INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 17, Issue 3, 2026: 879-894 www.ijcs.ro

DOI: 10. 36868/IJCS.2026.03.04

NANOSECOND PULSED LASER CLEANING OF BURIAL CRUSTS FROM ANCIENT PERUVIAN COTTON TEXTILES: AN INITIAL INVESTIGATION INTO THE OPTIMUM PARAMETERS WITH PHOTOACOUSTIC ASSESSMENT

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Abstract

This study evaluated the effectiveness of the pulsed photoacoustic technique in determining optimal laser fluence values for the laser cleaning of an ancient Peruvian archaeological textile. Scanning electron microscopy (SEM), diffuse reflectance spectroscopy, and atomic composition analysis confirmed the removal of dust and dirt layers adhered to the textile surface. Nanosecond-pulsed laser radiation at 532 nm and 1064 nm was directed onto the surface of the archaeological textile. During laser cleaning, the textile was manually displaced using a bidimensional micrometric translation stage. The photoacoustic technique allowed for the determination of the laser ablation threshold for dust and two distinct layers of adhered dirt. Laser cleaning at 532 nm with a fluence of 300 mJ/cm² was found to be optimal; however, it was not effective in removing salt deposits adhered to the textile surface. The effectiveness of laser cleaning was compared with conventional methods such as mechanical and wet cleaning. The results demonstrated that the 532 nm laser cleaning method successfully produced a clean archaeological textile without yellowing or morphological modifications to the cotton fibers.

Keywords: *Nd:YAG laser, Pulsed photoacoustic, Archaeological textiles, Cotton.*

Introduction

Ancient textiles represent a significant part of museum collections worldwide, providing valuable evidence of social history, international trade, agricultural development, artistic trends, and technological advancements. Consequently, preserving these textiles and passing them on to future generations is essential [1]. Pre-Hispanic Andean textiles, composed of organic materials, are among the best-preserved artifacts in archaeological records. Evidence indicates the use of cultivated cotton fibers (identified as Gossypium barbadense), which exhibit a wide range of natural colors, including lilac, beige, and brown, as well as diverse shades [2]. These textiles date back over 7,000 years, with some of the oldest and most intricate examples found in the Moche and Chicama valleys along Peru's northern coast [3], [4].

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Their preservation has been primarily attributed to the arid conditions of the Peruvian coast and its low annual precipitation [5]. Due to their historical, economic, symbolic, and political significance, pre-Hispanic textiles have been the focus of extensive research by archaeologists and specialists [6-9].

The removal of surface dirt from textiles remains one of the most challenging aspects of textile conservation. Various cleaning methods have been developed, including dry (mechanical) cleaning [10] and wet cleaning (which involves washing the textiles) [11]. Mechanical cleaning, the most common approach, is typically performed using soft brushes or vacuuming. However, it is often insufficient for removing particles with strong adhesion to the fibers. In exceptional cases, aqueous (wet) cleaning is conducted, although this method carries the risk of not only removing dirt but also erasing valuable historical evidence embedded within the textile.

Over the past two decades, laser cleaning has gained significant traction in the restoration of artworks and historical objects made from a variety of materials, including metals [12], sandstone [13], glass [14], marble [15], silk [16], wool [17], [18] and wood [19], [20]. However, in the specific case of cotton textile conservation-restoration, studies remain scarce.

Sutcliffe et al. [21] conducted a series of tests using an Nd:YAG laser at wavelengths of 1064, 532, and 266 nm to clean both new and naturally aged cotton textiles. They reported that a textile's resistance to laser radiation depends on its degree of aging, with older textiles being more susceptible to damage. Additionally, they observed surface yellowing during laser cleaning, which was more pronounced at 1064 nm, whereas it was minimal at 532 nm. They attributed this effect to excessive fiber heating or residual dirt during the laser ablation process. Furthermore, they reported laser fluence thresholds for inducing damage in clean cotton: 2.5 to 3.0 J/cm² for 1064 nm and 4.3 to 4.9 J/cm² for 532 nm.

Bloisi et al. [22] examined the impact of 532 nm Nd:YAG laser radiation on clean cotton samples and confirmed surface yellowing at a fluence of 0.6 J/cm². They further reported that at 2 J/cm², fiber breakage was observed in the majority of the cotton fibers, indicating structural damage at higher energy levels.

Belli et al. [23] investigated the irradiation of cotton textiles using a KrF excimer laser at 248 nm, exploring fluences ranging from 40 to 1600 mJ/cm² with pulse counts between 1 and 10000. Their study identified various forms of laser-induced damage, including darkening, yellowing, burning, and hole formation. They emphasized that effective laser cleaning requires an optimal balance between energy density and pulse number to prevent structural deterioration. Under carefully controlled irradiation conditions, they demonstrated that this approach holds promise for contaminant removal without compromising the integrity of the textile, as confirmed through scanning electron microscopy (SEM) analysis.

It is important to note that laser cleaning has also been applied to excavated metal artifacts, where corrosion and soil layers are typically removed [24], [25]. In such cases, elements associated with corrosion products, such as Cl, S, and O, have been identified, along with Si originating from dirt layers.

The pulsed photoacoustic technique has been employed to monitor the cleaning process and assess potential damage to laser-irradiated surfaces [26], [27]. The photoacoustic effect is defined as the generation of acoustic waves by a material that absorbs laser radiation. The intensity of the acoustic signal is proportional to the applied laser energy and the absorption coefficient of the interacting materials. Since the photoacoustic properties of contaminants and the underlying substrate differ, the amplitude of the photoacoustic signal varies throughout the laser cleaning process until the laser reaches the substrate [27]. Furthermore, pulsed photoacoustics has been proposed in combination with optical imaging to monitor laser cleaning of stonework [28].

