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NetLaPaTex project: Multi-technique evaluation of laser cleaning of heritage textiles

Abstract

The NetLaPaTex project aims to advance the understanding of laser cleaning of heritage textiles, a technique that remains relatively unexplored and rarely practised by textile conservators. Tests were conducted using Er:YAG (150 microseconds) and Nd:YAG (30–110 microseconds and 100 nanoseconds) lasers on artificially soiled cotton, silk and nylon fabrics. The irradiated samples were observed visually using a digital microscope and a colourimetric study was performed using a spectrophotometer. In addition, thermal imaging was employed to monitor laser irradiation and determine the maximum temperature reached during treatment. The results indicate that the Er:YAG laser did not allow safe cleaning of the tested samples, whereas the Nd:YAG laser showed promising outcomes. Under optimal parameters, dirt removal can be achieved without fibre damage. However, certain irradiation conditions can cause brown discolouration of the fibres.

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Keywords
laser cleaning, textile cleaning, heritage textiles, dirt removal, textile conservation

Introduction

Cleaning is one of the most common challenges in the field of conservation. Due to the diversity and specific characteristics and needs of different heritage objects, conservation professionals and scientists are constantly collaborating to develop new techniques tailored to the needs of specific objects. In the case of textiles, especially when they are old and/or fragile, current cleaning techniques generally rely on water, organic solvents or mechanical tools such as scalpels, whose drawbacks (swelling, fibre breakage and material loss) are becoming increasingly apparent (Lennard 2010). In addition, woven structures have surfaces that promote the deposition of impurities, making it difficult to clean them satisfactorily using traditional methods without causing damage.

Laser cleaning is an innovative technique that is becoming more widespread in certain areas of heritage, particularly historical monuments, sculptures and paintings, due to its non-contact, targeted, gradual and uniform mode of action. In contrast, its use on textile objects is scarcely documented, and only a limited number of authors have addressed this topic, highlighting that few specialists have yet explored it. Despite their theoretical interest, lasers are still rarely applied to sensitive organic materials, because their use may seem extreme due to their photosensitivity. Their immediate and long-lasting effects are not yet fully understood. This study aims to advance understanding of the complex interactions between lasers and soiled textile materials.

This paper discusses the NetLaPaTex project, a twelve-month research initiative conducted in collaboration with three French institutions: the Institut national du patrimoine laboratory, the Laboratoire de Recherche des Monuments Historiques (LRMH) and the Centre de Recherche et de Restauration des Musées de France (C2RMF), as well as the Centro Conservazione e Restauro "La Venaria Reale" in Italy.[1] The project aims to undertake a systematic investigation into the efficacy and effects of laser treatments on heritage textiles.

As the project is still ongoing, the paper reports on the work completed up until 2025. This initial phase focused on producing a state-of-the-art review of research in the field of laser cleaning of textiles, familiarising the team with the various laser systems available and investigating the influence of their multiple operating parameters. Also presented are the preliminary visual, colourimetric and thermal observations arising from these treatments.

State of the art

There are numerous types of lasers distinguished by various parameters, including: wavelength in nanometres (nm), defined by the type of laser used; fluence (also known as energy density), defined in J/cm^2 by the ratio of energy (J) to spot area (cm^2); frequency in hertz (Hz), corresponding to the number of shots per second; and pulse duration (mode), characterised by the duration of one pulse and defined in nanoseconds (ns), microseconds (µs) or milliseconds (ms) (Figure 1). The shorter the pulse duration (ns), the more photomechanical effects it produces; the longer it is (µs and ms), the more photothermal effects it produces.

Among these, the Nd:YAG laser has been the most studied in the field of conservation. It can produce wavelengths of 1064, 532 and 266 nm. Since the late 1990s, several studies have specifically investigated the use of this laser model for textile cleaning, primarily targeting plant fibres (cotton and linen) and protein fibres (wool and silk).

Sutcliffe et al. (2000) reported that Q-Switch (QS) mode on clean cotton at wavelengths of 532 and 1064 nm was safer and more effective than at 266 nm, which had a lower damage threshold due to its high energy. However, at excessively high fluence, the 1064 and 532 nm wavelengths induced cracks and fibre breakage due to thermal effects, while samples irradiated at 266 nm displayed clean cuts, resulting from the photochemical processes. The authors further observed that the weave of the fabric did not play a decisive role in the outcome of laser cleaning, since it is effective only on surface contaminants and cannot remove stains that have penetrated the fibres. Damage was influenced by the age of the textile, and discolouration was observed regardless of the wavelength used (also described in Strlič et al. 2003). Comparable results were reported for linen, wool and silk (Belli et al. 2006).

