RESEARCH

Investigating the potential of the Nd:YAG and Er:YAG lasers for the cleaning of feathers: a pilot study

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Abstract

A dual-wavelength Q-switched Nd:YAG laser emitting at 1064 nm and 532 nm and an Er:YAG laser were tested on a range of feathers containing melanin, carotenoids and psittacofulvins. Dyed, white and iridescent feathers, as well as down feathers, were also included in the study. First, the damage threshold fluence was determined for each type of feather and then, as appropriate, laser tests were conducted on feathers artificially soiled with dust or carbon black. The Nd:YAG laser was unsuccessful at cleaning feathers soiled with carbon black. Better outcomes were obtained on feathers soiled with dust: the Nd:YAG laser was effective at both wavelengths at removing dust from white feathers, dyed feathers and yellow feathers containing psittacofulvins. Feathers containing melanin, as their main colourant, were found to have a much lower damage threshold fluence than other feathers. Also, laser radiation at 532 nm at high fluences can cause discolouration on pink feathers containing carotenoids. Finally, it was not possible to remove dust from down feathers without causing thermal damage. This investigation showed that laser cleaning using a Q-switched Nd:YAG laser can remove dust from certain types of feathers. However, further research is needed to assess any potential chemical or long-term effects of laser cleaning on feathers. Finally, the Er:YAG laser was found to be unsuitable for laser cleaning resulting in thermal damage to all feathers at low fluences.

Keywords: Feathers, Bio-pigments, Carotenoids, Psittacofulvins, Laser, Melanin, Nd:YAG laser, Er:YAG laser, Damage threshold, Cleaning threshold

Introduction

Feathers have very complex structures and exist in a wide range of colours [1]. They can contain bio-pigments, which are rarely uniformly distributed within the different parts of the feather, varying in content in the shaft, barbs (i.e. the small branches fused to the shaft) and barbules (i.e. the tiny strands fused to the barbs) [2, 3]. Bio-pigments selectively absorb and reflect wavelengths of the incident light reaching the feather. They generally correspond to yellow, brown, orange, black, grey and red colours. Bio-pigments can be combined with structurally induced backscattered colouration to produce so-called "structural" colours, such as blue. Feathers can also display iridescence (i.e. the variation in hue at different angles of observation). Note that not all structural colours are iridescent: tiny air pockets in the barbs of feathers can scatter incoming light, resulting in non-iridescent colour. The only feather colour which contains no bio-pigment and is inherently only structural is white. Some bio-pigments absorb ultraviolet radiation and fluoresce, making feathers look brighter and more colourful [2, 4]. Bio-pigments in feathers are either metabolized by the bird or supplied by the bird's diet.

There are different types of bio-pigments present in feathers and the main three are melanin, carotenoids and psittacofulvins [2, 3, 5–11]. Melanin is endogenous and one of the most common but also complex

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colourants. It comes in two main forms—eumelanin and phaeomelanin [2, 8, 9, 11, 12]. Accordingly, this results in different colours: eumelanin is typically responsible for darker colours (e.g. the grey feathers of common pigeons) while phaeomelanin produces a reddish hue (e.g. the rusty brown feathers of red-tailed hawks). Further, the organisation of the melanin granules (melanosomes) and tiny air cavities in the β-keratin matrix are responsible for structural colours: crystalline nanostructures generate iridescent colours (e.g. the blue and green feathers of peacocks), while amorphous nanostructures generate non-iridescent blue and violet colours (e.g. the blue feathers of macaws). In fact, the air cavities, not melanosomes, are primarily responsible for non-iridescent structural colours (melanosomes affect colour saturation or contribute to colour by providing a dark background for instance). Melanosomes can be in spherical, rod, hollow-rod, or hollow-platelet shapes, which also impacts the resulting colour [13]. Carotenoids are responsible for red, yellow and orange colours and come from the bird's diet. Psittacofulvins exhibit the same hue as carotenoids but they are specific to the parrots and cockatoo species and independent of the bird's diet [2, 3, 8, 10].

The complex structure of feathers can make them difficult to clean [14, 15] and conservators usually clean them using gentle brushing or pinpoint vacuuming through a screen. Soiling is difficult to remove and requires the additional use of water, solvents or surfactants [16–19]. All these methods involve contact with feathers, which can disrupt their delicate structure. Laser cleaning is contactless [20–29], which makes it a potentially very attractive technique to conserve feathers.

However, only a few case studies on the laser cleaning of feathers have been published to date [30–39]. This study reports the outcomes of systematic laser cleaning tests on a wide range of feathers using a Q-switched Nd:YAG laser emitting at 1064 nm and 532 nm and an Er:YAG laser. Tests were conducted on feathers containing melanin, carotenoids and psittacofulvins, as well as on iridescent, white and dyed feathers. This was to investigate whether the nature of the colourant has an impact on the suitability of laser treatment. First, the laser damage threshold fluence value was determined for each type of feather and then laser cleaning tests were carried out on artificially soiled feathers.

Materials and methods

Feathers

Laser cleaning tests were conducted on pennaceous feathers of different colours collected from local parks, donated by local zoos or purchased online from private pet owners (Table 1). All these feathers had been cast from the birds naturally and, as described by the Royal Society for the Protection of Birds on their website, collecting such feathers is legally permitted. A few feathers from protected species of birds were used, which were feathers that had become detached from featherworks in the collection of The British Museum and were made available for research purposes. We selected different bird species in order to test feathers containing melanin, carotenoids and psittacofulvins, as well as white feathers. White down feathers were included to assess the effect of the feather's structure on laser cleaning. Iridescent feathers and feathers dyed with synthetic colourants were also tested. Every single feather appeared visually

Table 1 List of feathers used for the laser cleaning tests

Bird species	Genus	Species	Colours	Main colourant(s)	Provenance
Common wood pigeon	Columba	C. palumbus	Black/gray	Melanin	Local park
Common magpie	Pica	P. Pica	Iridescent dark brown/black	Melanin	Local park
Blue and yellow macaw	Ara	A. ararauna	Blue	Melanin Psittacofulvins[a]	Private pet owner
Green peacock	Pavo	P. muticus	Iridescent green	Melanin	Local zoo
Amazon parrot	Amazona	N.A.[b]	Red	Psittacofulvins	Private pet owner
			Yellow		
			Green	Psittacofulvins Melanin	Local zoo
Yellow-crested cockatoo	Cacatua	C. sulphurea	Yellow	Psittacofulvins	Private pet owner
			White	None	Local zoo
Caribbean flamingo	Phoenicopterus	P. ruber	Pink	Carotenoids	Local zoo
Unspecified species	N.A	N.A.[b]	Green Orange Yellow Red Blue	Synthetic dyes	Local art and craft shop
Down (unspecified species)	N.A	N.A	White	None	Local zoo

[a] Laser tests on the blue and yellow macaw were performed only on the blue areas

[b] The supplier could not provide us with any details about the birds' species

free of soiling and was not subjected to any cleaning prior to testing. Due to the inherent variability of feathers, the feathers did not represent a set of exact replicates. Some of the feathers used in our study are shown in Fig. 1.

To assess the potential of the dual-wavelength Q-switched Nd:YAG laser and the Er:YAG laser to remove contaminants, a range of feathers were artificially soiled using dust collected around the Museum and carbon black (purchased from Kremer, 47,000, Wine Black). Carbon black was selected to simulate the presence of soot, sometimes observed on museum objects due to past storage or display in coal-heated rooms in Victorian times or damage from fire. The dust and carbon black were applied using a brush on slightly damp feathers, previously sprayed with milli-Q water. The feathers were then left to dry at room temperature for seven days and the excess of soiling was brushed away, leaving the surface slightly soiled.

