can now deduce the matrix $\hat{g}_{m,n}$ according to equation (3) as:

$$\hat{g}_{m,n} = \begin{pmatrix} 1.266 & 1.313 & 1.363 & 1.398 & 1.382 & 1.392 & 1.372 & 1.355 & 1.334 & 1.352 \\ 1.558 & 1.598 & 1.573 & 1.604 & 1.623 & 1.516 & 1.561 & 1.522 & 1.480 & 1.480 \end{pmatrix}$$

Spectral density of power of the electric conductance.

By using equations 1, 2, 3, we have:

$$\Upsilon_G(\nu) = \sqrt{\left(A^2(\nu) + B^2(\nu)\right)^2 + 4\left(A^2(\nu)B^2(\nu)\right)} \qquad (10)$$

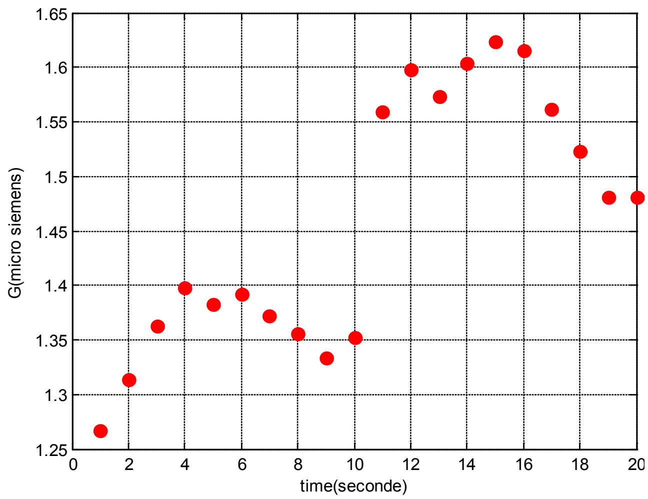

Figure 3. Behavior of electric conductance for the first 10 seconds in darkness and other 10 second in light. The values of G(t) are higher in light than in darkness; the average are 1.3531µS in darkness and 1.5619µS in light.

In the presence of light we have:

$$A(v) = \sum_{j=1}^{10} g_{1,j} \cos 2\pi v j$$

$$B(v) = \sum_{j=1}^{10} g_{1,j} \sin 2\pi v j$$

In the presence of darkness we have:

$$A(v) = \sum_{j=1}^{10} g_{2,j} \cos 2\pi v j$$

$$B(v) = \sum_{j=1}^{10} g_{2,j} \sin 2\pi v j$$

According to Figure4 (obtained by using equation 2 and $\hat{g}_{m,n}$ matrix), the DSP of signal G(ω,t), under light (blue curve) is below the DSP of the signal G(ω,t) when the plant is under darkness (blue-green curve) for the whole value of the frequency. The maximums DSP are attained for the normalized reduced frequency of 0.25, 0.35 and are 9000 and 6500 in darkness and in light respectively.

- **Statistical Average**

Figure 5 (obtained by using equation 5 and the $\hat{g}_{m,n}$ matrix) reveals that the electric conductance process

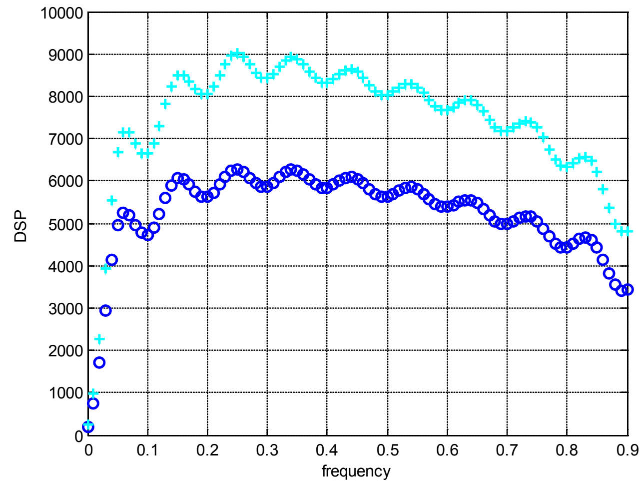

Figure 4. Spectral density of power of the electric conductance process. the DSP of signal G(ω,t) of *Spinacea pleracea* leaf plant under light (blue curve) is below the DSP of the signal G(ω,t) when the *Spinacea pleracea* leaf plant is under darkness (blue-green curve) for the whole value of the frequency; the maximum DSP is reached for the normalized reduced frequency of 0.25 and 0.35 and are 9000 and 6500 in darkness and in light respectively.