Before proceeding with laser cleaning, it is crucial to establish optimal laser parameters for each specific material, including wavelength, fluence, pulse count, and repetition rate, to ensure effective contaminant removal without compromising the integrity of the original object. This necessitates characterizing the physical properties of the material and its interaction with laser radiation. One key property is the laser ablation threshold, which must be determined for both the contaminants to be removed and the material to be preserved (in this case, cotton fibers).

Pulsed photoacoustics, based on detecting acoustic signals in the audible range (20 Hz–20 kHz) using a microphone, has proven to be a valuable tool for analyzing laser ablation on various materials, including metals [29], polystyrene, glass, paper, and thin films [30]. However, to our knowledge, its potential for determining optimal laser fluence values for the cleaning of archaeological textiles has not been previously explored. Furthermore, based on our review of the literature, no prior studies have applied pulsed photoacoustics to investigate the interaction between high-power pulsed lasers and archaeological textiles. This work addresses this gap by demonstrating the use of pulsed photoacoustics as a method to establish safe and effective laser parameters for textile conservation.

In this research, laser cleaning was performed on fragments of a Peruvian textile over 3000 years old. The cleaning process utilized a nanosecond Nd:YAG laser, and the effects of various parameters, including energy, wavelength, repetition rate, and pulse count, were evaluated. The ablation thresholds of dirt layers adhered to the textile surface were determined using the pulsed photoacoustic technique. The primary objective was to remove surface contaminants while preserving the integrity of the textile fibers. Additionally, laser cleaning was compared to mechanical and wet cleaning methods to assess its effectiveness in textile conservation.

Experimental part

Figure 1 presents the morphology of textile fragments recovered during excavations at the archaeological site of Gramalote, located in the district of Huanchaco, province of Trujillo, on the northern coast of Peru [31]. Absolute radiocarbon dating suggests that the Gramalote site was occupied between 1500 and 1200/1100 cal. BC [31].

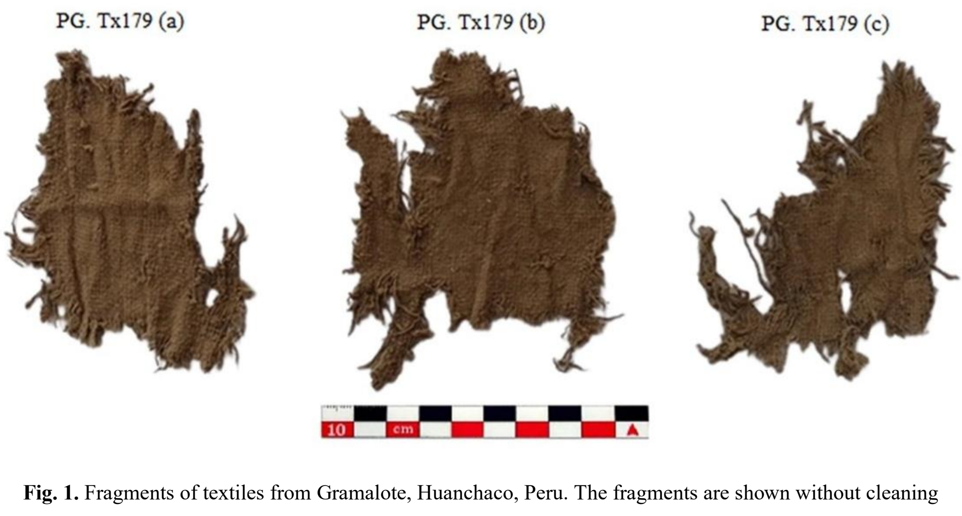

Fig. 1. Fragments of textiles from Gramalote, Huanchaco, Peru. The fragments are shown without cleaning

Special care was taken during sample selection to ensure that the textiles originated from secure archaeological contexts and belonged to the same original piece, guaranteeing uniform burial conditions and consistent technical-structural characteristics. The three textile fragments were composed entirely of cotton fiber, with dimensions not exceeding 10 cm per side. None of these fragments had undergone prior cleaning; therefore, dust and dirt remained adhered to their surfaces. The textile structure, specifically the interlacing of warp and weft threads, was considered in the selection process. These fragments exhibit irregular shapes, frayed edges, and some broken internal threads. Their coloration is predominantly brown with slight gray stains.

The first fragment in figure 1 (PG.Tx179(a)) was selected for cleaning tests using a Q-switched Nd:YAG laser, while the second fragment (PG.Tx179(b)) underwent wet cleaning, and the third fragment (PG.Tx179(c)) was subjected to mechanical cleaning. For mechanical cleaning, the textile surface was protected with a plastic mesh, and a micro-suction vacuum cleaner was used. Wet cleaning was performed via immersion in deionized water with neutral soap. The textile fragment was placed between two layers of tulle, with the entire contour secured using thread stitches to prevent displacement during washing. After the process, excess water was removed with filter paper, and the fragment was left to dry at room temperature.

After more than 3000 years of burial, layers of dust, dirt, and salts accumulated on the surface of the cotton fibers. Figure 2 presents SEM micrographs of the archaeological textile before laser cleaning, revealing micrometric dirt particles (approximately 5 μm) adhered to the cotton microfibers, along with agglomerates ranging from 200 μm to 500 μm. The cotton microfibers exhibited diameters between 15 μm and 25 μm, which align with the values reported by Valverde et al. [32] for Peruvian cotton microfibers.