Further investigations on silk cleaning conclude that, within the defined 'safe' parameter ranges,[2] no short-term significant changes were observed in the samples except for a minor colour variation (von Lerber 2004, Brockmann 2024). This discolouration could be explained by the thermal decomposition of carbon particles that can lead to the formation of iron-rich

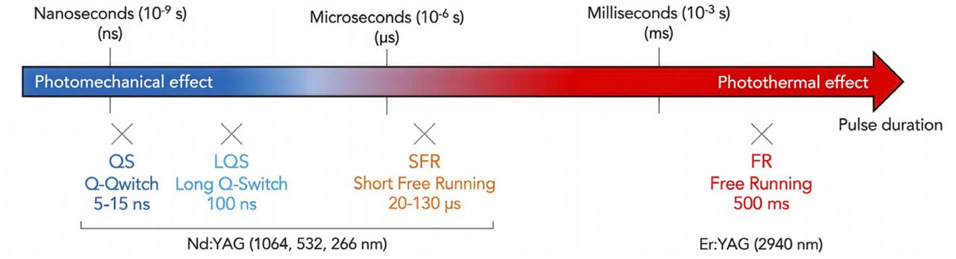

Figure 1 Relationship between laser pulse duration and the types of effects induced in materials, illustrated by the laser types used in this study: Er:YAG (2940 nm) and Nd:YAG (266, 532 and 1064 nm)

chromophore nanoparticles (10–200 nm) (Godet et al. 2017). Brockmann (2024) further compared laser cleaning with conventional dry and wet cleaning methods commonly used by conservators, highlighting that none of these techniques are risk-free for objects and that lasers can offer excellent results in cases where other methods fail or are considered too hazardous for use.

Tests were also carried out on historical and contemporary silk using a 2940 nm wavelength Er:YAG laser (on free-running mode between 150 and 400 µs), leading to defragmentation, melting or evaporation of the contamination material. Surface deposits were generally removed by a secondary step involving solvents, but some studies have explored its use as a stand-alone cleaning technique (Andreotti et al. 2007).[3] The results demonstrated that the fibres could absorb sufficient energy to remove surface dust without being damaged at fluences below approximately 0.4 J/cm^2. Above this threshold, thermal damage, such as matting effects, became apparent. The authors recommend cleaning textiles using a multi-stage laser process, exposing the surface multiple times to very low energy.

Materials and methods

Sample preparation

Textile objects can be made of a variety of natural and synthetic materials. To streamline this study, the focus was on three types of fibres: silk, cotton and nylon. Although natural fibres such as silk and cotton dominate heritage collections, chemical fibres are becoming increasingly common and now require treatment methods adapted to their ageing process. This is why the study includes nylon, which has never before been studied for laser cleaning.

Based on the literature survey carried out, which indicated that the weave structure does not significantly affect laser cleaning outcomes, plain weave fabrics were selected (Sutcliffe et al. 2000). Uncoated fabrics were used in all experiments.

In a museum context, the primary source of soiling is the deposition of fine dust particles (Uring 2019, Piot 2020). These particles are typically made up of a complex mixture of carbonaceous, organic and inorganic compounds whose relative proportions vary according to environmental conditions. The removal of such deposits depends not only on the characteristics of the substrate but also on the size, shape and chemical composition of the soiling materials, and on the nature of the bonds formed between the surface and the deposit (Lennard 2010). Under conditions of high relative humidity (RH), dust particles tend to adhere more strongly to textile fibres and can transfer their acidity to them. The stronger the adhesion to the fibres, the more difficult and likely harmful the removal process becomes.

To replicate the composition of typical soiling found on heritage objects, a synthetic dirt mixture was prepared, inspired by formulations reported in the literature (Wolbers 1992, Ormsby et al. 2010, Chillè et al. 2023). The mixture consisted of 0.2 g carbon black, 0.1 g iron oxide, 0.2 g silica, 1.2 g starch, 1.2 g powdered gelatine, 2.1 g cement, 2.4 g kaolin, 0.5 mL olive oil and 0.9 mL glycerine. All components were blended and gently crushed using a pestle to obtain a homogeneous powder, which was then evenly applied to the fabric surface using a soft brush.