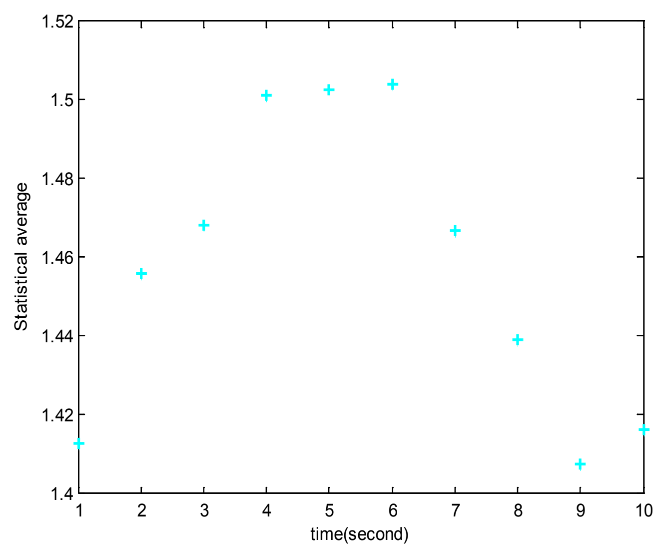

Figure 5. Statistical average of electric conductance signal G(ω,t) according to time. The curve reveals that the electric conductance process G(ω,t) is non-statistics in the broad sense (non SSL); due to the fact that the statistical average of the R(ω,t) process Is not constant during the time evolution. The statistical average increase according to time till 1.08µS at the 6th second then decrease till 1.09 µS.

G(ω,t) is non-statistics in the broad sense (non SSL); due to the fact that the statistical average of the G(ω,t) process Is not constant during the time evolution. The statistical average increases according to time till 1.08μS in the 6th second then decreases till 1.09 μS.

- **Autocorrelation Function**

The statistical autocorrelation curve of Figure 6 was obtained by using equation (5) and the corresponding matrix obtained from the experimental measures. The autocorrelation linearly increases when the plant passes from darkness to light. The autocorrelation does not depend only to displacement parameter k when passing from darkness to light, but also on time; it is not stationary as shown in the figure 6. This implies that the electric conductance signal G(ω,t) of the plant is not a statistics process in the broad sense (SSL).

- **Temporal Average**

The temporal average of the process, calculated using equation (8) and the corresponding experimental matrix is 1.5619μS in light and 1.3531μS in darkness; so the temporal average vector of the electric conductance signal G(ω,t) of the plant is given by:

$\boldsymbol{\mu}_G$(1.3531 1.5619)

The G(ω,t) electrical process is not an ergotic signal due to the fact that the temporal average of the process is different in the light as it is in darkness.

- **Temporal Autocorrelation Function**

The temporal autocorrelation curve of Figure 7 was obtained by using equation (9) and the corresponding matrix obtained from the experimental measures. Autocorrelation linearly increases when *S. pleracea* leaf plant passes from darkness to light. It depends both on the parameter of time evolution and the state of the plant; this implies that electric conductance G(ω,t) of the plant is a non ergotic signal.

In fact, the excitement provoked by the photons in the antennas is transmitted with high efficiency from chlorophyll to chlorophyll by resonance until the reaction center. The excitement that is not transmitted is emitted as heat and fluorescence. The excitement which reaches P680 (the heart of photosystem II is made up of 2 or 4 special chlorophyll 'a' called P680):

