Performance Analysis of Digital Filters Employed to Plants Electrical Signals

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Abstract: Electrical signals are generated and transmitted through the plant in response to disturbances like leaf burning, touching, and luminosity. Moreover, the whole structure of the plant is informed almost instantly by these signals. Taking into consideration variation potentials (VPs), system potentials (SPs), and action potentials (APs), even if a small region of the plant has suffered a stimulus, the excitation is spread from the top of the stem to the roots, in either direction. By investigating the electrical signals of a specific plant, it is conceivable to elucidate the impact of external aspects (i.e., soil moisture, mechanical stress, thermal shock) in the plasma membrane potential, and identify the electrical response origin. Therefore, this project addresses a brief plant electrophysiology theory and a detailed performance analysis of digital filters to this application. The filters were tested by using ECG signals due to some characteristics similar to plants electrical signals. The most efficient one was chosen by considering two signal parameters. The filter project selected to be applied in this work can be used to various plants' electrical responses, making a few adjustments through MATLAB software.

Resumo: Os sinais elétricos são gerados e transmitidos ao longo da planta em resposta a estímulos provocados por algum elemento no meio externo, como queima da folha, toque e luminosidade, ademais, permitem que toda a estrutura do vegetal seja informada de maneira quase instantânea. Quando se trata de potenciais de ação (PAs), potenciais de variação (PVs) e potenciais sistêmicos (PSs), ainda que apenas uma pequena parte dele tenha sofrido um distúrbio, a excitação é transmitida do topo do caule até as raízes, e vice-versa. Por meio da análise dos sinais elétricos de uma determinada planta, é possível descrever o impacto de fatores externos (umidade do solo, estresse mecânico, choque térmico) no potencial elétrico da membrana plasmática, e identificar a origem da resposta elétrica. Este trabalho aborda a teoria relacionada à eletrofisiologia vegetal, além de apresentar alguns projetos de filtros digitais, que foram testados empregando-se um sinal de ECG, devido a algumas características similares a de sinais elétricos das plantas, sendo que aquele mais eficiente foi selecionado, levando em consideração dois parâmetros do sinal elétrico. O projeto de filtro escolhido para este trabalho pode ser aplicado em várias respostas elétricas de plantas, desde que o usuário realize alguns ajustes, empregando-se o *software* MATLAB.

Keywords: Electrical Signals; Plant Electrophysiology; Response to Stimuli; Signal Processing.
Palavras-chaves: Sinais Elétricos; Eletrofisiologia Vegetal; Resposta a Estímulos; Processamento de Sinais.

1. INTRODUCTION

Diverse environmental factors can affect the plants, such as light and soil moisture. Plants are required to continuously adapt their metabolism and growth in reaction to changes in the habitat, so they developed means to react quickly to external stressors and environmental modification aspects. They perform it by transmitting electrical signals through their structure. The electrical activities of the plants are related to transient changes in the plasma membrane potential, as stated in Fromm and Lautner (2007). The matter that plants electrostimulation results in the activation of ion channels and the flow of ions, which induces a local and transient change in the potential of the cell membrane, taking into consideration all cells (mainly root cells associated with ions uptake) detain practically the whole time, ions crossing the membrane, is the chief reason for this event (Davies (2006)).

Chemical, physical and mechanical disturbances do not influence just the stimulated area but may also affect the whole plant body. Then, the electrical signals caused by these irritants can transmit information quickly over long distances, from the top of the stem to the roots in either direction, in contrast to chemical signals, like hormones, as detailed in Volkov et al. (2007). Moreover, stimulus diffusion in plants has a complex characteristic, alongside an internal change in tissues and cells, since the provoked excitation disseminates in both directions of their structure. Besides that, some factors, like chemical treatment, mechanical wounding, and the intensity of the stress, for example, influence the speed of the electrical signal propagation (Labady Jr et al. (2002)).

Over the years, it was shown by numerous studies that distinct types of stimuli could generate specific electrical responses in living plant cells (Vodeneev et al. (2012); Fromm and Lautner (2007); Yan et al. (2009); Hagihara and Toyota (2020)). Once triggered, these signals disseminate to adjoining excitable cells. The excitability of plant cells is connected to their balance with the environment and the structuring of internal processes (Labady Jr et al. (2002)). Furthermore, a significant point is that it is possible to acquire electrical signals emitted by plants applying two methods: extracellular and intracellular.