Laser cleaning tests

Two types of laser were tested in this study: a Phoenix Athena Q-Switched Nd:YAG laser from Lynton emitting 10 ns pulses at 532 and 1064 nm and an XS Fidelis Er:YAG laser from Fotona emitting at 2940 nm with a pulse duration ranging from 100 μs to 1 ms. For the Nd:YAG laser, a custom-made laser beam homogeniser designed by Ed Teppo was used with the Nd:YAG laser to reduce hotspots in the laser beam. This restricted the fluence range that could be used on feathers to 0.6–1.8 J/cm^2 at 1064 nm and 0.2–1.2 J/cm^2 at 532 nm. For the Er:YAG laser, the range of fluence tested varied from 0.3 to 1.3 J/cm^2. The laser fluence was determined by dividing the energy per pulse by the laser spot area, measured on photographic and thermal paper for the Nd:YAG and the Er:YAG laser, respectively. The working spots used were in the range of Ø 0.1–0.5 cm according to the different lasers. Each fluence measurement was repeated at least three times and conducted on several feathers of the same type. Laser tests were carried out with both lasers using water as wetting agents, but then excluded due to the uneven cleaning outcomes. Each feather was placed on a piece of white paper for the laser cleaning tests. The paper was inspected visually afterwards and no effect of the laser irradiation on the paper was observed.

Analytical techniques

The assessment of the bio-pigments present in the feathers was carried out by Raman spectroscopy using a Jobin Yvon LabRam Infinity spectrometer from HORIBA. The instrument was equipped with a green laser emitting at 532 nm, with a maximum power of 2.4 mW at the sample, integration times varying between 10 and 25 s, averaging of up to five scans, a spectral range between 400 and 1800 cm^{-1}, a fine grating of 1800 g/mm and a 50×objective.

The effect of the laser irradiation on the feathers was monitored with a Dino-Lite handheld digital microscope during the laser cleaning tests. A more detailed assessment of the treatment's outcome was also performed using a Keyence digital microscope fitted with a VH-Z 20R lens and an automated VHX-S 550E stage. Further, feathers were examined at high magnification using an S3700 variable pressure scanning electron microscope (VP-SEM) from Hitachi to compare their morphological condition before and after laser irradiation. The observations were carried out using backscattered electrons in low vacuum mode, operating at 40 Pa with an accelerating voltage of 15 kV.

The feathers were also assessed before and after cleaning using Attenuated Total Reflection-Fourier transform infrared (ATR-FTIR) spectroscopy. However, only the characteristic absorption bands of the keratin protein could be detected both before and after cleaning, without any variation of the relative intensity. Therefore, the results are not reported here.

Results and discussion

Characterisation of feather colourants

Raman spectroscopy was carried out to confirm the identity of the bio-pigments present in the feathers selected for our study and characterise the synthetic dyes used in the dyed feathers. It was not possible to obtain a spectrum of melanin for the pigeon and the blue macaw feathers as burning occurred on the barbs' surface, even when using the lowest laser power.

The Raman spectra obtained for the flamingo and yellow cockatoo feathers are shown in Fig. 2. The Raman

Fig. 1 Feathers tested with the Nd:YAg and Er:YAg lasers © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.
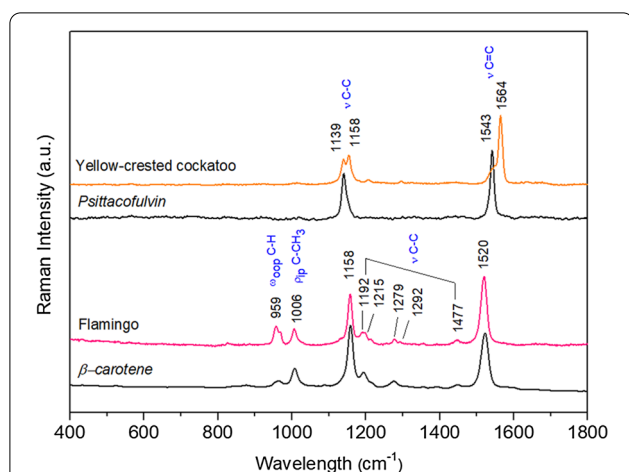
Fig. 2 Raman spectra of the yellow cockatoo and pink flamingo feathers, together with the reference spectra for psittacofulvin and β-carotene. © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

The Raman spectrum of the yellow-crested cockatoo matched those obtained for psittacofulvins, showing bands at 1564, 1543, 1158 and 1139 cm^{-1}. The bands at 1564 and 1543 cm^{-1} correspond to the C=C bond stretching, while the other two bands correspond to C–C bond stretching [45, 46].

According to the literature, feathers are generally dyed using acid dyes [47, 48]. However, no colourants were detected with Raman on the dyed feathers: their spectra were identical to those of white feathers.
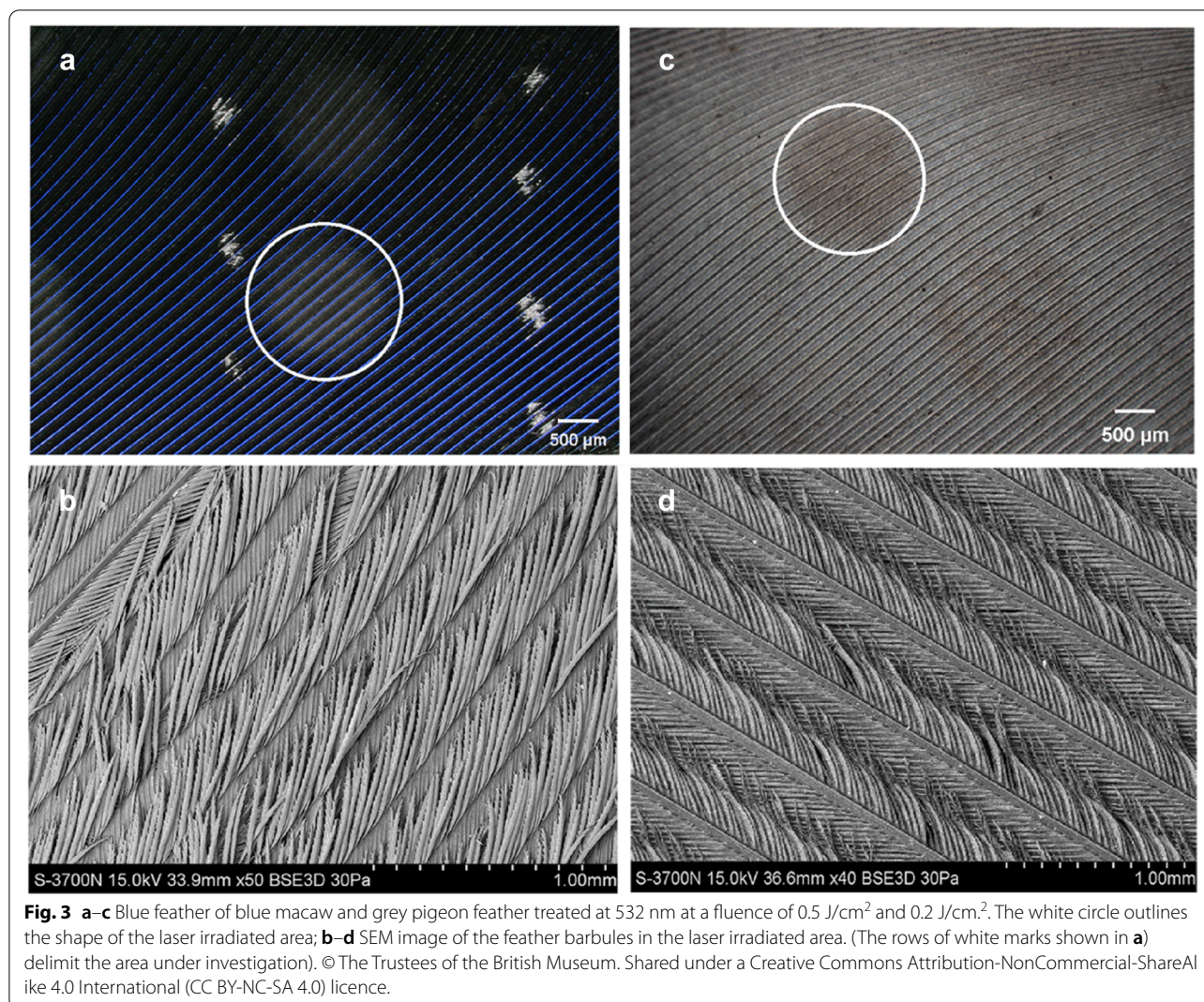
Determining the feathers' damage threshold fluence for the Nd:YAG laser