All tests were carried out on new, clean and artificially soiled textile samples. Because the smooth surface of nylon fibres does not retain particulate matter well, a fixation step was required consisting of conditioning in a Binder KBF-240 oven for 26 hours at 50°C and 50% RH to ensure adequate adhesion of the soiling layer. The soiling mixture adhered to the silk and cotton samples without additional fixation.

Tested lasers

The lasers employed in this initial phase of the study were those available at the C2RMF and the LRMH: a Light Brush 2 Er:YAG (2940 nm) and an EOS Combo

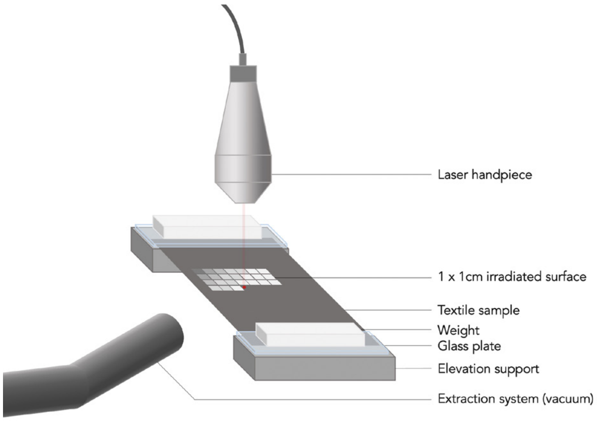

Figure 2 Schematic diagram of the experimental setup

Parameters	Settings tested
Wavelength	2940 nm
Pulse duration (mode)	150 µs (very short mode (VSM))
Energy	50 and 100 mJ
Frequency	3 Hz
Working distance	0.5÷4 cm (0.5 step)
Pre-humidification	None. Pre-moistened with an ultrasonic nebuliser (3 s so that the sample is just moist on its surface)

Table 1 Table of parameters used with the Er:YAG laser

Parameters	Settings tested
Wavelength	1064 nm
Pulse duration (mode)	SFR (30–110 µs) and LQS (100 ns)
Energy	SFR: 25*, 50*, 100, 200÷2000 mJ (200 step) LQS: 38*, 75*, 150, 300, 450 mJ
Frequency	4 Hz
Focal length (f)	3, 4, 5, 6÷21 (3 step)
Pre-humidification	None

Table 2 Table of parameters used with the Nd:YAG laser. The values marked with an asterisk were obtained by adding T50 and T25 filters to reduce the laser energy

Nd:YAG (1064 nm) from El.En. Group. Each type of fibre was irradiated under various parameter combinations, informed by both the literature and the specific capabilities of the equipment. During irradiation a vacuum extraction system was positioned close to the irradiated area to remove dislodged particles (Cooper et al. 2005). All tests were performed on a surface area of 1 cm^2 (Figure 2).

The Er:YAG laser (150 and 400 µs) was tested on samples first exposed to selected parameter sets designed to minimise photothermal impact (Table 1).

The Nd:YAG laser can operate in two pulse modes: short free-running (SFR) (30–110 µs) and long Q-switch (LQS) (100 ns). The experimental parameters tested are detailed in Table 2.

Analytical methodology

To quantify the colour variations in the irradiated areas, colourimetric measurements[4] were taken using a Konica Minolta CM-2600d portable spectrophotometer and the results were expressed in the CIE L*a*b* colour space using Delta E76. The measurement points were compared to each other and with the reference samples for both soiled and clean fabrics. To obtain a representative assessment of the Nd:YAG laser treatments, colourimetric data was analysed under the following conditions: all energy levels were tested at a focal length of f3 in SFR and f5 in LQS, and all focal lengths were tested at an energy of 400 mJ in SFR and 150 mJ in LQS.

The test specimens were examined using a Keyence VHX-7000 digital microscope and photographs were acquired under reflected light at different magnifications ranging from 20× to 500×.

