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Real-time monitoring of de-thorning process in Opunctia Nopalea by using a PILA technique

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It is demonstrated that Photo-acoustic Induced by Laser Ablation (PILA) technique is suitable for the real time control and monitoring of the de-thorning process of nopal vegetable using pulsed laser. Two methods for detection of thorns are proposed; the first one uses the photo-acoustic amplitude and the second one is based in the harmonic composition of photo-acoustic signals. The latter detects clearly, thorns positions, differentiating them from other features that could exist in the nopal cortex. Harmonic composition of photo-acoustic signals also allows defining when thorns have been removed. Finally, it is obtained a characteristic pulse duration that, for the used energy range, maximizes thorns removal.

Keywords: pulsed photo-acoustic, laser cleaning, laser ablation, photo-acoustic monitoring, laser-matter interaction.

INTRODUCTION

Recently, it has been demonstrated the possibility to carry out the de-thorning of Nopal using high-energy laser pulses [1]. This method relies on the strong absorption of the laser pulses by the thorns, both spine and glochids, to reach their ablation. Furthermore, it is possible to laser scan the surface of the Nopal, selectively eliminating the thorns without affecting the rest of the product, due to the low absorption of the laser beam in the cladode cortex.

The latter add significant advantages to this method if compared with the traditional form used to remove thorns, which is basically carried out using knives. These advantages are:

- The best use of the useful volume and the consequently reduction of waste. By using mechanic methods, the waste reach 30% of product [2], while using laser method only the spines are ablated.
- The increase of the useful life of the product from one-two days to more than 15 days. In fact this advantage opens the possibility of long-term commercialization and export of opuntia in fresh form.

Yet, an important aspect to take into account is the productivity of this method, which has to overcome the 40 kg/h reached by the traditional form. Two key factors for increasing the productivity of the de-thorning process are the precise identification of the thorns position over the cladode cortex and the detection of the exact moment when they are completely removed. The control of these two parameters would make possible the automation of the de-thorning process enabling both an increase in the productivity and a reduction in the product affectation.

Photo-acoustic is a standard characterization technique particularly for the spectroscopy of gaseous materials. This technique relies on the acoustic waves generated as consequence of light absorption [3]. During the de-thorning of nopal by laser ablation, a high power laser pulse interacts with the cladode inducing a photo-acoustic signal which may be termed Photo-acoustic Induced by Laser Ablation (PILA). Different photo-acoustic signals are produced depending on whether the laser pulse interacts with the cladode cortex, an areola with thorns or a cleaned areola and consequently much information can be obtained analyzing these signals. The aims of this work are firstly, to study the capabilities of PILA as a monitoring technique to identify when the laser pulse interacts with each of mentioned Nopal features and secondly, to study the dependence of the photo-acoustic (PA) signal intensity on the laser pulse parameters.

For the analysis of the photo-acoustic signal two methods are proposed. The first, and the simplest one, is to compare the amplitude difference of the PA signal. The second is based on the processing of the acoustic signal through the Fast Fourier Transform (FFT), which allows the identification of the frequencies in the spectrum and consequently a better discrimination between thorns, areoles and cortex damages and surface pollutants [4].

1. EXPERIMENTAL SET-UP

Figure 1 shows a diagram of the experimental installation. A Nd:YAG (1064 nm) laser is used to perform the thorns ablation. It operates in free generation regime enabling the variation of the pulse energy, pulse width and the triggering frequency. The laser pulses are directed to the sample through mirrors. The laser beam was focused on the cladode surface with a lens (f=10 cm) producing a spot of 1.5 mm in diameter at the sample surface.