Additionally, it is needful to highlight the matter that there are four different kinds of electrical activities in plants (de Toledo et al. (2019)): *(i)* local electrical potentials (LEPs); *(ii)* action potentials (APs); *(iii)* variation potentials (VPs); and *(iv)* system potentials (SPs).

Electrical signals generated by plants are closely attached to environmental aspects. This leads to the motivation to develop a work in this field since it is conceivable to monitor the plants' growth, for example, in a garden or a farm, and be aware of whether the soil the plant where inserted is too wet or insects are damaging the plant. Besides that, the detection of landslides (Aditya et al. (2013)), fires, or even the existence of acid rain in a determined area is possible too, all of it by just monitoring these electrical responses.

The process that must be applied to acquire plants' electrical responses is shown in Figure 1. Note that this work addresses the last step of this process.

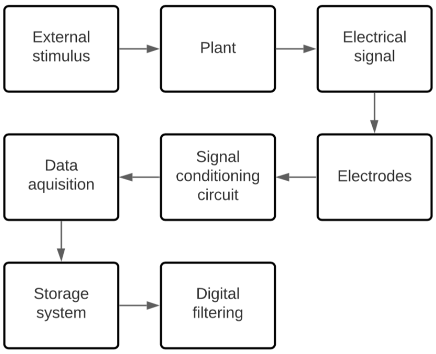

Figure 1. Flowchart of plant electrical signals acquisition.

It is essential to know the original shape of an electrical signal transmitted by the plant since the type of the stimulus can be known by analyzing the format of the excitation, along with other aspects, like amplitude and propagation velocity. The filter projects developed in this work and the chosen parameters were implemented to cause the least possible distortion to the signals, only removing undesired frequency components, which are acquired alongside the electrical response.

An influential fact is that the implemented digital filters, along with a signal conditioning circuit and environmental aspects acquiring circuit, can be employed as a foundation for creating a low-cost instrument that has the objective to inform the user about the parameters formerly mentioned, among others. Therefore, this work's primary purpose is to present essential knowledge about plant electrophysiology and the instructions to develop digital filters. In this sense, even a user, who has a brief familiarity with these matters, can understand plant electrophysiology and implement digital filters to make the electrical response as clear as possible. The principal contributions can be compiled as follows:

- Presents important knowledge associated with plants electrophysiology, directing the explanation to the different types of electrical signals;
- Describes in detail the process of implementing digital filters used to improve the electrical responses transmitted by plants.

2. TYPES OF ELECTRICAL SIGNALS

Action potential was the first plant's electrical response recorded and is provoked by non-invasive disturbance (e.g., thermal stress, electrical stimulation, or mechanical stimulus (de Toledo et al. (2019); Szechyńska-Hebda et al. (2017))) and is defined by being capable of rapidly transmitting the excitation over long distances. A significant fact that opposes the variation potential is that an increase in the magnitude of the stimulus above a certain threshold does not change the electrical signal's amplitude and shape (Yan et al. (2009)). One of the most important characteristics of the AP is that it follows the all-or-nothing principle. To put it another way, the trials to generate stimuli that are weaker than a determined threshold cannot trigger an AP. Moreover, after the period AP is triggered, the cell membrane enters a refractory period, in which another action potential is not able to be generated or transmitted (Davies (2006); Szechyńska-Hebda et al. (2017)). Besides that, slower repolarizing and after-hyperpolarizing periods are preceded by a rapid depolarizing phase (Trebacz et al. (2006)). Action potentials are capable of propagating through the plant body with constant speed and without loss of amplitude, unlike VP (Fromm and Lautner (2007)). According to Galle et al. (2014), action potentials transmission speed of most plants studied previously range from 0.5 cm/s to 20 cm/s.

SP is a self-propagate systemic signal with a magnitude and duration that depends on the nature of the provoked stressor. Besides, it is linked to the activation of H^+-ATPase. It is important to highlight too that this signal is deeply dependent on treatments and the conditions of the experiments (Choi et al. (2016)). Moreover, system potential does not follow the all-or-none rule as the action potential. Furthermore, unlike VP and AP that begin with a depolarization, system potential is triggered by a hyperpolarization of the plasma membrane. According to de Toledo et al. (2019), system potential has a propagation speed which range from 5 cm/min to 10 cm/min (de Toledo et al. (2019)).