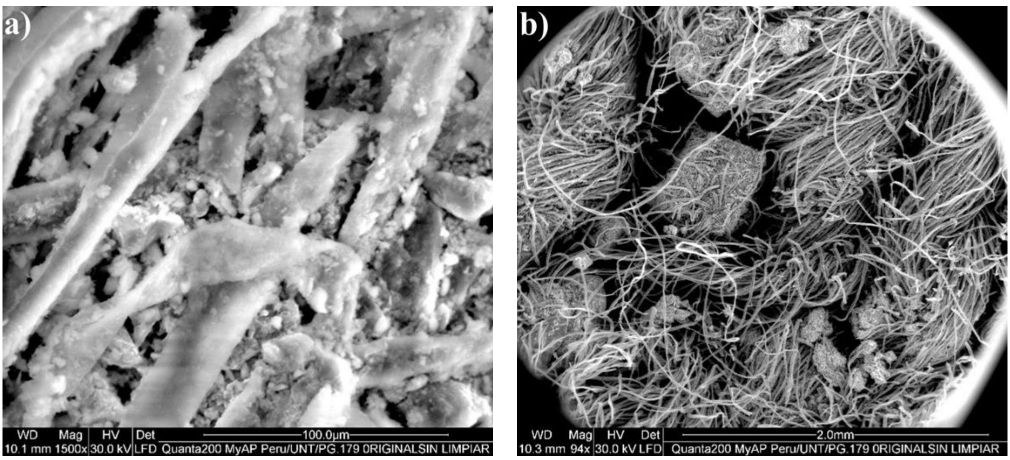

Fig. 2. SEM microphotographs of a fragment of the textile before the cleaning process, with a magnification of (a) 1500× and (b) 94×

Figure 3 illustrates the experimental setup used to determine the ablation thresholds and perform laser cleaning of the textile. A Q-switched Nd:YAG laser (Q-smart 450, Quantel) was used, which can operate at pulse repetition frequencies of up to 10 Hz, with a pulse duration of 4 ns. The laser could be operated at wavelengths of 1064 nm or 532 nm (first or second harmonic). The textile fragment was mounted on a manually operated bidimensional micrometric stage controlled by two micrometer screws for movement in perpendicular directions. Laser radiation was directed perpendicularly onto the textile surface using a high-reflectance mirror (for 1064 nm and 532 nm radiation). A beam splitter, combined with a Newport 1936 R energy meter equipped with a pyroelectric sensor, was used to monitor the energy incident on the textile. Additionally, an electret-type microphone was positioned 10 cm from the irradiated area to detect acoustic signals generated by laser-textile interactions. The microphone was connected to a Tektronix MSO 2024 B digital oscilloscope (200 MHz), which was linked to a computer for signal analysis. During the laser cleaning of the archaeological textile, contaminants such as dust and dirt were expelled, and a vacuum cleaner was positioned near the working area to collect them.

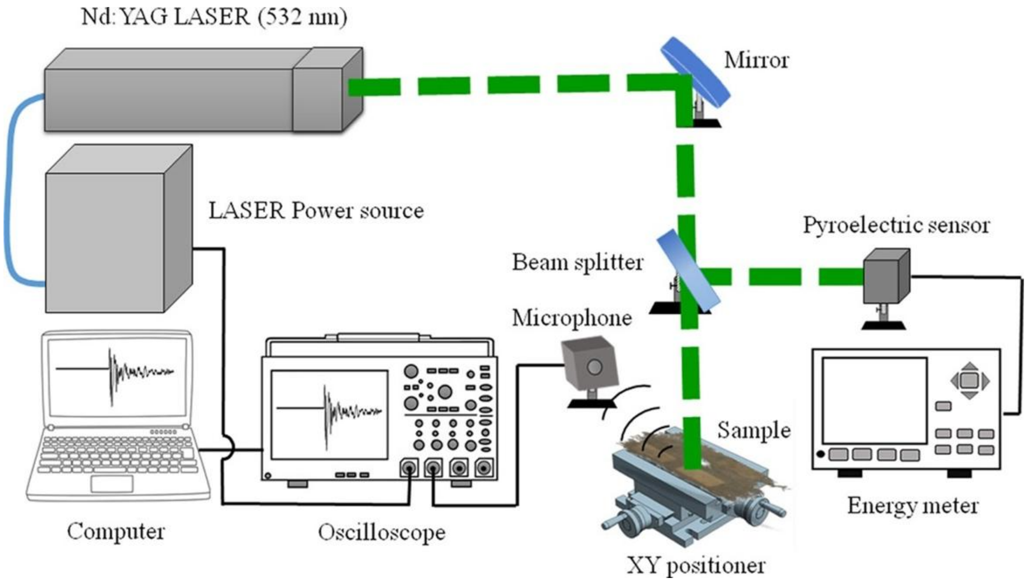

Fig. 3. Experimental setup for the determination of laser ablation thresholds through photoacoustic signal analysis and for laser cleaning of the archaeological textile

To determine the laser fluence, the ratio between laser pulse energy and the area of the imprint left on laser-sensitive paper was calculated. Photosensitive paper was used because, at low fluences (energy per unit area), the laser-affected area on the textile surface was not visually discernible. For each laser fluence value, four acoustic signals (produced by four laser pulses) were averaged using an oscilloscope. By progressively increasing laser energy and analyzing the ablated area on photosensitive paper for each energy level, fluence values were systematically determined.

Acoustic signals were analyzed as a function of laser fluence to estimate the ablation thresholds of contaminant layers (dust and dirt) adhered to the threads of the PG.Tx179(a) textile and to identify an optimal laser fluence for the laser cleaning of the archaeological textile.