The damage threshold fluence for each type of feather was assessed using the Nd:YAG laser at 1064 and 532 nm. The results are listed in Table 2. Many of the feathers experienced no damage when irradiated with the Nd:YAG laser at 532 nm and 1064 nm at the maximum fluence available with our setup (i.e. 1.2 and 1.8 J/cm^2 respectively). However, some feathers could be damaged at lower fluences. In that case, both the structure of the feathers and the nature of the colourant was observed to affect the value of the damage threshold fluence. For instance, down feathers had a lower damage threshold fluence probably due to the filamentous structure of the barbules.

Also, the damage threshold fluence was much lower at both wavelengths for feathers with grey barbules (as seen for the grey pigeon feathers, blue macaw feathers and iridescent magpie feathers). As a matter of fact, morphological damage, as well as loss of colouration and iridescence, were observed at the lowest fluence delivered

spectrum of the flamingo feather was a good match with β-carotene [40–44], with two strong peaks at 1520 cm^{-1} and 1158 cm^{-1}, which are associated with the stretching of the C=C and C–C bonds respectively. An additional medium-intensity peak is observed at 1006 cm^{-1} assigned to the C–CH$_3$ in-plane rocking mode. There were also several weak peaks between 1400 and 1000 cm^{-1}, which correspond to the C–C stretching mode of the hydrocarbon chain [42]. The peak at 959 cm^{-1} results from the out-of-plane wagging of the C–H groups of the carotenoids' molecules.

Table 2 Damage threshold fluences of the feathers using the Nd:YAG laser at 1064 and 532 nm

Bird species	Main colourant(s)	Colour	532 nm	1064 nm
Common wood pigeon	Melanin	Black/grey	≤ 0.2 J/cm^2	≤ 0.6 J/cm^2
Common magpie	Melanin	Iridescent dark brown/black	≤ 0.2 J/cm^2	≤ 0.6 J/cm^2
Blue and yellow macaw	Melanin Psittacofulvins	Iridescent	≤ 0.2 J/cm^2	≤ 0.6 J/cm^2
Green peacock	Melanin	Iridescent green	≤ 0.2 J/cm^2	1.8 J/cm^2
Amazon parrot	Psittacofulvins Melanin	Green	0.5 J/cm^2	1.0 J/cm^2
Yellow-crested cockatoo	Psittacofulvins	Yellow	> 1.2 J/cm^2	> 1.8 J/cm^2
	None	White	> 1.2 J/cm^2	> 1.8 J/cm^2
Caribbean flamingo	Carotenoids	Dark pink	0.8—1 J/cm^2	> 1.8 J/cm^2
		Light pink	> 1.2 J/cm^2	> 1.8 J/cm^2
Unspecified species	Synthetic dye	Green Light blue Pink Purple	> 1.2 J/cm^2	> 1.8 J/cm^2
		Red Blue	0.5 J/cm^2	> 1.8 J/cm^2
Down (unspecified species)	None	White	0.5 J/cm^2	1.0 J/cm^2

Fig. 3 **a–c** Blue feather of blue macaw and grey pigeon feather treated at 532 nm at a fluence of 0.5 J/cm² and 0.2 J/cm.². The white circle outlines the shape of the laser irradiated area; **b–d** SEM image of the feather barbules in the laser irradiated area. (The rows of white marks shown in **a**) delimit the area under investigation). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

with our laser setup at both wavelengths for these feathers, i.e. 0.2 J/cm² at 532 nm and 0.6 J/cm² at 1064 nm (Fig. 3a–c). This is consistent with findings published by other researchers: for instance, Karantoni and Ekaterini reported discolouration and damage of the barbules at 1064 nm on pigeon feathers at 0.9 J/cm² [34].

In addition, when the iridescent and the structural colours were lost following laser irradiation at low fluence, no damage to the barbules and the hooks (i.e. the far end of the barbules with an indented shape) of the feathers was observed with the SEM for the feathers containing melanin as illustrated in Fig. 3b. This suggests that damage occurred at a smaller scale within the feather. As reported in the literature [2, 9], complex nanoscale arrangements of melanosomes and/or tiny air cavities within the keratin cortex are responsible for iridescent and structural colours and the laser irradiation possibly damage these nanostructures.

Alternatively, differences in the structure of the feather may explain the higher damage threshold fluence of the green parrot feather. From these results, it was concluded that feathers containing preponderantly melanin (i.e. all feathers with grey barbules) were more sensitive to laser radiation and would not be good candidates for laser cleaning.

Also, the green iridescent feathers of peacock seemed to be less sensitive to laser irradiation, as it was possible to use a slightly higher fluence at 1064 nm than with the other feather containing melanin, but not at 532 nm. The lower sensitivity might be due to the saddle-shape of the peacock feathers and to the uneven thickness of the barbules. Thus, the thickness of the layer of melanosomes can vary along the same barbules and the light can be absorbed differently making the feather slightly more resistant to laser irradiation compared to other types of feathers [49]. Rogalla et al. showed that the melanin
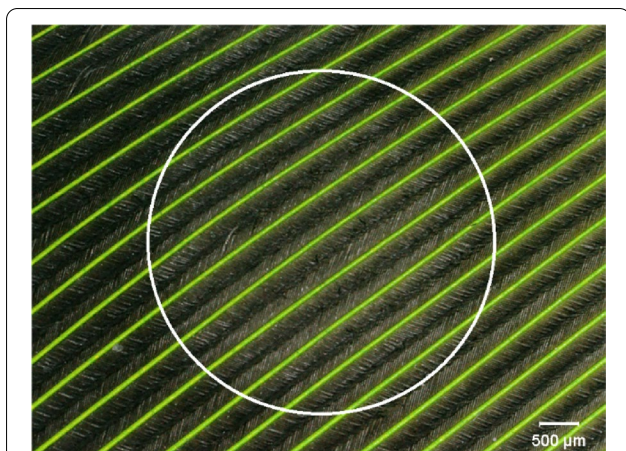
Fig. 4 Optical microscope image showing the very slight discoloration/bleaching of the dark barbules of a green parrot feather after laser irradiation at 532 nm. © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

absorbance at 532 nm is greater than 1064 nm [50], which may explain the lower damage threshold recorded at 532 nm for the peacock feathers.