An FLIR T650sc infrared (IR) camera[5] was used to monitor surface temperature variations of the textiles during laser irradiation. Several tests were carried out using the Nd:YAG laser. The IR camera was positioned at a 45-degree angle relative to the sample surface, while the laser was oriented at 90 degrees. A central point within the irradiated spot was defined on each video to analyse temperature fluctuations frame by frame. It should be noted that the temperature data were approximate as the IR camera captures only twenty-five frames per second, whereas laser pulses occur within microsecond or nanosecond range. Consequently, the standard deviations of the measured values are relatively high. To obtain more accurate thermal data, a high-speed camera would be required.

Results

Er:YAG

The most prominent observation was that the Er:YAG irradiation of all three types of clean fabrics resulted in degradation characterised by fibre melting (Figure 3). Tests conducted at different working distances showed that at 3 cm, the fibres exhibited localised scorching and partial surface melting. At 1.5 cm, the fibres were completely melted and displayed a glossy surface, whereas at 0.5 cm, the surface became matte and the fibre ends showed evidence of cross-linking.

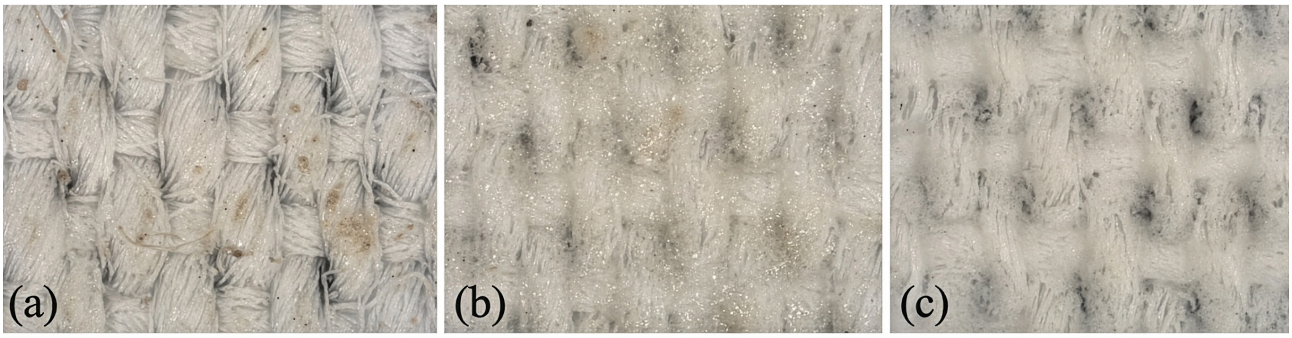

Figure 3 Digital microscope images (200×) of clean cotton irradiated with an Er:YAG laser in VSM at 100 mJ, 3 Hz and at a working distance of (a) 3 cm, (b) 1.5 cm and (c) 0.5 cm

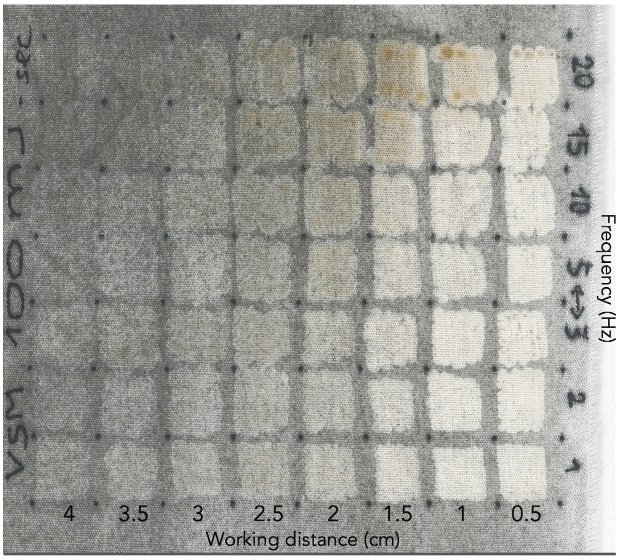

Figure 4 Cleaning tests on soiled textile treated with an Er:YAG laser in VSM. Soiled cotton irradiated at 100 mJ at a working distance ranging from 0.5 to 4 cm and frequencies from 1 to 20 Hz

For soiled fabrics, the effects of Er:YAG irradiation differed according to the fibre type. At first glance, cotton appeared to respond favourably; the dirt layer was visibly removed, revealing the underlying white colour of the textile (Figure 4). However, at high frequency,[6] burn marks became apparent. Silk, by contrast, developed a pronounced and uniform orange discolouration. In the case of nylon, the irradiation did not seem to affect the dirt layer present on the surface. Conversely, at high fluence,[7] the nylon melted to the point of being perforated in the shape of the laser beam (Figure 5a).