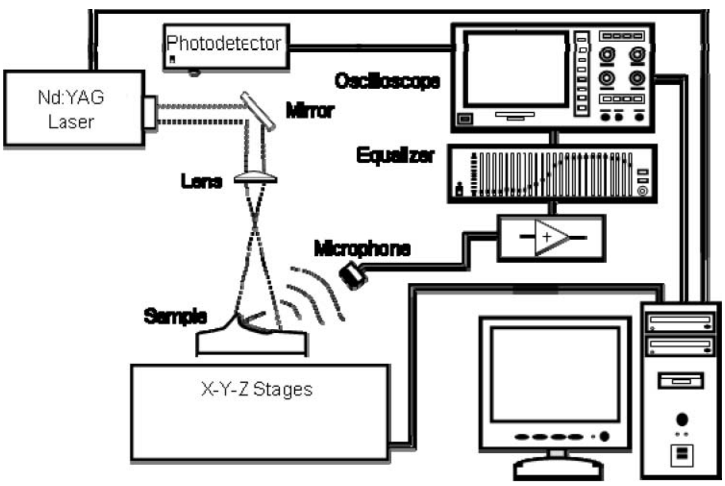

Figure 1. Diagram of the experimental installation

The locations of the samples are adjusted using a PC-controlled x, y, z micro positioning system with step motors. The photo acoustic signal is detected using a capacitive electreto type microphone, which is placed at a distance of 10 cm from the sample. Electric signal coming out of the microphone are fed into a pre-amplifier and from it to a professional audio equalizer that allows selection of frequencies. Finally, filtered PA signal are acquired using a TDS3032 Tektronix oscilloscope and exported as a data file to the computer for further processing.

To synchronize the photo acoustic signal with the laser pulse, a fast response photodetector was used to externally trigger the oscilloscope. Moreover, the photodetector is used to obtain the temporary profile of the laser pulses. In previous experiments [5], it was empirically determined that the most adequate pulse width to reach pulse cleanliness is between 100 and 280 μs; consequently, pulse durations within this range were used, with a separation of 50 μs between pulses. The energy of the laser pulses was changed between 400 and 900 mJ. Data captured in each experiment were processed with a data analysis package, in order to determine their harmonic composition using the Fast Fourier Transform (FFT). As samples, nopal cladodes were selected and cut in 1×1 cm squares, each one including an areole in their center. To be irradiated, they were placed in a Petri dish, which is mechanically locked to the micro positioning system.

2. RESULTS AND DISCUSION

2.1. Laser Ablation of Thorns and Glochids

In principle, the de-thorning process using laser is very simple [1]. The samples are placed on the micro positioning system and moved until they are located in the irradiation zone of the cladode or of the areole. When the elimination of the thorns is needed, successive pulses are applied up to a complete removal, which is easily corroborated by using an optical microscope or, inclusive, by visual inspection.

Figure 2 shows a typical de-thorning sequence. Figure 2a exhibits an areola before it is irradiated. The spines are located at the center of the areola, surrounded by a dense agglomerate of glochids. It is such agglomeration of glochids, which becomes the areola a highly absorbent system [5]. Photograph in figure 2b was captured after several laser pulses. It can be observed that only one spine and some glochids sectors remain. Finally, in figure 2c all the areola is completely cleaned, free of spines, glochids and any remains. An important aspect to be taken into account by the industry is the fact that the crater produced after removing the thorns remains completely sealed preventing the mucilage from flowing out. This is very important since the entrance of bacteria is hindered, and in general, the protection of the product is guaranteed [6].

Figure 2. Images of the de-thorning process: a) Before irradiation; b) After some pulses are triggered; and c) Complete removal of thorns and glochids

2.2. Monitoring of the elimination of thorns by the amplitude of the PA signal

In order to monitor the de-thorning process, two experiments were conducted. The first compares the PA signals produced when the laser pulse falls on the areola and when it falls on the cladode cortex. The second compares PA signals produced by successive pulses on the same areola, up to total thorns elimination.

Results of the first experiment are shown in figure 3. Three different PA signals are presented, one after a laser pulse hits the cladode cortex (3b), another after the 5^{th} laser pulse hits the areola (3d) and one after the 20^{th} laser pulse hits the areola (3c). Dotted line (3a) represents a cleanliness reference level. It is the signal amplitude recorded after a laser pulse hits a clean areola.

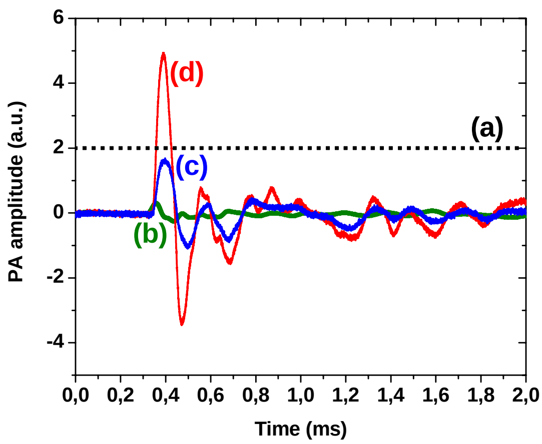

Figure 3. Comparison of the pa signals.
a) Cleanliness reference level; b) PA signal from the cladode; c) PA signal generated by pulse 5 in the areola; and d) PA signal generated by pulse 20 in the areola

It can be observed that the PA signal corresponding to the cladode cortex shows an amplitude well below the reference level, while the PA signal corresponding to the 5^{th} pulse on the areola generates an amplitude that widely surpasses the cleanliness reference level. However, after 20 laser pulses, when the thorns have been removed, the amplitude of the PA signal is below the amplitude marking the cleanliness level. It unequivocally indicates that the thorns were eliminated.