The variation potential, also known as slow-wave potential or electro potential wave, is induced by damaging stressors such as burning and wounding (Szechyńska-Hebda et al. (2017)). This signal consists of a local variation in the plasma membrane, a result of the passage of some other signal (hydraulic, chemical, or both combined) (Vodeneev et al. (2015)). Variation potential is characterized by a decrease in the speed of the signal's propagation and amplitude as it moves away from the area which has suffered a disturbance (Vodeneev et al. (2015); Aditya et al. (2013)), unlike the action potential. Additionally, another crucial point is that the selected plant and the intensity of the stimulus influence the magnitude and shape of the variation potential. According to Galle et al. (2014), this electrical signal type has a propagation speed between 0.1 cm/s and 1 cm/s.

As a result of natural changes in factors associated with the external environment, such as fertility, phytohormones, and air temperature, LEP is generated at the stimuli site, which causes a sub-threshold electrical response in plants. This signal type is local and is not transmitted to other parts of the plant's structure. Besides that, it significantly influences the plant's physiological status. Besides, the duration and intensity of the stimulus influence its amplitude. Furthermore, it can be generated by the transient inactivation of H^+-ATPase and also by means of changes in ion channel activity (Szechyńska-Hebda et al. (2017); de Toledo et al. (2019)).

3. PROPOSED METHODOLOGY

Plants signals have amplitudes that are in the order of the tens of µV to the tens of mV (Tian et al. (2015)). Thus, it is necessary to use a signal conditioning circuit to improve the signal-to-noise ratio of the electrical signal before applying the digital filters.

In an effort to get rid of undesired frequencies, like power line interference and instrumentation noise, it is necessary to employ digital filters to the electrical response. The ideal circumstance is when the signal is acquired in the best way possible. In other words, by applying a good signal conditioning circuit before the electrical response goes to the analog-to-digital converter (ADC), and using a sampling frequency (f_s) that is not much larger than twice the highest frequency component of the signal, for the sake of a huge f_s, it results in a great amount of background noise captured along with the electrical response. This causes a signal of interest that occupies a small fragment of the spectrum. Besides that, one of the issues is that the frequency range out of the desired spectrum can be aliased since the value of its frequency components is unknown, distorting the electrical signal.

Usually, it is used in ADC, f_s between $40Hz$ and $100Hz$ to acquire plant's electrical responses (Macedo et al. (2021)). Some plants have very low frequencies (Mousavi et al. (2013); Stolarz et al. (2010); Tian et al. (2015)). The signal frequency of plants depends on the plant growth stage, the plant species, the stimulus applied, and the tissue that is measured (Zhao et al. (2015)). Suppose the frequency range of the plant signal is not known. In that case, the ADC sampling frequency can be set by means of using an instrument with a reasonably high sampling rate, something between $1kHz$ and $10kHz$. As the user is analyzing the signal frequency, it is feasible to reduce the f_s up to a value that does not occur aliasing. It is suggested to reduce the f_s, for the sake of the higher the f_s, the larger will be the size of the created files (Mousavi et al. (2014)).

The filters sampling rate must be adjusted according to the f_s that the signal was acquired. Furthermore, the filters' order has to be set considering the parameters required, such as the attenuation in the stopband, the sampling rate of the filter, the transition band, among others.

These filter projects were designed to take into account a plant electrical signal, which has frequency components between $5Hz$ and $25Hz$ (Cabral et al. (2011); Wu et al. (2013)). Suppose the plant electrical response has frequency components greater than the power line frequency ($50/60Hz$). In that case, it is necessary to employ an alternative filter project, as shown in the flowchart of Figure 2.

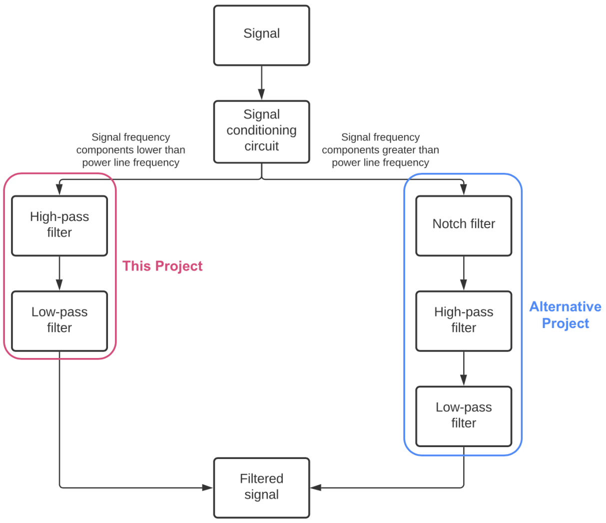

Figure 2. Flowchart of the proposed methodology.