Under the microscope, the fibres appeared to be embedded in a rigid material: translucent in the case of cotton and brown in that of silk (Figure 5). The dirt appeared to have melted due to the temperature induced by the photothermal effect of the laser and then resolidified again on the surface of the fibre, whereas in the case of nylon, the fibre itself melted before the dirt.[8]

Nd:YAG

In contrast to the Er:YAG laser, the results obtained with the Nd:YAG laser on the different fibres were relatively homogeneous. Irradiation of clean samples did not produce any observable damage to the fibres, even when the machine settings were set to their maximum values.

On soiled fibres, using the SFR mode, the onset of dirt removal could be observed without any mechanical damage at fluences above approximately 1.5 J/cm^2, confirmed by a progressive reduction in the number of dirt particles under the microscope and an increase in L* (Figure 6 and Table 3). This removal process was gradual and revealed an increasingly orange discolouration corresponding to a rising b* (Figure 6, orange and purple), except for the cotton when the focal length was maintained at f3 (Figure 6, red). This phenomenon was particularly noticeable on silk and in some areas of the cotton at very high fluence and was accompanied by a reduction in fibre diameter, indicative of burning (Figure 6, purple). No orange colouring was observed on nylon (b* is stable); however, the fibre began to melt at high fluence (around 22 J/cm^2).

In LQS mode, at low fluences, a brown discolouration could be observed and confirmed by colourimetric analysis, corresponding to a decrease in L* and a slight increase in b* (Figure 7, red, and Table 3). As the fluence increased, the dirt layer progressively lightened, revealing the underlying white surface of the cotton (Figure 7, yellow). Under the microscope, the number of dirt particles visibly decreased, and the fibres remained in good condition. The L* values rose and nearly reached the reference level of the clean fibre.[9] However, the fibre still displayed a slight orange tint (Figure 7, green, compared to clean cotton). The b* value returned to the level of soiled fibres and remained higher than the reference value of clean fibre.

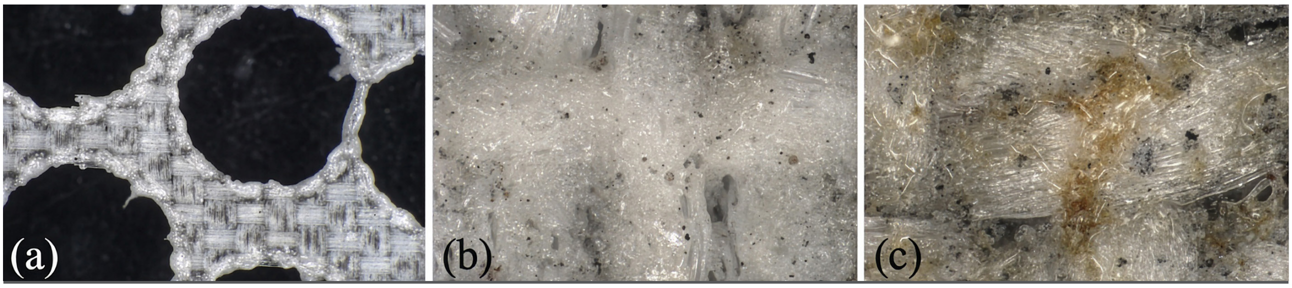

Figure 5 Digital microscope image of: (a) soiled nylon irradiated at 200 mJ and 1 Hz at a 0.5 cm working distance (100×); (b) soiled cotton; (c) and soiled silk irradiated at 50 mJ and 3 Hz at a 1 cm working distance (500×)