For laser fluences below the textile's ablation threshold, acoustic signals were analyzed based on the number of pulses to determine the number of laser pulses required for effective cleaning.

Throughout the cleaning process, visual examinations and photographic documentation were conducted in specific areas using a portable digital microscope (Zarbeco, MiScope) to assess changes after each laser radiation treatment. Additionally, reflectance spectra were obtained from different working areas using a fiber optic diffuse reflectance spectroscopy module consisting of a Thorlabs QTH-10 tungsten halogen lamp, a mini-spectrometer (HR4000, Ocean Optics), and a bifurcated optical fiber. Reflected light from the sample surface was collected at a 45° angle and directed to the spectrometer for analysis using Ocean View 2.0 software. Since the illuminated circular area had a diameter of 6 mm, data were collected from 10 different sectors of the sample and averaged.

Micrometric observations of the morphology of the analyzed areas were performed using scanning electron microscopy (SEM), and elemental composition was determined through energy-dispersive X-ray spectroscopy (EDS). A Quanta 200 SEM (operating at 30 kV) with a backscattered electron detector (SSD) in low-vacuum mode was used for this analysis.

Results and discussion

Figure 4 illustrates the variation in the peak-to-peak amplitude of the acoustic signal as the laser fluence increased. The lower inset shows an amplification of the initial experimental data, while the upper inset displays the acoustic signal corresponding to a laser fluence of 300 mJ/cm². A wavelength of 532 nm and a repetition rate of 1 Hz were used for the Nd:YAG laser.

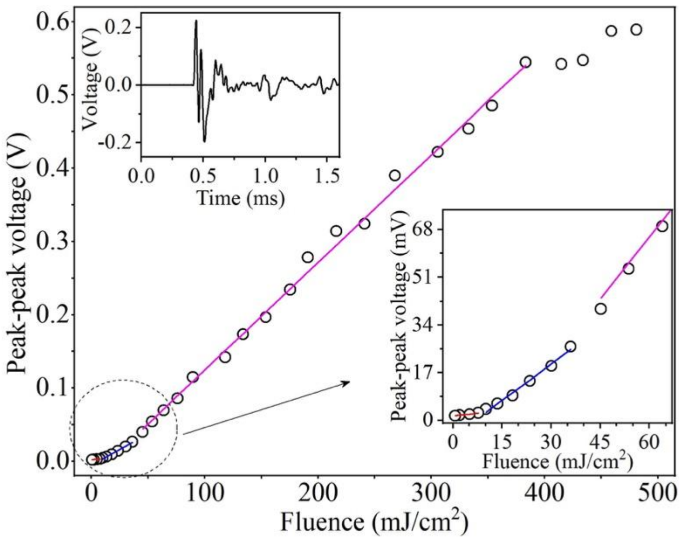

Fig. 4. Amplitude of the acoustic signal (peak-to-peak voltage) as a function of laser fluence for the Nd:YAG laser at 532 nm with a pulse repetition rate of 1 Hz. The lower inset magnifies the initial experimental data, while the upper left inset displays the acoustic signal corresponding to a laser fluence of 300 mJ/cm².

At low laser fluences, ranging from 0.68 to 7.73 mJ/cm², a linear increase in the amplitude of the acoustic signal was observed. A similar linear trend was observed in the fluence range from 10.13 to 36.04 mJ/cm². Likewise, another linear trend was found in the fluence interval from 45.21 to 383.23 mJ/cm². The three fitted lines yielded a Pearson linear correlation coefficient greater than 0.99, and their slopes increased as the laser fluence transitioned from one fluence interval to the next. The corresponding slope values were $(1.46 \pm 0.09) \times 10^{-4}$ V·cm²/mJ, $(8.59 \pm 0.46) \times 10^{-4}$ V·cm²/mJ, and $(14.7 \pm 0.24) \times 10^{-4}$ V·cm²/mJ, respectively. The presence of three distinct linear regions suggests the laser ablation of three contaminant layers that formed over the years on the archaeological textile. These layers are proposed as follows: (1) an outer layer composed of dust, (2) an intermediate layer of moderately adhered dirt, and (3) a layer of tightly bound dirt and salts.

For the last four experimental data points (fluences above 383.23 mJ/cm²), changes in the behavior of the acoustic signal were observed, suggesting damage to the cotton microfibers. At fluences exceeding 383 mJ/cm², visible textile damage was evident, as its coloration turned black, and when multiple pulses were directed at the same spot, a hole formed.

As an approximation, the following laser ablation thresholds are proposed: the ablation threshold of dust must be lower than 0.68 mJ/cm²; the ablation threshold of the moderately adhered dirt layer is 8.93 mJ/cm², calculated as (7.73 + 10.13)/2; the ablation threshold of the strongly adhered dirt layer is 40.63 mJ/cm², calculated as (36.04 + 45.21)/2; and the ablation threshold of the archaeological textile made of cotton is 399.08 mJ/cm², calculated as (383.23 + 414.92)/2. Our damage threshold value for cotton fibers in the archaeological textile is lower than the values reported by Sutcliffe et al. [20] and Bloisi et al. [21]. This difference is likely due to the fact that they reported damage thresholds for clean and well-preserved cotton, whereas in our study, laser ablation was performed on an excavated archaeological textile that was both ancient and covered with dirt.

To perform laser cleaning of the archaeological textile, it is necessary to select a laser fluence within the third linear fit (the line with the highest slope), as this ensures the removal of dust, moderately bound dirt, and strongly bound dirt from the textile's surface. Additionally, a minimum number of laser pulses must be considered, which depends on the fluence value. However, it is important to note that any fluence within the third interval remains below the ablation threshold of the archaeological textile; therefore, overexposure to laser radiation would not cause damage to the material.