The strong difference between the PA signals produced on the areola with thorns and on the cladode cortex is of great utility to establish a control protocol during the nopal de-thorning process. Monitoring of PA magnitude allows not only knowing when laser pulse is interacting with thorns but knowing when they have been completely removed.

Figure 4 shows results of second experiment, for which laser pulses of 900 mJ and 250 μs of energy and time duration were used, respectively. It can be observed the typical dependence of the PA signal with respect to the number of pulses; practically the first pulse neither causes thorn ablation nor generates a perceptible acoustic signal. During the first pulse a combustion process is generated, which induces darkening of thorns, so increasing their absorption [7]. In the following pulses, the amplitude of the PA signals increases to a maximum value that coincides with the maximum extraction of material, as proven through visual observation and the intense emission of produced plasma.

After few laser pulses, the amplitude of the PA signal decreases as the thorns and glochids of the areola are removed and the amount of absorbing material is reduced. It should be noticed that even though a satisfactory level of cleanliness is reached, the amplitude of the areola PA signal does not decrease enough to be identified as a cladode cortex PA signal. This could be explained if we take into account that the cladode cortex exhibits a different morphology in comparison with the bottom of the crater generated when the thorns are completely removed.

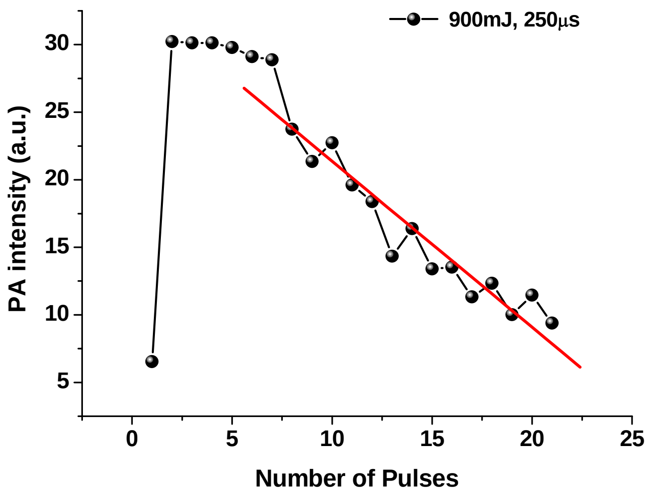

Figure 4. Dependence of the PA signal intensity versus the number of pulses for a pulse energy E=900 mJ. The slope of the linear fit (straight line) to the experimental data in the lineal region is an estimative of the ablation speed

2.3. Optimizing thorns removal

In order to optimize thorns removal it was developed a study of the behavior of thorn ablation process as a function of the laser pulse width and energy. Figure 5 shows the dependence of the photo-acoustic signal maximum on the pulse width, obtained for the second pulse of a series, where the pulse energy was kept constant at 900 mJ. The acoustic signal was measured for three different pulse durations, confirming that the higher signal intensity was obtained for 250 μs.

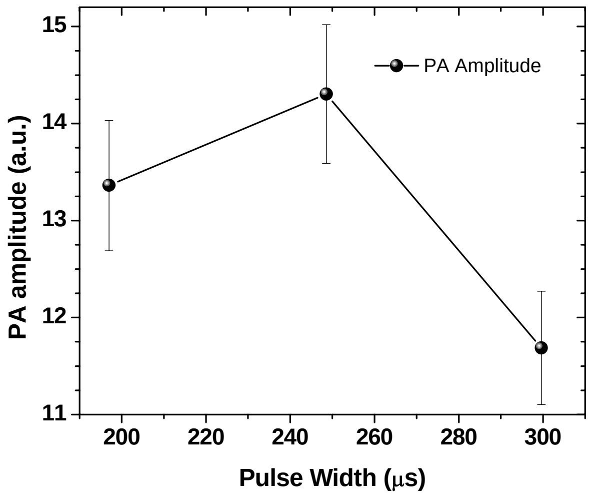

Figure 5. Dependence of the maximum intensity of the acoustic signal with respect to the pulse width

At first sight, this result is astounding if we consider that for constant pulse energy the pulse power increases as pulse width decreases. Such result can be explained using reports of Anisimov and collaborators [7]. They quoted in a simple manner the boundaries between quasi-steady vaporization and explosive vaporization.