The presence of melanin in the green parrot feathers also seemed to affect the damage threshold fluence, which was lower than for the red and yellow parrot feathers at both wavelengths. As can be seen in Fig. 4, the barbules of the green feathers were dark grey and, most likely, the melanin stored in the barbules absorbed the laser radiation causing thermal damage and discoloration. Note that red and yellow feathers also contain some melanin granules but these are embedded deeply within the barbules [51] (when viewed with the

microscope, the barbules of red and yellow feathers were red and yellow respectively, not grey). The green colour of feathers is the result of the presence of bio-pigments, but also structural effects. It appeared that the presence of psittacofulvins might have a protective effect for the green parrot feathers as their damage threshold fluence was greater than those of the blue and grey feathers, which contained no (or very little) psittacofulvins but had dark grey barbules.

The yellow feathers (containing psittacofulvins) seemed to behave like the white feathers at 1064 nm. In the case of the flamingo feathers (containing different amounts of carotenoids), the dark pink feathers were prone to discolour at 532 nm but not the light pink feathers. Carotenoids are sensitive to light and their discolouration is more noticeable when feathers contain a higher concentration of them as in the dark pink feather (i.e. bleaching is less visible on a light background than on a dark one).

Most of the dyed feathers behaved like the white feathers at both wavelengths. They were irradiated at the highest fluence available with our equipment without any morphological damage or discolouration, except for the red and blue feathers for which the damage threshold fluence was lower than 0.5 J/cm^2 at 532 nm (Fig. 5). Unfortunately, as the colourants present on the dyed feathers could not be identified, it is difficult to speculate on any possible causes for the differences observed. Another possibility could be that the red and blue feathers had finer barbules than the other dyed feathers, the finer structure leaving the feather more vulnerable to laser irradiation.

On the white down feathers, the damage threshold was found to be much lower at both wavelengths than on the pennaceous feathers. With the optical
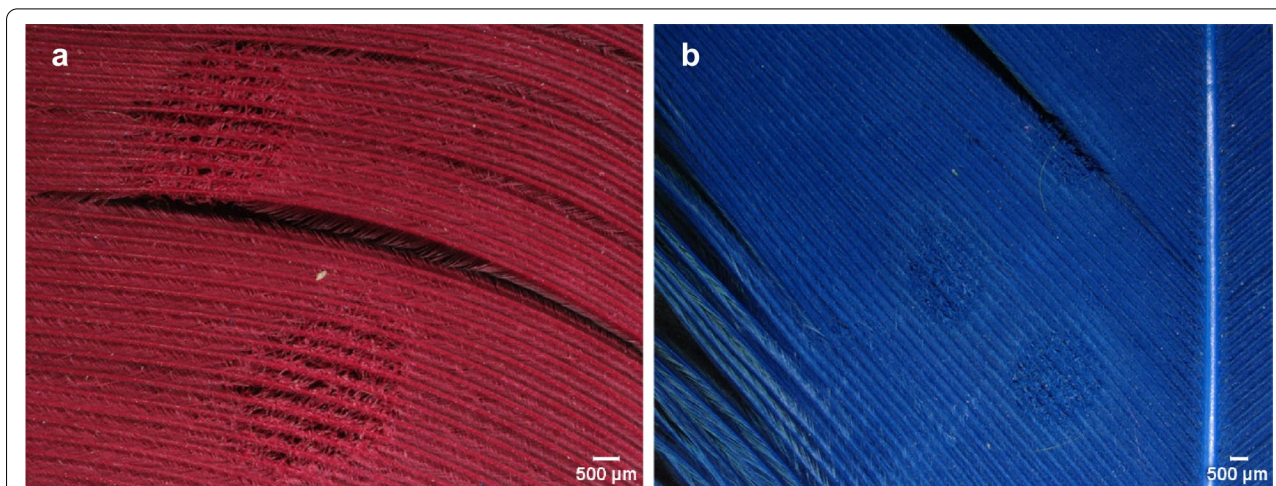

Fig. 5 Optical microscope images of damage on red (**a**) and blue (**b**) dyed feathers using 532 nm laser. © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

microscope, the very fine barbs and barbules of the down feathers were observed to have burnt at high fluences. Thus, laser cleaning of down feathers or of the after shaft of pennaceous feathers (i.e. the "downy" lower portion of some feathers), if present, should be avoided or conducted at very low fluences.

Removal of soiling from feathers using the Nd:YAG laser

Laser cleaning tests were performed on feathers that had a damage threshold value greater than 1 J/cm^2 at both wavelengths, i.e. the yellow cockatoo feathers (psittacofulvins), the white cockatoo feathers, the light pink and dark pink flamingo feathers (carotenoids) and the dyed green feathers. No wetting agent was used.

In general, laser cleaning was effective at removing dust from all feathers at a fluence of 1.8 J/cm^2 at 1064 nm and 1.2 J/cm^2 at 532 nm, except for the light pink flamingo feathers which were cleaned at 1 J/cm^2 at 532 nm due to their lower damage threshold (Table 3). As shown in Figs. 6, 7 and 8, the dust was removed from the feathers and no damage was observed using SEM. For the feathers containing psittacofulvins, this is in agreement with the research by Solajic et al. [39], who reported successful removal of soiling using a QS Nd:YAG laser at 1064 nm from red–orange scarlet macaw feathers (containing psittacofulvins [10]) with no apparent damage or discolouration to the feathers. Similar results were also reported by Ciofini et al. [38] with QS and Long Q-Switch (LQS) Nd:YAG laser emitted at 1064 nm: they observed selective removal of soot-like deposits from red and yellow feathers from scarlet ibis and possibly scarlet macaw without any physical damage at both pulse widths. However, they noticed whitening and possible physical damage at prolonged exposures at elevated fluences. They also reported that the LQS pulse duration was preferred to the QS duration because of its more gradual cleaning action and wider operative fluence ranges.

Interestingly, for the white feathers, yellowing was observed after laser cleaning at 1064 nm at a lower fluence (i.e. 1.0 J/cm^2), but not higher fluences. Other researchers have reported yellowing of white feathers after laser cleaning at 1064 nm: Dignard et al. [33] observed yellowing at 0.08 J/cm^2 on soot-soiled white

feathers whereas Pacaud and Lamaire [32] at 1.3 J/cm^2 on white feathers soiled by dust and soot. In particular, Pacaud and Lamaire [32] suspected the presence of a pre-existing yellow layer on the white feathers but our study suggests it could have been due to an interaction between the laser irradiation and the soiling. The green dyed feathers behaved like white feathers and the dust was removed at the highest fluence both at 1064 and 532 nm without any morphological damage or discolouration.

Laser irradiation was not effective at removing carbon black from any of the feathers at either wavelength and caused darkening, even at the lowest fluence delivered by our set up (Fig. 9). It was not entirely clear what caused this darkening as no damage was seen using SEM (Fig. 9a'–c'). It is possible that the laser irradiation triggered the formation of dark compounds through interaction with the carbon particles. For instance, Berthonneau et al. [52] investigated the darkening observed when laser cleaning gypsum soiled with carbon black using a QS Nd:YAG laser at 1064 nm at fluences of 0.2–0.4 J/cm^2. They proposed that partially oxidised hydrocarbons formed through reactions between the carbon atoms and the water molecules coming from the dehydration of the gypsum surface. Our results on the laser cleaning of feathers soiled with carbon black are consistent with published research. For instance, Dignard et al. [33] reported that the Nd:YAG laser was unsuccessful at removing soot from white feathers both at 1064 and 532 nm.

Determining the feathers' damage threshold fluence for the Er:YAG laser

Feathers were irradiated with the Er:YAG laser at increasing values of fluence and the outcome was assessed using optical microscopy and scanning electron microscopy. The laser had different laser pulse widths ranging from 100 µs to 1 ms. All the pulse ranges were tested and found to have no significant effect.