Figure 5 shows different laser ablation zones on the textile surface.

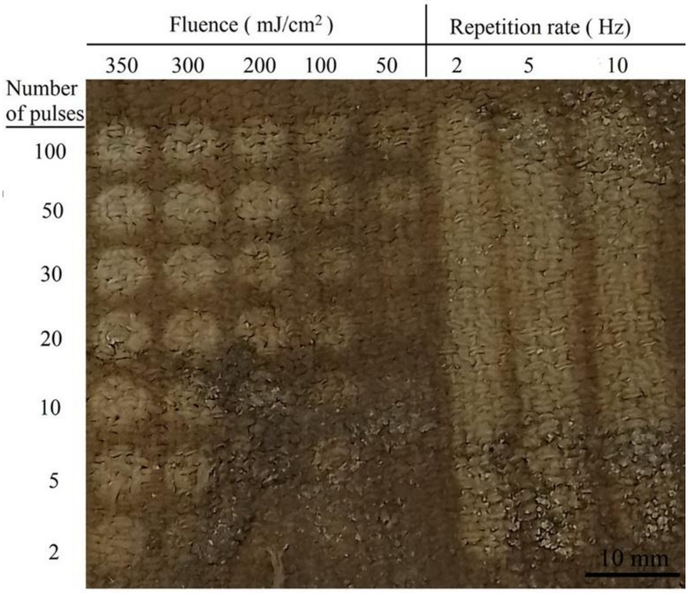

Fig. 5. (Left) Textile areas irradiated with 532 nm laser pulses at different fluences and pulse numbers. (Right) Three cleaned textile lines resulting from a unidimensional laser sweep at a 300 mJ/cm² fluence and three different pulse repetition rates of the Nd:YAG laser. Along each laser sweep line, at least 30 Nd:YAG laser pulses were applied at each position

The left side of figure 5 presents circular ablation zones obtained by considering different numbers of laser pulses and various laser fluence values within the fluence range from 45.21 to 383.23 mJ/cm². The ablation areas are circular, and their diameters depend on the laser fluence due to the Gaussian intensity profile of the Nd:YAG laser. Visually, it is evident that at lower fluences, a higher number of laser pulses is required compared to higher fluences to achieve a clean circular area. Additionally, it is confirmed that the laser ablation threshold of the strongly adhered dirt on the archaeological textile is lower than 50 mJ/cm².

The right side of figure 5 presents three linear laser cleaning sweeps performed at a laser fluence of 300 mJ/cm² with pulse repetition rates of 2, 5, and 10 Hz, respectively. For each adjacent laser cleaning position along the three laser ablation lines, a minimum of 30 pulses from the Nd:YAG laser was applied. Varying the pulse repetition rate (2, 5, or 10 Hz) and performing multiple cleaning sweeps along the same line did not produce significant differences in the appearance of the archaeological textile. This confirms that, once the dust and dirt layers are removed, prolonged exposure of the textile to laser radiation does not cause damage, as the laser fluence of 300 mJ/cm² is below the ablation threshold of the archaeological textile.

During the laser cleaning process, an observer could hear the sound generated by laser ablation and visually detect the ejection of contaminants (dust and dirt rising from the textile surface). The sound intensity gradually decreased; once the textile was clean, no sound was distinguished from the laser-irradiated area, nor was any material ejection observed from the surface of the archaeological textile.

The pulsed photoacoustic technique was used to determine the minimum number of laser pulses required to clean the PG.Tx179(a) textile fragment. Figure 6 illustrates the decrease in the amplitude of the acoustic signal (peak-to-peak voltage) as the number of laser pulses increased, for a laser wavelength of 532 nm and a fluence of 300 mJ/cm².

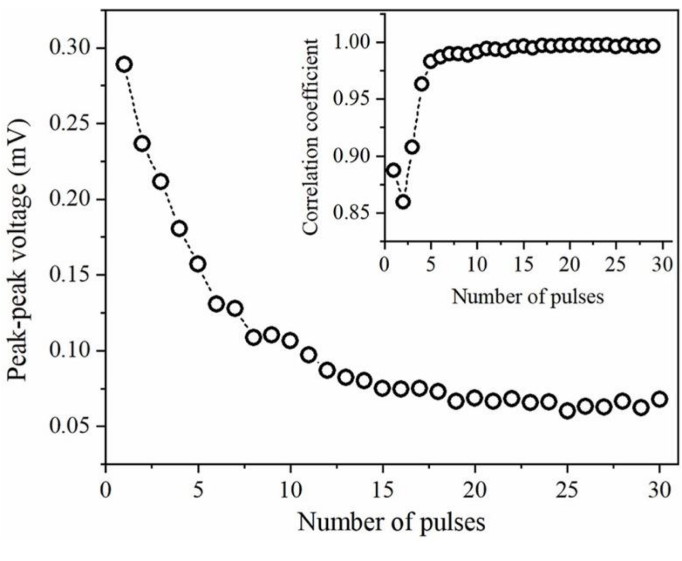

Fig. 6. Amplitude of the acoustic signal (peak-to-peak voltage) as a function of the number of laser pulses. A wavelength of 532 nm and a fluence of 300 mJ/cm² were used for the Nd:YAG laser. The inset shows the variation in correlation values by comparing each acoustic signal with the one corresponding to laser pulse number 30

The amplitude changes in the acoustic signal were significant during the first 20 pulses and then stabilized, showing no substantial variations. Therefore, at least 20 laser pulses were necessary to remove dust and dirt particles adhered to the textile. The inset in Figure 6 presents the correlation analysis of the acoustic signals as a function of the number of laser pulses. In this analysis, the shape of the signals was compared to a reference signal, where all acoustic signals were correlated with the signal corresponding to a laser pulse count of 30. Significant changes were observed in the correlation coefficient values during the first 20 laser pulses, after which the coefficient remained approximately constant.