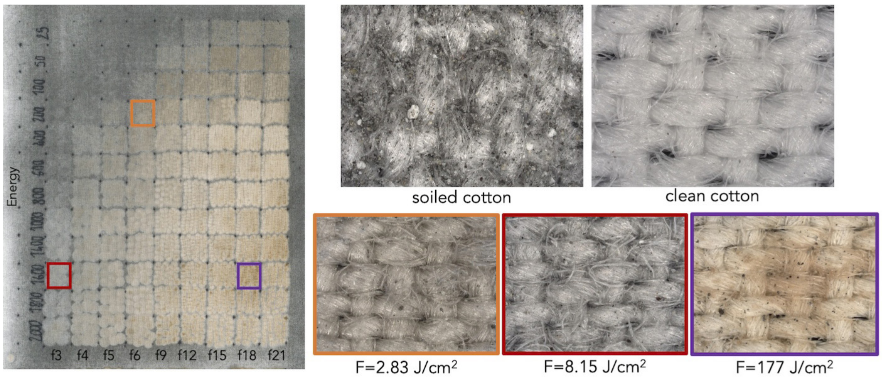

Figure 6 Cleaning tests on soiled cotton using the Nd:YAG laser in SFR mode with 200× digital microscope observations

		L*	b*
SC		53.72	−3.13
SC irradiated in SFR mode at f3	400 mJ	57.79	−3.59
	600 mJ	55.51	−2.67
	800 mJ	58.30	−3.35
	1000 mJ	65.41	−3.82
	1200 mJ	64.63	−3.38
	1600 mJ	65.16	−2.09
	1800 mJ	65.85	−2.08
	2000 mJ	67.71	0.00
SC irradiated in SFR mode at 400 mJ	f3	57.79	−3.59
	f4	62.21	−2.70
	f5	63.23	−0.54
	f6	66.02	2.67
	f9	70.35	4.68
	f12	74.93	5.97
	f15	75.82	8.40
	f18	76.45	5.89
	f21	77.72	5.88
SC irradiated in LQS mode at 150 mJ	f3	51.98	6.78
	f4	59.73	6.23
	f5	69.65	5.72
	f6	72.00	3.76
	f9	75.52	1.11
	f12	78.51	−1.25
	f15	76.31	0.78
	f18	80.14	−1.70
	f21	82.90	−2.47
CC		87.79	−11.11

Table 3 Colourimetric measurements according to the L* and b* axes of the CIE L*a*b* space for samples of soiled cotton (SC); soiled cotton irradiated at different energies in SFR mode and at f3; different focal lengths in SFR mode at 400 mJ; in LQS mode at 150 mJ; and clean cotton (CC). The variations on a* never exceed two units, which can therefore be considered negligible

Thermal camera

The first observation made possible using the thermal camera was that no significant temperature increase could be detected on clean fabric in contrast to soiled fibres (Figure 8a). This indicates that the temperature elevation was induced by interaction between the laser and the dirt layer and increased proportionally with fluence. Consequently, all the temperature values recorded during these tests were valid only within this specific context and depended on the composition and quantity of the soiling.

The cumulative temperature effect could be observed under irradiation with a series of pulses. The temperature increased and then stabilised without exceeding a maximum value (AFNOR 2016), influenced by both fluence and frequency (Figure 8b). The higher these parameters, the higher the maximum temperature reached.

Thermal camera measurements also highlighted the critical role of suction, which is generally recommended during irradiation to reduce suspended particles and their redeposition. It was further observed that the use of suction drastically lowered the surface temperature of the textiles. For example, on cotton, in SFR mode and at 100 mJ, 122°C was obtained with suction versus 172°C without.

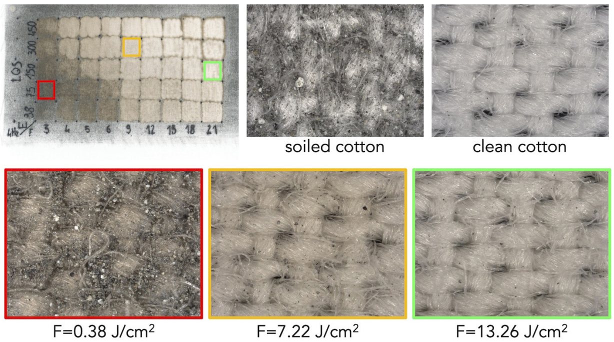

Figure 7 Cleaning tests on soiled cotton using the Nd:YAG laser in LQS mode with 200× digital microscope observations