The damage threshold values were equal to 0.4 J/cm^2, or lower, for all the feathers. Such a low fluence considerably limits the potential of this laser to remove contaminants from feathers without damaging them. This result is not surprising though: the Er:YAG laser emits radiation at 2940 nm, which corresponds to the main absorption

Table 3 Cleaning threshold for the removal of dust from feathers using the Nd:YAG laser

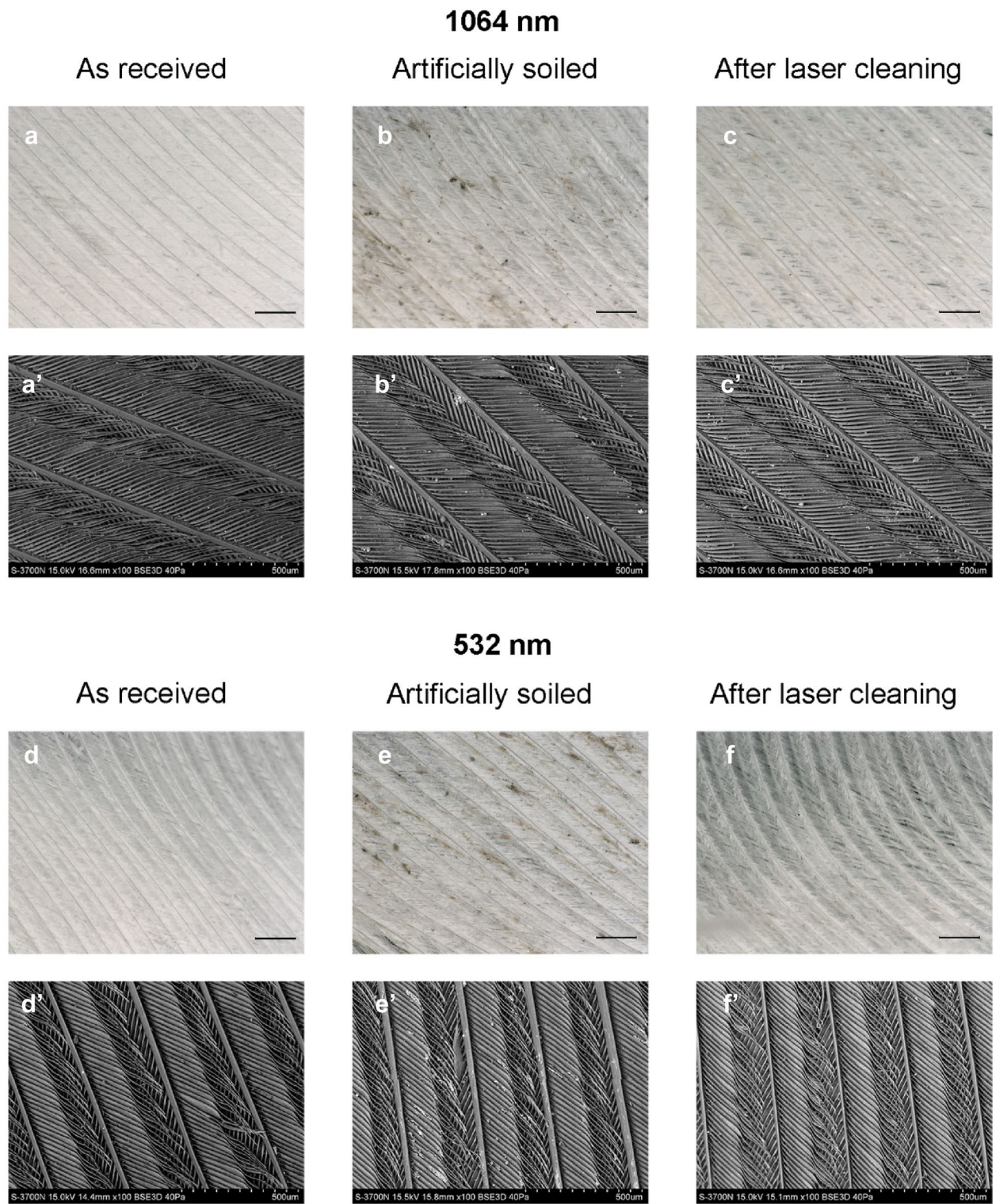| Bird species	Main colourant(s)	Colour	532 nm	1064 nm
Yellow-crested cockatoo	Psittacofulvins	Yellow	> 1.2 J/cm^2	> 1.8 J/cm^2
	None	White	> 1.2 J/cm^2	> 1.8 J/cm^2
Caribbean flamingo	Carotenoids	Dark pink	1 J/cm^2	> 1.8 J/cm^2
		Light pink	> 1.2 J/cm^2	> 1.8 J/cm^2
Unspecified species	Synthetic dye	Green	> 1.2 J/cm^2	> 1.8 J/cm^2