Based on these findings, at a laser fluence of 300 mJ/cm², a minimum of 20 laser pulses applied to a fixed point is required to remove a considerable amount of dust and dirt, resulting in a localized area of the textile that can be considered clean.

As reported by Lu et al. [33], Bilmes et al. [14], and Tserevelakis et al. [26], the acoustic signal decreases as the number of laser pulses increases during laser cleaning monitoring. At the beginning of the laser cleaning process, the amplitude of the acoustic wave reflects the level of contamination on the surface, and as the dirt is removed, the amplitude of the acoustic signal tends to decrease.

Figure 7 presents the three fragments of the archaeological textile after undergoing the three proposed cleaning methods: laser cleaning, wet cleaning, and mechanical cleaning, respectively. The left side of Figure 7 illustrates the effect of the Nd:YAG laser wavelength (1064 and 532 nm) on the final visual appearance of the archaeological textile (PG.Tx179(a) fragment) after laser cleaning.

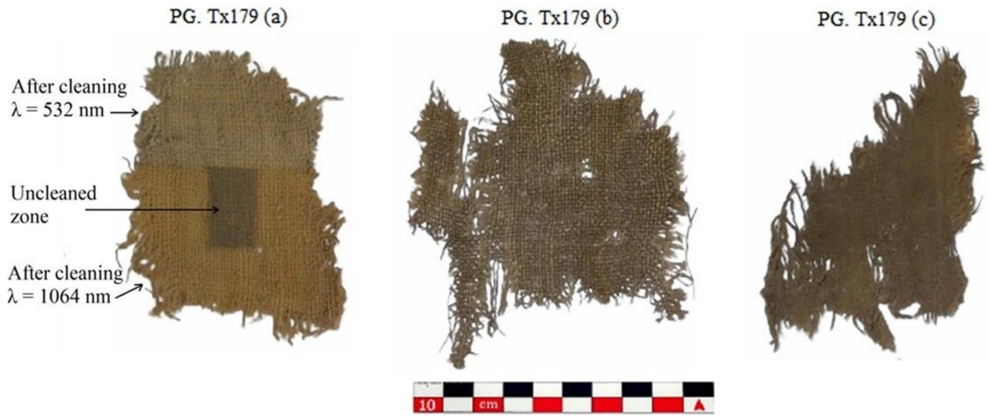

Fig. 7. Photographs of the textile fragments cleaned using the three methods considered in this study. On the left, PG.Tx179(a) was cleaned with pulsed laser radiation from an Nd:YAG laser. In the center, PG.Tx179(b) underwent wet cleaning, and on the right, PG.Tx179(c) was subjected to mechanical cleaning.

The visual effects of laser cleaning varied depending on the wavelength used. Three areas of the textile are shown: one cleaned using a 532 nm Nd:YAG laser, another cleaned using a 1064 nm Nd:YAG laser, and one that was not subjected to laser cleaning. The laser-ablated areas were obtained by performing multiple back-and-forth laser cleaning sweeps at a fluence of 300 mJ/cm² and a repetition rate of 5 Hz for the Nd:YAG laser pulses. The area cleaned with a 532 nm wavelength exhibited a beige tone, closely resembling the result obtained with wet cleaning. In contrast, the area cleaned with a 1064 nm wavelength showed a color shift (yellowing) of the threads. These results are consistent with those reported by Sutcliffe et al. [20], who described that laser cleaning at λ = 1064 nm alters the thread color, whereas cleaning at λ = 532 nm does not cause significant color changes. Therefore, it is proposed that laser radiation at λ = 532 nm is suitable for cleaning excavated cotton textiles. However, as will be discussed later, laser radiation was unable to remove salt crystals adhered between the textile threads.

To further assess the cleaning options for the archaeological textile, wet cleaning was also performed. Wet cleaning (PG.Tx179(b) fragment) was the most effective method for dirt removal, as no dust or dirt particles were detected, and salt clusters were significantly reduced. The cleaned textile surface exhibited a beige color alternating with gray areas, which likely represented the original color of the archaeological cotton fibers. However, wet cleaning caused fraying and separation of the threads, altering the original arrangement of the textile's fibers.

In contrast to wet cleaning, mechanical cleaning only removed loosely adhered dust and dirt particles, leaving behind significant amounts of embedded microparticles of dirt and salts. No substantial changes were observed in the visual appearance of the textile.

To better understand the effect of the Nd:YAG laser wavelength on laser cleaning, Figure 8 presents the diffuse reflectance of the same three areas of the archaeological textile (fragment PG.Tx179(a)) previously described in Figure 7: one cleaned using a wavelength of 532 nm, another cleaned using a wavelength of 1064 nm, and one that was not subjected to laser cleaning. Due to the removal of dust and dirt from the surface, the cleaned textile exhibited higher reflectance compared to the untreated textile across most of the visible electromagnetic spectrum and part of the near-infrared region. Additionally, in nearly the entire range shown in Figure 8, the highest reflectance was observed in the area cleaned with the 532 nm Nd:YAG laser, suggesting a greater degree of cleanliness.