In order to testify the filter project efficiency, it was used an ECG signal that is available in the database[1]. The signal presented in this database and chosen to be applied to the filter projects has two versions: *(i)* the original; and *(ii)* the filtered one. Thus, it was possible to measure the signal-to-noise ratio (SNR) of the database filtered signal, taken as the reference signal, and compare to the electrical response SNR after passing through each filter project, using Equation (1). The test signal applied in this work is uncorrupted.

$$SNR(dB) = 10 \log_{10} \frac{\sum_{i=1}^{n} x_i^2}{\sum_{j=1}^{n} y_i^2} \tag{1}$$

where x is the signal and y is the noise.

Besides that, it was calculated the error (ERR) between the filtered signal from the database and the filtered electrical response by applying Equations (2) and (3). The filter project option was selected, resulting in a signal that holds an SNR closer to the database filtered signal SNR and has the smallest normalized error value.

$$ERR = \sum |S1(n) - S2(n)|^2 \tag{2}$$

$$ERR(NORMALIZED) = \frac{\sum |S1(n) - S2(n)|^2}{\sum |S1(n)|^2} \tag{3}$$

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[1] Person01-rec04: https://physionet.org/content/ecgiddb/1.0.0/

where $S1(n)$ is the database filtered signal and $S2(n)$ is the filtered signal after passing through the filter project.

ECG signals were selected to be applied because some of their characteristics are similar to plants' signals, like low amplitude and high noise level. ECG signals have frequencies that range from $0.01Hz$ to $250Hz$ (Cardoso (2010)) and, according to Zhao et al. (2015), plants' electrical signals frequency components range from very low frequencies to several hundreds of Hertz.

It was not possible to measure the electrical signals transmitted by some plants because of a lack of funds. Moreover, it was not feasible to go to university laboratories.

3.1 Filters' Project

Infinite Impulse Response (IIR) filters hold a non-linear phase response, resulting in a phase and group delay that are not linear. This fact introduces a distortion in the electrical signal filtered, modifying its shape, so it is needful to design IIR filters setting a low order. The higher the filter order, the greater the signal distortion will be. IIR filters are also known as recursive filters, since associate the input/output by means of a linear difference equation, shown in Equation 4, in which the current output sample is computed from the past M output samples plus the previous N inputs and the current input sample (Lai (2003)). a_k and b_k represent the coefficients of the filter and n is the time index.

$$y(n) = -\sum_{k=1}^{M} a_k y(n-k) + \sum_{k=0}^{N} b_k x(n-k) \qquad (4)$$

If symmetry exists in the time domain (Equation 5), a Finite Impulse Response (FIR) filter has a linear phase response, constant phase and group delay. As soon as all signal frequency components suffer the same delay, the phase delay of the filter is constant. Consequently, the electrical signal reaches the filter output as close as possible to the original signal shape. Nonetheless, holding a little delay. All signal frequency components will have the same number of delayed samples when the filter has a constant group delay. All components will achieve together the filter output with the same sample delay. FIR filters are also known as non-recursive filters. The second term on the right-hand side in Equation 4 is of the identical form as FIR filters (Lai (2003)).

$$h[n] = \pm h[N-n] \qquad (5)$$

The design method chosen for FIR filters was the windowing one. The development of the FIR filter through the windowing method is given by multiplying the impulse response of an ideal filter by the chosen window function, as presented in Equation 6.

$$h_t[n] = h_d[n].w[n] \Leftrightarrow H_t(\omega) = H_d(\omega) * W(\omega) \qquad (6)$$

An ideal filter has infinite duration. In other words, n varies from -∞ to $+\infty$, and it is non-causal. In order to put it in another way, its output also depends on future entries, in addition to current and past entries, as in a causal filter. Due to these points, the ideal filter is classified as unrealizable.