Fig. 6 Laser cleaning at 1064 nm (top) and 532 nm (bottom) of white cockatoo feathers artificially soiled with dust. Optical microscope images (**a**, **b**, **c**, **d**, **e**, **f** _ bars = 500 μm) and their corresponding SEM images (**a'**, **b'**, **c'**, **d'**, **e'**, **f'**). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.
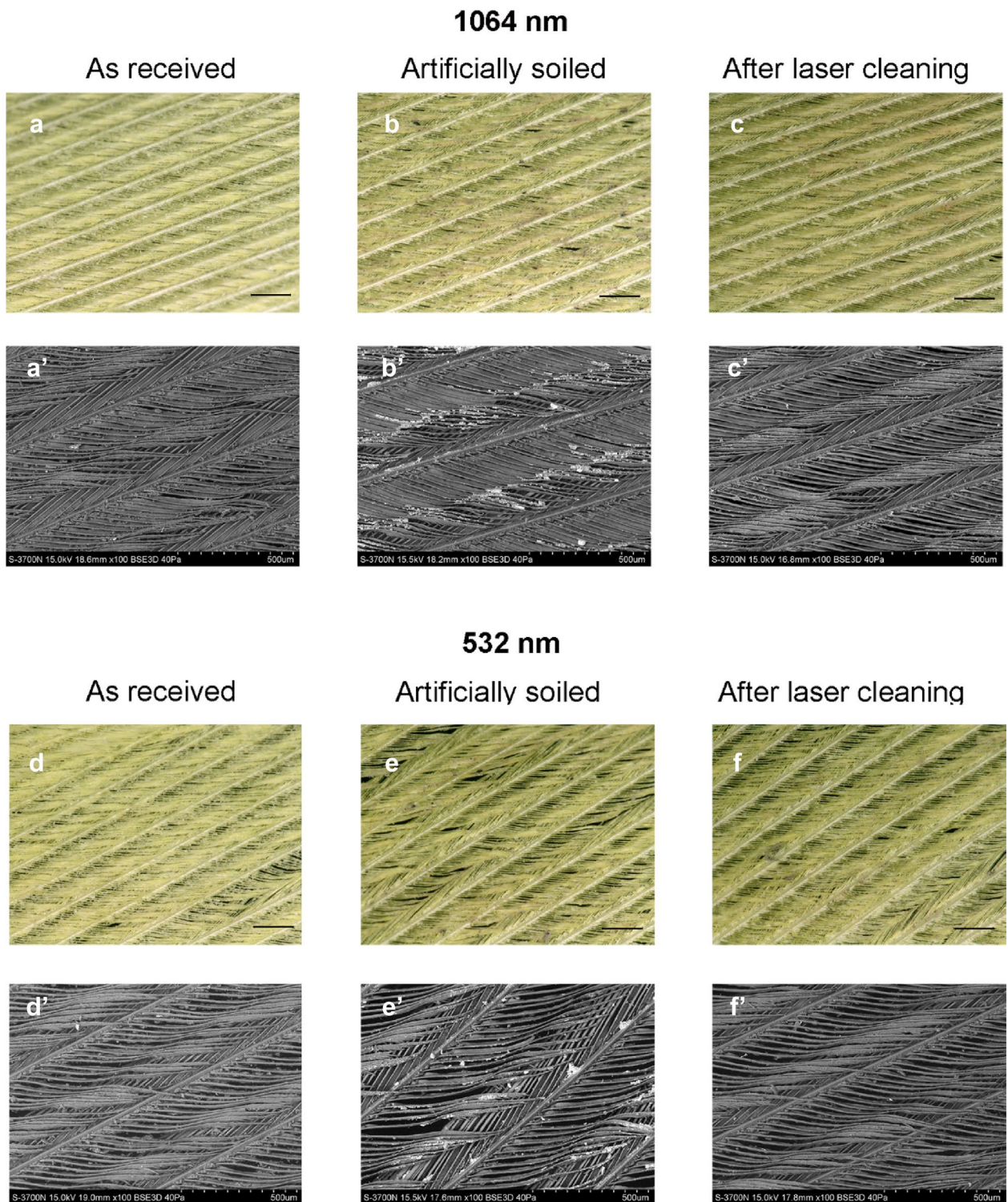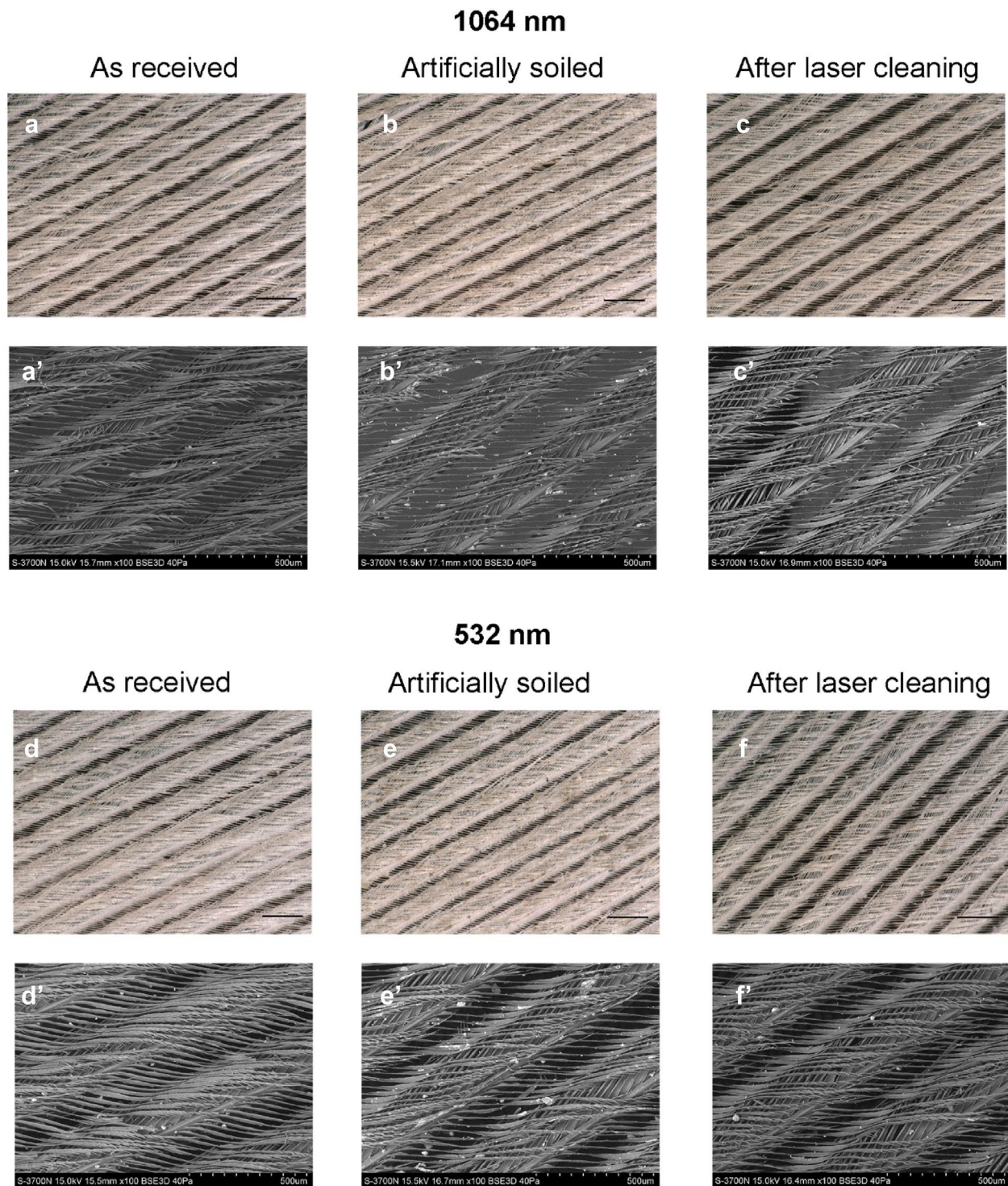
Fig. 7 Laser cleaning tests at 1064 nm (top) and 532 nm (bottom) of yellow cockatoo feathers artificially soiled with dust. Optical microscope images (**a**, **b**, **c**, **d**, **e**, **f**—bars = 500 μm) and their corresponding SEM images (**a′**, **b′**, **c′**, **d′**, **e′**, **f′**). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.
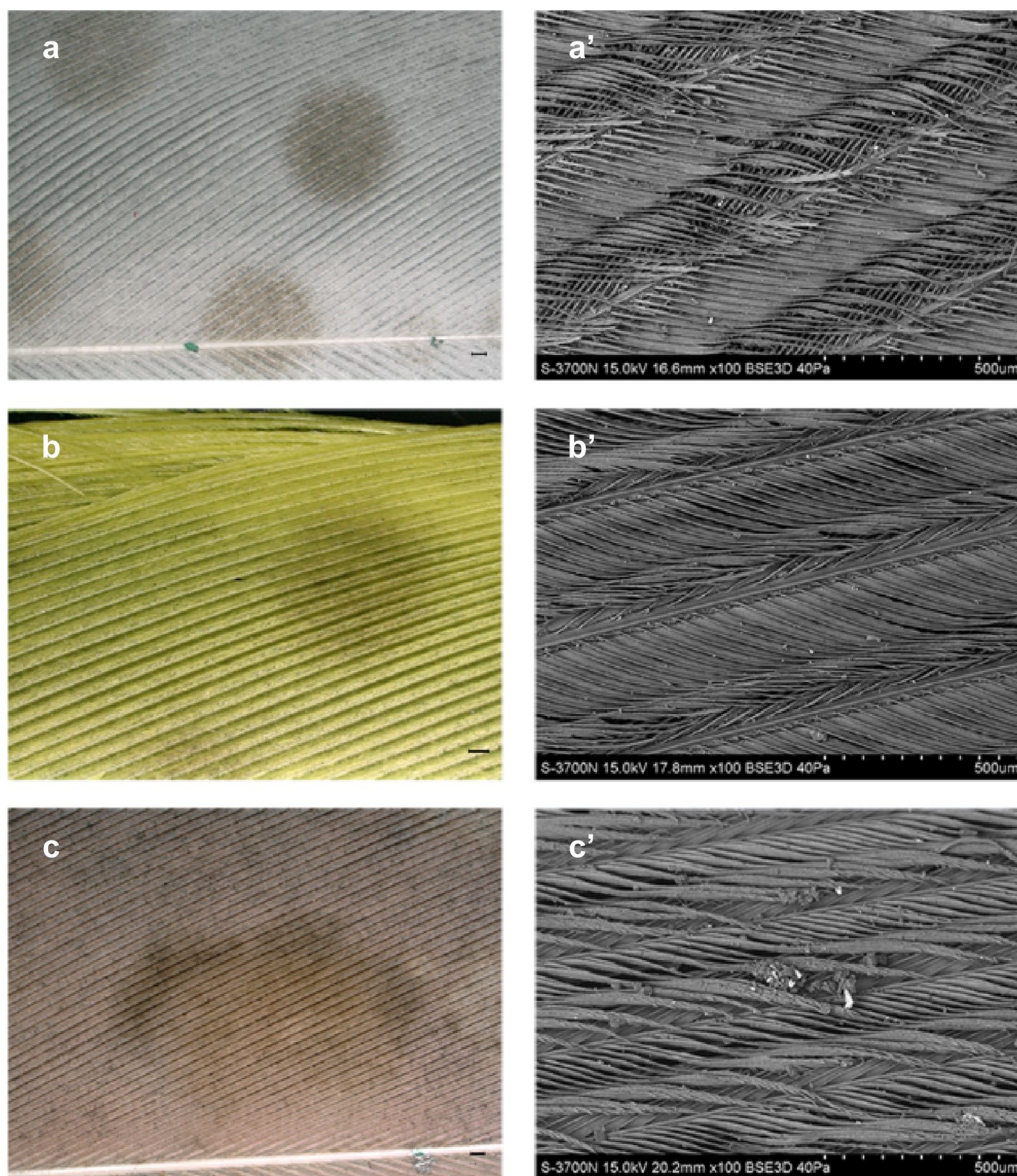
Fig. 8 Laser cleaning tests at 1064 nm (top) and 532 nm (bottom) of light pink flamingo feathers artificially soiled with dust. Optical microscope images (**a**, **b**, **c**, **d**, **f**—bars = 500 μm) and their corresponding SEM images (**a'**, **b'**, **c'**, **d'**, **e'**, **f'**). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