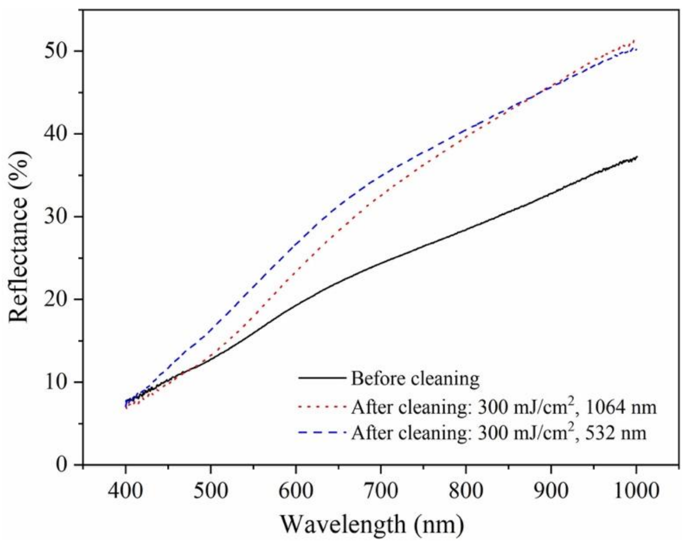

Fig. 8. Diffuse reflectance spectra comparing three areas of the archaeological textile: one cleaned with 532 nm laser radiation (second harmonic of the Nd:YAG laser), another cleaned with 1064 nm laser radiation (first harmonic of the Nd:YAG laser), and an untreated area that was not exposed to Nd:YAG laser radiation.

Figure 9 presents SEM images of the archaeological textile fragments subjected to different cleaning processes. In figure 9a, corresponding to fragment PG.Tx179(c) after mechanical cleaning, a large amount of micrometric dirt particles and salts remain adhered to the cotton fibers. Additionally, the characteristic twisted ribbon-like morphology of the cotton fibers is not clearly visible.

In figure 9b, corresponding to fragment PG.Tx179(b) after wet cleaning, a significant removal of dirt and salt particles initially adhered to the fibers is observed. Furthermore, the twisted ribbon-like structure of the cotton fibers is clearly distinguishable.

Figures 9c and d show different areas of fragment PG.Tx179(a) cleaned by laser ablation using an Nd:YAG laser operated at wavelengths of 1064 nm and 532 nm, respectively. The images reveal a significant removal of dirt adhered to the textile, with no observable modifications in the morphology of the cotton fibers. This confirms that the selected laser fluence for the cleaning process was appropriate.

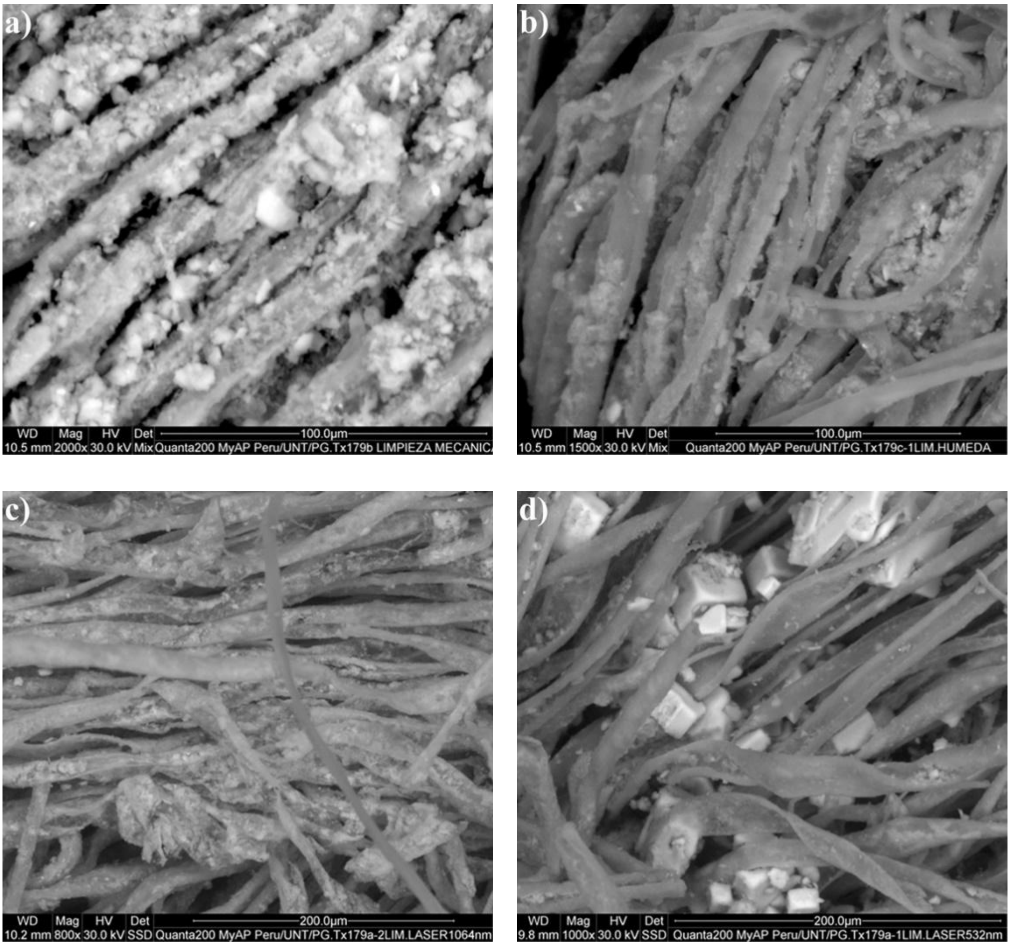

Fig. 9. SEM microphotographs of textile fragments after a cleaning method: (a) mechanical cleaning, (b) wet cleaning, (c) laser cleaning (λ = 1064 nm, 300 mJ/cm²), and (d) laser cleaning (λ = 532 nm, 300 mJ/cm²).