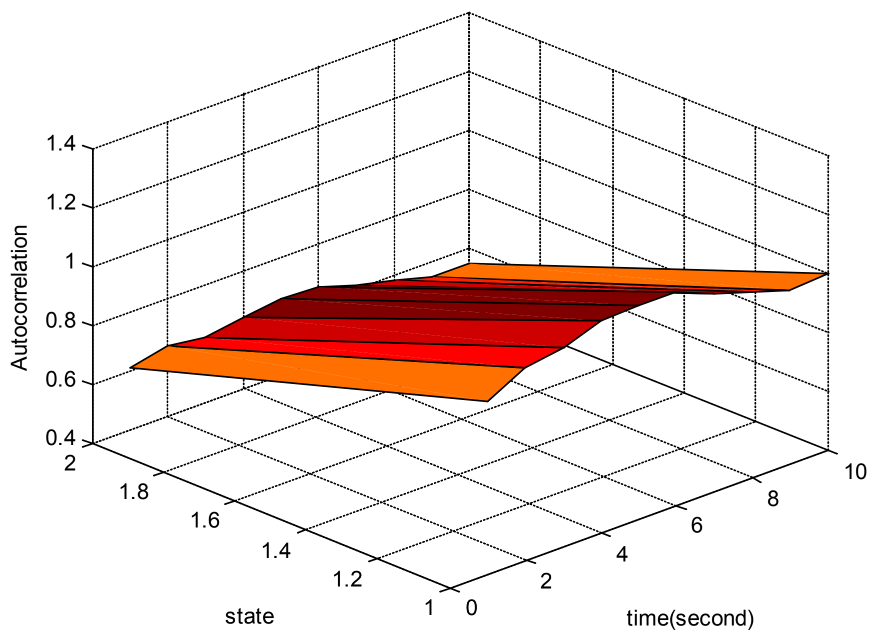

Figure 6. Statistical autocorrelation of electric conductance signal G(ω,t) according to time and the state of *Spinacea pleracea* leaf plant (1: under light, 2: under darkness). The autocorrelation linearly increases when *Spinacea pleracea* leaf plant passing from darkness to light. The autocorrelation not depends only to displacement parameter k when passing from darkness to light, but also on time; it is not stationary as it is shown in the figure. This implies that the electric conductance signal G(ω,t) of *Spinacia pleracea* leaf plant is not a statistics process in the broad sense (SSL).

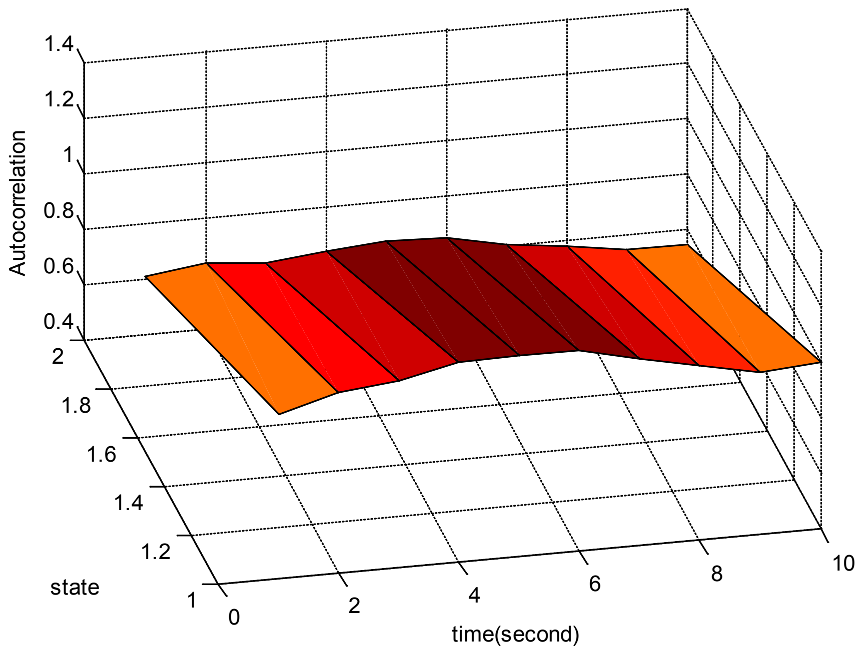

Figure 7. Temporal autocorrelation function according to time and the state of *Spinacea pleracea* leaf plant (1: under light, 2: under darkness). Autocorrelation linearly increases when *Spinacea pleracea* leaf plant passing from darkness to light. It depends on both of the parameter of time evolution and the state of the plant; this implies that electric conductance G(ω,t) of the plant is a non ergotic signal.

- May be the cause of a transfer of electrons in the photosynthetic channel,
- Can be converted into fluorescence and heat,
- When the centers are closed, the excitation returns to the antenna where it is lost in the form of fluorescence (and heat). This implies that the closure of centers is linked to an increase in the emission of fluorescence produced. One can deduce that the opening of centers is linked to the transfer of electrons in the photosynthetic channel and the variation of electric conductance due to light intensity.

6. Conclusion

Our purpose is to study the photo-electric behavior of *S. pleracea* using the T.E-model of chlorophyll pigment. At 36°C, in front of light source, the electric conductance of the plantwas measured successively in darkness during the first 10 seconds and lit during the other 10 seconds. It comes out from our study that, the electric conductance of the plant increases when passing from darkness to light. Under darkness, the spectral density of power (DSP) of the electric conductance process G(ω,t) is up to the DSP of the signal when the plant is under light for the whole value of the reduced normalized frequency. The process is non-statistics in the broad sense (SSL) and nonergotic. The resemblance of the flow charge with it for different values of the shift parameter is higher in light than in darkness. This study provided an additional tool to have an idea about the state of reactional center of photosystem II, knowing that the fluorescence emission testifies the loss of energy during the transfer of excitation to the reactional centers. In the same way, the electric conductance testifies the transfer of electrons released from the special chlorophyll 'a' of the reactional center to the photosynthetic channel.

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