Fig. 9 Laser cleaning tests at 1064 nm at a fluence of 0.5 J/cm.² of feathers covered with a thin layer of carbon black, from top to bottom: white, yellow and pink feathers. Optical microscope images (**a**, **b**, **c**—bars = 500 µm), and their corresponding SEM images (**a'**, **b'**, **c'**). © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

bands of −OH groups. As the main component of feathers is β-keratin, an OH-group-rich protein, feathers readily absorb the Er:YAG laser radiation and experience thermal damage.

In particular, the colour of the feathers was seen to play an important role. Dark feathers that contain melanin, like pigeon feathers, were extremely sensitive to laser damage, displaying pronounced physical damage at the lowest fluence delivered by our setup (i.e. 0.3 J/cm²).

Figure 10 shows the important damage of the barbs and barbules caused by laser irradiation.

The other coloured feathers had the same damage threshold fluence as the white feathers (i.e. 0.4 J/cm²). For the red Amazon parrot feathers. There was a marked discoloration alongside physical damage, see the yellow pale region in Fig. 11a. Note that the red parrot feather had its barbules disturbed in its "as received" condition and no morphological change related to the laser ablation was observed using the SEM (Fig. 11b). Amazon red
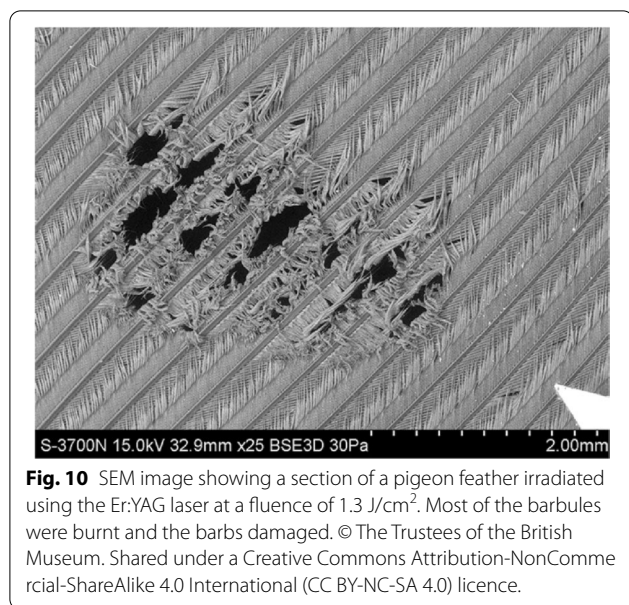
Fig. 10 SEM image showing a section of a pigeon feather irradiated using the Er:YAG laser at a fluence of 1.3 J/cm^2. Most of the barbules were burnt and the barbs damaged. © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

parrot feathers contain psittacofulvins, which are known to be chemically sensitive to light [7]. The laser irradiation most likely caused bleaching of the psittacofulvins, as often observed on carotenoids [40, 53–55]. No discolouration was observed visually on yellow and green parrot feathers (also containing psittacofulvins), possibly due to a less pronounced colour contrast than on red feathers (i.e. bleaching is less visible on a light background than on a dark one) or a greater lightfastness of the yellow bio-pigment.

Based on these observations, it was concluded that the Er:YAG laser would be unsuitable for the cleaning of any kind of feathers.

Conclusions

This study investigated the potential of the Nd:YAG and Er:YAG lasers to remove soiling from a set of feathers with different bio-pigments, synthetic dyes and structural colours, but also iridescent and white feathers.

The outcomes with the Nd:YAG laser were promising. White, yellow (psittacofulvins) and pink (carotenoids) feathers tended to experience no visible laser damage at the highest fluence delivered by our setup, i.e. 1.8 J/cm^2 at 1064 nm and 1.2 J/cm^2 at 532 nm. However, in the feathers with black or grey barbules (i.e. all the other feathers tested, apart from the dyed and down feathers) the damage threshold fluence was lowered both at 1064 and 532 nm and loss of iridescence and discoloration were observed after laser irradiation. This showed that laser cleaning is not suitable for feathers rich in melanin, due to its capacity to absorb light and release it as heat especially in the near infrared wavelength [11, 56]. Also, the dark pink flamingo feathers (carotenoids) had a lower damage threshold fluence at 532 nm than paler pink feathers. This was possibly due to the high absorption of carotenoids at 532 nm, their light sensitivity and their higher quantity within the feather. Further, laser cleaning of down feathers should be avoided as their extremely fine barbs suffered thermal damage.