Visual analysis suggests that the cotton fibers were cleaned more effectively when the laser was operated at 532 nm. However, at a laser fluence of 300 mJ/cm², neither wavelength was effective in removing the salts adhered to the textile fibers. To further investigate the feasibility of laser cleaning for salt removal, additional tests were performed using fluences higher than 300 mJ/cm² but still below the ablation threshold of the archaeological cotton textile. Nevertheless, the salts remained on the fibers and could not be removed.

Atomic composition analysis using energy-dispersive X-ray spectroscopy (EDS) allowed for the identification of salts adhered to the archaeological textile. A microanalysis of the salts presents in the textile, similar to the crystals shown in Figure 9(d), revealed the presence of calcium sulfate, calcite, and halite.

Table 1 summarizes the weight percentages of the elements identified through EDS. The elemental percentages after the different cleaning processes were compared to those before cleaning.

Table 1. Results of the SEM-EDS analysis, referring to the weight percentages of the elements identified before and after different cleaning processes

	Weight percentage (wt %)												
	C	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe
Before cleaning	31.9	43.3	1.2	1.7	2.7	5.6	0.3	1.1	3.9	1.6	3.6	0.1	2.9
After mechanical cleaning	33.7	42.1	0.9	1.5	2.9	6.4	0.5	1.1	3.2	1.5	3.6	0.1	2.6
After wet cleaning	52.1	40.3	0.3	0.5	0.8	1.4	0.4	0.6	0.0	0.5	1.9	0.1	1.1
After laser cleaning (λ = 532 nm)	34.9	43.3	2.5	1.2	1.8	3.7	0.3	1.1	5.5	1.2	2.9	0.1	1.7
After laser cleaning (λ = 1064 nm)	32.7	44.7	1.1	1.9	2.5	4.8	0.4	1.4	3.2	1.4	3.5	0.1	2.3

During mechanical cleaning, only minor variations in the elemental percentages were observed, indicating that no significant changes occurred during this process, as corroborated by the SEM micrographs.

In wet cleaning, a reduction in the percentage of most identified chemical elements was observed. However, there was a significant increase in the carbon percentage, which is the primary component of cotton cellulose. This suggests the removal of a substantial amount of dirt and salt particles adhered to the cotton fibers. The greatest reduction in the elemental percentages associated with salts was achieved through wet cleaning.

Regarding laser cleaning using the 532 nm wavelength of the Nd:YAG laser, significant reductions were observed in the percentages of several elements commonly found in dirt (Fe, Ti, K, P, Si, Al and Mg). However, these reductions did not reach the levels achieved with wet cleaning. The percentages of chlorine and sodium increased, indicating that laser cleaning effectively removed dust and dirt particles adhered to the cotton fibers but was ineffective in removing halite crystals, which were initially covered by dirt.

For laser cleaning at a wavelength of 1064 nm, changes were also observed in the percentages of elements commonly found in dirt (Fe, Ti, K, P, Si, Al and Mg); however, these changes were less pronounced than those observed with laser cleaning at 532 nm.

Conclusions

The analysis of acoustic signals generated during the laser ablation of dirt layers adhered to the surface of an archaeological textile, detected using an electret microphone, enabled the determination of the ablation thresholds for these layers. Additionally, it allowed for the identification of optimal laser fluence values and the minimum number of laser pulses required for effective textile cleaning.

The study also demonstrated that, as long as the laser fluence remained below the damage threshold of the archaeological cotton fabric, the pulse repetition rate of the Nd:YAG laser (2, 5, and 10 Hz) had no significant effect on the final appearance of the textile. Moreover, multiple laser cleaning passes did not alter its structure, ensuring the preservation of its integrity throughout the process.

Laser cleaning at a wavelength of 1064 nm induced noticeable yellowing of the textile, whereas cleaning at 532 nm did not cause such discoloration. While mechanical cleaning only removed loosely adhered dust and dirt, wet cleaning was more effective in eliminating dust, dirt, and salts. However, the latter method caused fiber fraying and thread separation, altering the original structure of the textile. Although laser cleaning at 532 nm effectively removed dirt without inducing yellowing, it was not sufficient to eliminate salt crystals adhered to the fibers.

These findings highlight the suitability of 532 nm laser radiation for the cleaning of archaeological textiles, as it provides effective dirt removal while preserving the textile's original appearance. Furthermore, the study demonstrates the effectiveness of the photoacoustic technique, utilizing an electret microphone, in determining optimal laser fluence values and the minimum number of laser pulses necessary to achieve an archaeological textile that can be considered clean.

Additionally, scanning electron microscopy (SEM) confirmed the removal of dirt particles, while atomic composition analysis reinforced these findings by verifying the reduction of elements associated with soil contamination. The combination of these analytical techniques provides valuable insight into the potential of laser cleaning as a non-invasive method for the conservation of ancient textiles.

Acknowledgments

The authors acknowledge the support of the CONCYTEC-World Bank Project "Improvement and Expansion of the Services of the National System of Science, Technology, and Technological Innovation" (Project No. 8682-PE) through its executing unit ProCiencia [Contract No. 07-2018-FONDECYT-BM-IADT-MU]. The Huanchaco Archaeological Project provided textile fragments from its collection for experimentation. We also extend our gratitude to the Chuguay Textile Research Center for supplying the MiScope Digital Microscope (ZARBECO).

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Received: October 15, 2025
Accepted: July 10, 2026