When the impulse response of an ideal filter is multiplied by a window, only $n = N + 1$ coefficients are kept, and the rest are thrown out. The amount of preserved coefficients is determined by the order N of the filter. Finally, the filter's impulse response is shifted to the right by $N/2$ samples, so the first sample occurs at $n = 0$. In the end, the result is a stable, causal filter with finite duration and, compared to the ideal filter, because of the inserted delay, holds a phase factor of $e^{-jN/2}$.

Nonetheless, the truncation of an ideal filter by a window contributes to the Gibbs phenomenon, characterized by an oscillatory phenomenon in the frequency domain that occurs in transition band proximity. It is necessary to choose a window that holds a smoother band transition if it is desired to reduce the Gibbs phenomenon.

The narrower is the main lobe of a window. The better will be its frequency resolution. However, the problem is the fact that the higher the side lobes, which appear as background noise in the spectrogram, the narrower the main lobe. In cases where signal frequency components are near each other, it is necessary to pick up a window with better frequency resolution. Nevertheless, when the signal frequency components are more separated, the frequency resolution is not a problem.

The background noise can hide the components with the lowest amplitude values in situations where the frequency components' magnitude is rather distinct from each other. If the magnitude of frequency components holds similar values, the background noise is not a problem.

Another filter employed was Savitzky-Golay, a low-pass FIR filter, which is an algorithm for filtering random noise present in the electrical response. The SNR of the signal measured is increased without changing its shape. Usually, polynomials of higher degrees in this filter can detect heights and widths of narrower peaks more precisely. They may hold a poor performance at smoothing larger peaks, though.

Moreover, the coefficients of the Savitzky-Golay filter come from performing a non-weighted linear adjustment of least squares, applying a polynomial of a certain order at the center point of the window, as in Haider et al. (2018); Nishida (2017).

According to Zhao et al. (2014) and Luo et al. (2005), considering the Savitzky-Golay filter, each successive subset of $2m+1$ points is adjusted by a polynomial of certain degree p, being $p \leq 2m$, in the sense of least-squares. The original data d_{th} differentiation at the midpoint, where $0 \leq d \leq p$, is acquired through carrying out the differentiation on the fitted polynomial, instead of on the original data. In order to finish, the running least-squares polynomial fitting can be accomplished by doing the convolution of the whole input data with a $2m + 1$ length digital filter.

4. RESULTS AND DISCUSSION

The f_c of low-pass (LP) filters were set at $40Hz$ to get rid of the power line frequency ($50Hz$), alongside background noise that is not in the signal frequency range. The f_c of

Table 1. Filter projects configurations.

Project Option	**Filter Type**	**Configuration**
First	Elliptic	LP; N=3; PR= 3dB; SA=60dB; IIR
Second	Hann	LP; N=80; FIR
Third	Blackman-Harris Chebychev	HP; N=80; FIR LP; N=80; SA=60dB; FIR
Fourth	Hamming Chebychev Type 2	HP; N=80; FIR LP; N=4; SA=60dB; IIR
Fifth	Blackman-Harris Savitzky-Golay	HP; N=80; FIR LP; N=3; L=15; FIR

high-pass (HP) filters were equal to $0.5Hz$ to eliminate DC frequency. Depending on the frequency range of the plant signal, it might be necessary to change these two cut-off frequencies. The overall configurations of each filter project are shown in Table 1. N is the filter order, PR is the passband ripple, SA is the stopband attenuation, and L is the frame length of the Savitzky-Golay filter.

It was used MATLAB filtfilt function in IIR filters to perform zero-phase digital filtering. However, one of the implications of this function is that it results in a filter order that is double the order specified when the filter was designed. IIR filters order shown in Table 1 corresponds to the order set, not the order after employing filtfilt function. Furthermore, the delay introduced by FIR filters was corrected by shifting the electrical response in time.

The SNR of the database filtered signal (reference signal) is equal to $4.1064dB$. Thus, taking into consideration how close the SNR signal after passing through each filter project option is to that and the error between the filtered signal from the database and the filtered electrical response, it is possible to conclude that the best choice is the third option. Table 2 presents this result.

The original signal from the database and the filtered electrical response after passing through the third filter project chosen is shown in Figure 3.