When the speed of the vaporization front exceeds the product of the optical absorption coefficient and the thermal diffusivity of the solid, the explosive vaporization or phase explosion can occur. For smaller values of the vaporization speed, occurs the quasi-steady vaporization [7, 8]. Within this range, the speed of the vaporization front is constant and is determined by the conditions of processing atmosphere and the physical properties of the material [9]. It doesn't depend on the incident power density. A constant vaporization speed means that for a characteristic material thickness there will exist a characteristic time (pulse width) in which the energy is transferred optimally to the layer of vaporized material.

In the specific system of the Nopalea glochids, this characteristic thickness is determined by the length of penetration of the radiation in the glochids agglomerate. Each system will have associated a characteristic pulse width. This characteristic penetration length can change from pulse to pulse because the modification in the optical properties of the glochids induced by the action of the previous pulses. In the experiments reported in this work it was observed that the optimal pulse width is around 250 μs.

Once the most convenient pulse width is determined, it was studied the dependence of the ablation speed on the pulse energy, using optimal pulse width. It is worth mentioning, that the speed in this process is inversely proportional to the amount of pulses necessary to remove the thorn i.e. if thorns are removed with lower amount of pulses, then the speed will be higher. Similar graphs as the one presented in figure 4, were obtained for 400, 500, 800 and 900 mJ pulse energy obtaining each ablation speeds from the slopes of the linear fits to the experimental data in the linear region (solid line in figure 4). Results of these calculations are presented in figure 6.

As expected, the ablation speed increases proportionally to the energy, within the studied energy range. Due to experimental reasons, it was not possible to investigate the behavior of the ablation speed beyond 900 mJ, where we speculate that saturation will take place.

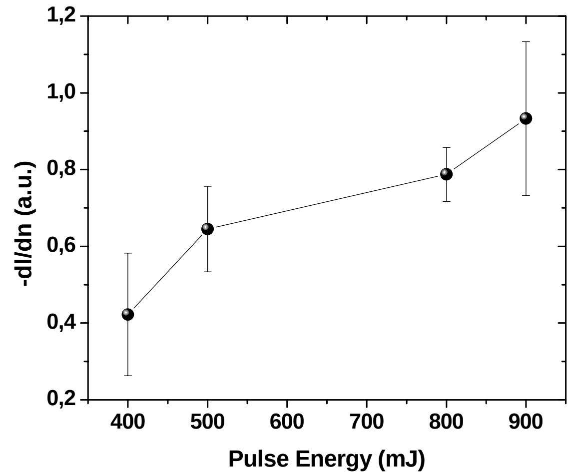

Figure 6. Pulse energy dependence of the ablation speed calculated for a constant pulse width of 250 μs

2.4. FFT spectrum analysis

Although the PA signal amplitude analysis provides suitable information to monitor the de-thorning process, the existence of different impurities or damages on the cladode surface could generate PA signals that are not associated to thorns. Thus, it is important to have a method that indicates the unequivocal presence of the thorn.

A more precise identification alternative is offered by the frequency analysis of the PA signals generated after the laser pulse incidence. Figure 7 shows the FFT spectra of the PA signal generated by both the areole with thorns and the cladode cortex. The amplitude of the shown spectra was normalized, as the cladode cortex PA signals have lower intensity than those of the areola with thorns.

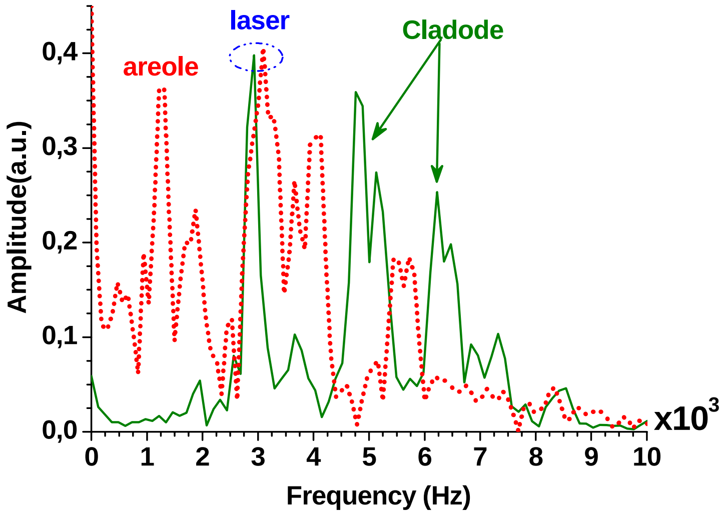

Figure 7. FFT spectra of the photo acoustic signal generated by both the areole with thorns (solid line) and the cladode cortex (dot line), after irradiation with a high energy laser pulse

In both spectra, a band of 2600–3400 Hz is observed, and was associated to the incidence of the laser pulse, because it is detected when it falls on any surface.