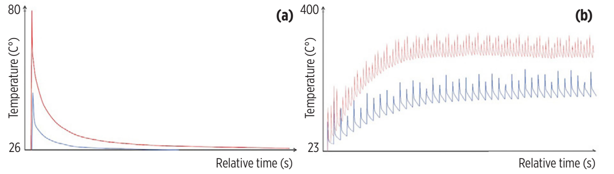

Figure 8 (a) Temperature evolution at the centre of the laser spot over time. Single shot on soiled cotton in LQS mode at 1.3 J/cm² (blue) and 15.9 J/cm² (red); (b) multiple pulses on soiled cotton in SFR mode at 1000 mJ, a focal of f3 at 2 Hz (blue) and 4 Hz (red)

Conclusion

The results of this study do not currently support recommending the use of Er:YAG lasers on textiles, as fibre damages occurred even at low settings. By contrast, the Nd:YAG laser shows promising results. The SFR mode carries a high risk of excessive heating and consequent fibre degradation. However, if parameters are carefully controlled (low fluence and frequency) and the temperature of the textile is maintained within safe limits, no degradation or discolouration could be observed, while still allowing for satisfactory cleaning. The LQS mode enables more effective dirt removal than the SFR mode and presents a lower risk of temperature increase. Nevertheless, it may leave a slight brown tint on the fibre surface, which warrants further investigation.

According to the literature and tests carried out during this first phase of the project, laser cleaning of cotton, silk and nylon shows considerable potential. Mastering the equipment and its parameters is a complex learning process, but one that is essential to ensure laser treatment proceeds safely without risking irreversible damage to heritage material. Each case differs in terms of the materiality of the object being treated, its degree of ageing and the composition and bonding of the dirt to be removed. Therefore, it is not sufficient to rely solely on parameters reported in the literature; tests must be performed directly on the object to be treated. Infrared camera monitoring and a thorough understanding of the chemical and thermal properties of both the fibres and the dirt are recommended.

Further tests, particularly in QS mode (5–15 ns) and at 532 nm, would be highly valuable. In addition, cleaning experiments should be conducted on larger surfaces and on fibres artificially aged before and after irradiation to evaluate the long-term durability of the treatment. Further analyses will be performed, notably by taking more colourimetry measurement points and using a scanning electron microscope to detect potentially the nanoparticles reported in Godet et al.'s work and to explore ways to limit or remove them following laser treatment. Tensile tests are also planned to be carried out in the next phase to assess the preservation of the fibres' mechanical properties.

Notes

1 This work is supported by the Ecole Universitaire de Recherche Paris Seine Humanités, Création, Patrimoine, Investissement d'avenir ANR-17-EURE-0021, Fondation des Sciences du Patrimoine, France, and the Fondation Carnot, France.

2 Parameter ranges found to allow soiling removal without damaging the substrate: 0.5 to 1.5 J/cm² and 5 to 20 pulses for the 532 nm laser; 1 to 2 J/cm² and 5 to 20 pulses for the 1064 nm laser.

3 At 5 and 10 Hz at 0.1–1.5 J/cm².

4 Measurement parameters: SAV, SCI, UV at 100%, 10° observation angle, D65 illuminant. Three measurements were taken by the spectrophotometer and averaged. Given the surface area of the irradiated zones, only one measurement was taken per parameter type. Only the soiled and clean control samples were averaged with five measurements.

5 Calibrated from −40°C to 2000°C.

6 Greater than or equal to 10 Hz.

7 Based on the following parameters: VSM, 50 mJ, 2 Hz, 1 cm distance.

8 This is due to its melting point of around 250°C.

9 Starting from 13 J/cm².

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Materials list

Carbon black (47250), iron oxide (40420), starch (63451), cement (31210), kaolin (58250)
Kremer Pigmente, Aichstetten, Germany
https://www.kremer-pigmente.com

EOS Light Brush 2, EOS Combo
El.En. S.p.A., Florence, Italy
https://elengroup.com/en

Fuji Silk Natural (S23A)
Whaleys Fabrics, Bradford, England
https://www.whaleys-bradford.ltd.uk

Gelatine powder (SR196), glycerine (SR201)
Sordalab, Étampes, France
https://sordalab.com

Plain weave cotton (S228i)
Rauch S.A., Tarare, France
https://www.rauch-sa.fr

Plain weave nylon 66 (1453 DES)
Coublanc Textile, Coublanc, France
http://www.coublanctextiles.fr

Silica (R0100010)
CTS Conservation, Altavilla Vicentina, Italy
https://ctsconservation.com/en