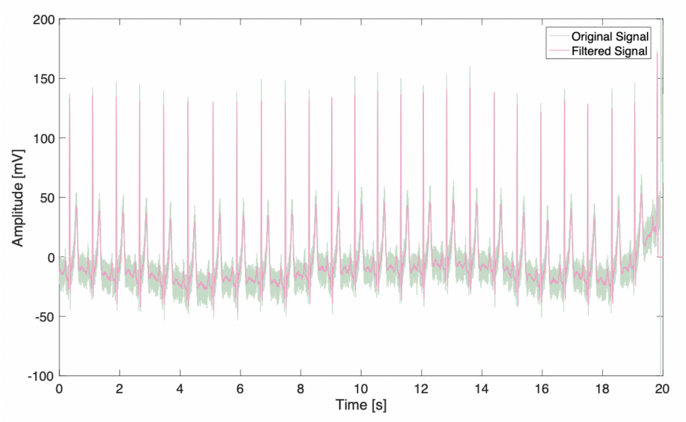

Figure 3. Original and filtered signal.

The electrical response after passing through the third filter project, and the reference signal, are shown in Figure 4. The frequency response is shown in Figure 5.

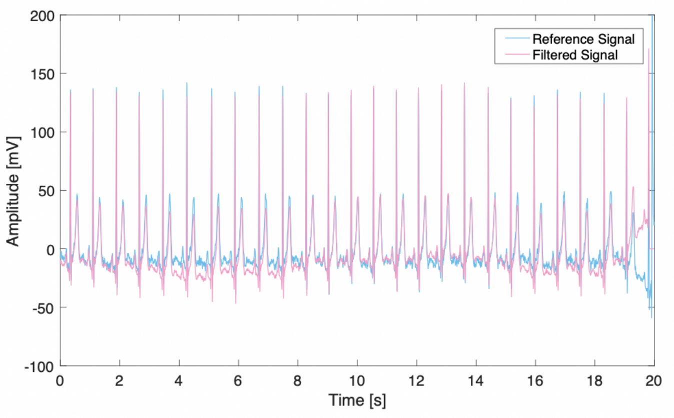

Figure 4. Reference and filtered signal electrical response.

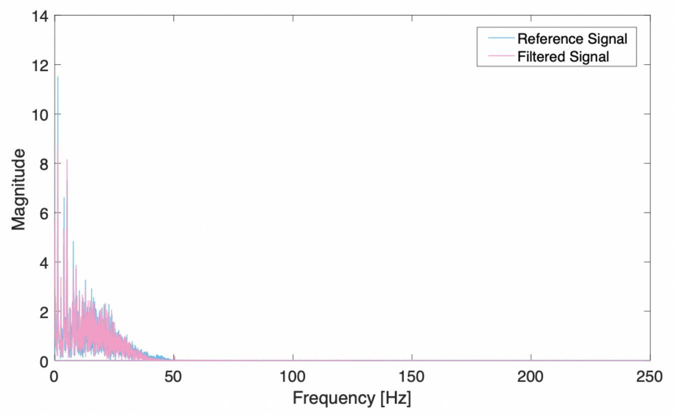

Figure 5. Reference and filtered signal frequency response.

Table 2. SNR and ERR of the signal after passing through each filter project option.

Project Option	**SNR** $[dB]$	**ERR (Normalized)**
First	3.4510	0.3286
Second	4.3666	0.2726
Third	4.0515	0.2350
Fourth	2.5781	0.4168
Fifth	4.0014	0.2624

5. CONCLUSIONS AND FUTURE WORK

The selected filter project applied to the electrical response works efficiently since the SNR of the original signal after passing through the filter project has a difference of the only $0.0549dB$ from the reference signal SNR. Furthermore, the error between the reference and the filtered signal is quite short, proving the project's significance. Note that this argument is valid because the test signal used in the paper is uncorrupted. Another point is the fact that the filter project can be easily implemented by employing a numerical analysis software.

Beyond that, this filter project can be employed to many types of plants' signals, only modifying some parameters. Taking into account f_s between $40Hz$ and $100Hz$ are generally used, it can be assumed considering Nyquist theorem that many plants signals have frequency components lower than $50Hz$, as shown in Parisot and Degli Agosti (2014), Zhao et al. (2015) and Favre and Agosti (2007). Future works include measuring plants' electrical signals when a stimulus is applied with frequency components higher and lower than the power line frequency in order to use both methodologies shown in Figure 2, the one employed in this work and the other suggested in this flowchart. But with a greater degree of reliability because it will be employed genuine plant signals.

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