The frequency bands observed from 4500–5500 Hz and from 6000–7000 correspond to the cladode cortex.

The pressure wave generated in the areola, caused by the expansion of ablated thorns occurs in a time window whose duration is higher than the period of oscillations generated by the laser pulse at the cladode surface. Frequency bands from 300 Hz to 2200 Hz correspond to this process. Obviously, this band does not appear in the cladode cortex frequency spectrum, because there are different types of material, present on the cortex, being ablated.

Other experiments were conducted to better understand the differences between the areola and cladode cortex spectra in the 4500–8000 Hz frequency region. Considering that the mechanical response of any physical system could be markedly linked to its geometry, a more appropriate comparison would be drawn between an areola with and without thorns.

The three characteristic frequency bands of the areola are from 200 Hz to 2200 Hz, 2600 Hz to 4200 Hz, and 5000 Hz to 6500 Hz. The first frequency band arises from the combustion of thorns; the second band is generated by the action of the laser pulse since it appears regardless of the zone where it is irradiated.

To analyze the third frequency band, was performed a comparison between the spectra captured at different moments of the areola de-thorning. Figure 8 shows the Fourier Transform of the PA signal produced by the 5th pulse, while figure 9 shows the Fourier Transform of the PA signal produced by 20th pulse. In both cases the pulse energy and time duration were 400 mJ and 200 μs, respectively.

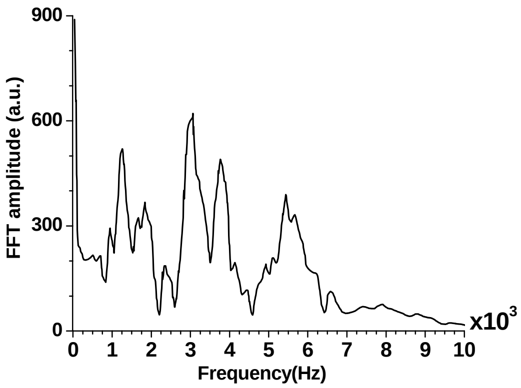

Figure 8. FFT spectrum of the PA signal produced by the 5th pulse using 200 μs pulse duration and 400 mJ energy

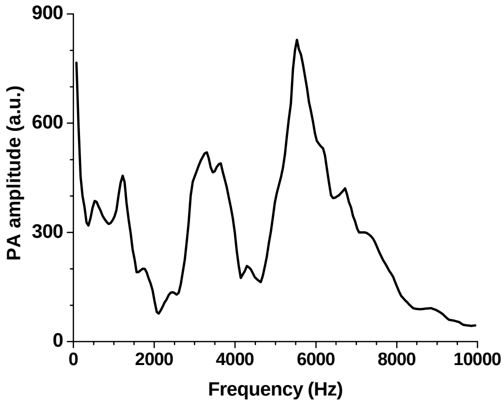

Figure 9. FFT spectrum of the PA signal produced by the 20th pulse using 200 μs pulse duration and 400 mJ energy

When the spectra of the two figures are compared, we can notice that the amplitude of the third frequency band increases as the de-thorning process progresses. If we consider that when successive pulses are applied, the area occupied by the glochids in the diameter of the areola decreases, then the energy that falls directly on the cladode and the de-thorned areola will progressively increase, causing vibration in the 5000 to 6500 Hz frequency band. Thus, we can attribute this frequency band to the cladode vibrations.

CONCLUSIONS

The use of the photo acoustic signal allows the real time control and monitoring of the de-thorning process of the nopal vegetable. The amplitude of the signal allows a first approximation of the detection of the thorns and the verification of the level of cleanliness. Furthermore, the analysis of the frequency spectrum allows differentiating between areolas with thorns and other possible absorbent feature on the cladode cortex as well as a more precise determination of the complete thorns removal.

During the interaction of the laser pulse with the thorns, three processes regarding the generated PA signal are recognized: the thermal expansion due to the action of the laser pulse; the expansion and combustion of the extracted material; and the vibrations generated in the surface of the nopal cladode. Each of these processes produces different characteristic frequencies.

It was possible to recognize a characteristic pulse duration (250 μs), at which the removal process is maximized, for the specific used Nopal cladodes and energy range.

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