Laser cleaning tests were conducted on a set of feathers (white feathers, green dyed feathers and feathers containing psittacofulvins and carotenoids) that were artificially soiled with dust or carbon black. The Nd:YAG laser was successful at removing dust at both wavelengths from all these feathers, with no apparent damage as observed by optical microscopy and SEM. However, it was not possible to remove carbon black from any of the feathers and darkening was observed.
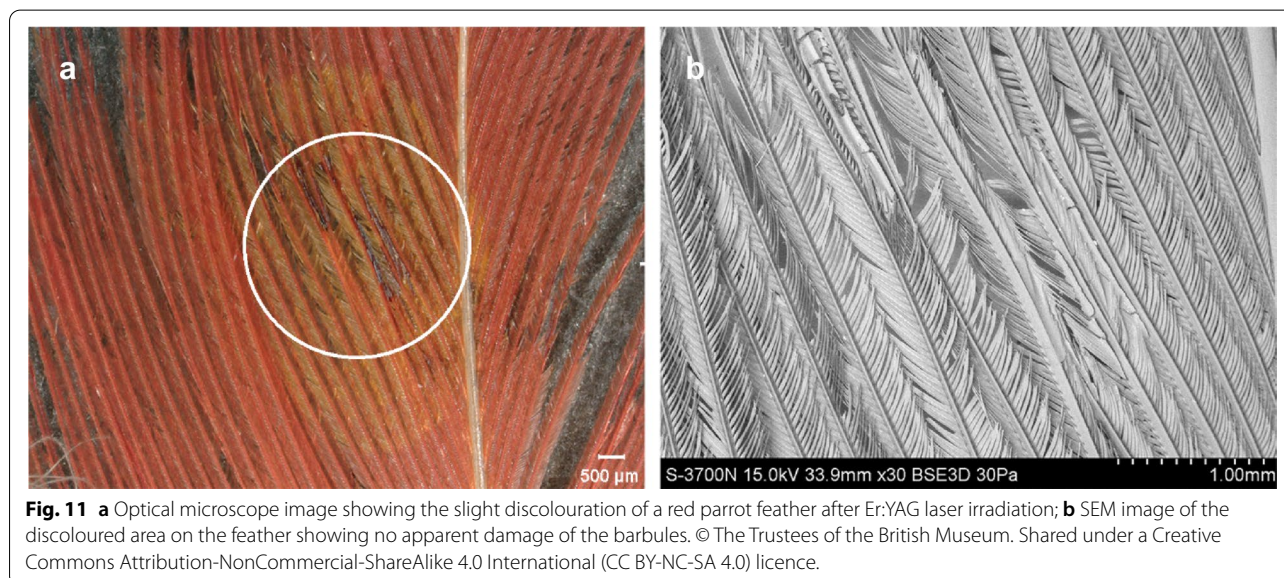

Fig. 11 **a** Optical microscope image showing the slight discolouration of a red parrot feather after Er:YAG laser irradiation; **b** SEM image of the discoloured area on the feather showing no apparent damage of the barbules. © The Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

The fact that feathers containing melanin are extremely sensitive to laser damage limits the application of laser cleaning to feathers. Even for feathers that contain little or no melanin, their structure and bio-pigment concentration could make them vulnerable to thermal damage or discolouration. All these factors would need to be pondered carefully before considering laser cleaning.

With thermally sensitive objects, such as feathers, the assessment of the cleaning outcomes only with microscopy and visual observation is not entirely reliable to ensure that laser cleaning does not have any detrimental effect in the long-term. For instance, silk has been reported to be laser cleaned visually successfully, but further tests revealed that its chemical structure had been affected and its mechanical strength considerably lowered [57]. Therefore, to ensure that laser cleaning is entirely suitable for feathers and bio-pigments, chemical and spectroscopic analysis should be carried out in the future.

Also, our study was limited to dust lightly deposited on feathers and it would be beneficial to investigate the removal of other types of contaminants, such as cohesive and hard-to-remove layers of dust (i.e. cement dust, see [58–60] for more details) or oily deposit, which can be very difficult to remove using traditional conservation methods.

To conclude, the laser could be a useful tool for conservators tasked with the delicate job of cleaning feathers. However, the differing complexities of feathers across the many and varied species in cultural heritage objects make it difficult to create a "one size fits all" approach to their cleaning.

Abbreviations

Er:YAG: Erbium-doped Yttrium Aluminium Garnet; Nd:YAG: Neodymium-doped Yttrium Aluminium Garnet; QS: Nd:YAG—Q-switched Nd:YAG; LQS: Nd_YAG—Long Q-switched Nd:YAG; N.A.: Not available; OM: Optical microscopy; VP-SEM: Variable pressure—scanning electron microscopy; SEM: Scanning electron microscopy; ATR-FTIR: Attenuated Total Reflection-Fourier Transform Infrared.

Author contributions

MB and CK designed the experiments; MB performed and interpreted the data for the Raman analyses; MB performed the laser cleaning tests and the OM and SEM assessment; MB and CK interpreted the data; MB and CK wrote and edited the manuscript; CK supervised the project. All authors read and approved the final manuscript.

Declarations

Competing interests

The authors declare no competing interests.

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References

1. Lucas AM. Avian anatomy integument: Avian Anatomy Project, Poultry Research Branch, Animal Science Research. Washington: US Department of Agriculture; 1972.
2. Riedler R, Pesme C, Druzik J, Gleeson M, Pearlstein E. A review of color-producing mechanisms in feathers and their influence on preventive conservation strategies. J Am Inst Conserv. 2014;53(1):44–65.
3. Delhey K, Peters A, Kempenaers B. Cosmetic coloration in birds: occurrence, function, and evolution. Am Nat. 2007;169(S1):S145–58.
4. Osorio D, Ham A. Spectral reflectance and directional properties of structural coloration in bird plumage. J Exp Biol. 2002;205(14):2017–27.
5. Hudon J. Considerations in the conservation of feathers and hair, particularly their pigments. Fur trade legacy The preservation of organic materials. 2005:127–47.
6. Toral G, Figuerola J, Negro JJ. Multiple ways to become red: pigment identification in red feathers using spectrometry. Comp Biochem Physiol B: Biochem Mol Biol. 2008;150(2):147–52.
7. Daher C, Tournié A, Sauvagnargues F, Andraud C, Cuisin J, Illes V, et al. Colored feathers in museum collections: a spectroscopic study of 3 bio-pigments and their lightfastness. J Cult Herit. 2020;45:59–70.
8. Hill GE, McGraw KJ, Kevin J. (Eds.). Bird coloration, volume 1: mechanisms and measurements. Harvard University Press. 2006;1.
9. McGraw KJ. Mechanics of melanin-based coloration. In: Hill GE, McGraw KJ, editors. Bird coloration. Harvard Uniersity Press: Cambridge; 2006. p. 243–94.
10. McGraw KJ, Nogare MC. Carotenoid pigments and the selectivity of psittacofulvin-based coloration systems in parrots. Comp Biochem Physiol B: Biochem Mol Biol. 2004;138(3):229–33.
11. Shawkey MD, Morehouse NI, Vukusic P. A protean palette: colour materials and mixing in birds and butterflies. J R Soc Interface. 2009;6(suppl_2):S221–31.
12. Shawkey MD, D'Alba L. Interactions between colour-producing mechanisms and their effects on the integumentary colour palette. Philos Trans R Soc B Biol Sci. 2017. https://doi.org/10.1098/rstb.2016.0536.
13. Jeon D-J, Paik S, Ji S, Yeo J-S. Melanin-based structural coloration of birds and its biomimetic applications. Appl Microsc. 2021;51(1):1–11.
14. Pearlstein E. The conservation of feather work from Central and South America. Americas. 2017;75(1):198–9.
15. Wright MM. The conservation of fur, feather and skin: seminar organised by the conservators of ethnographic artefacts at the museum of London on 11 December 2000. Archetype Publications; 2002.
16. Barton G, Weik S. Ultrasonic cleaning of ethnographic feather work in aqueous solutions. Stud Conserv. 1986;31(3):125–32.
17. da Silveira L. A note on the poultice cleaning of feathers using Laponite RD gel. Stud Conserv. 1997;42(1):11–6.

18. Schaeufelbut S, Tello H, Schneider S, editors. Cleaning of feathers from the Ethnological Museum, Berlin. The conservation of fur, feather and skin: seminar organised by the conservators of ethnographic artefacts at Matthew House of London on 11 December 2000; 2002.

19. Greene V. Using case studies to examine the decision-making process for cleaning ethnographic objects. J Am Inst Conserv. 2006;45(3):183–99.

20. Kolar J, Strlič M, Müller-Hess D, Gruber A, Troschke K, Pentzien S, et al. Laser cleaning of paper using Nd: YAG laser running at 532 nm. J Cult Herit. 2003;4:185–7.

21. Strlič M, Kolar J, Šelih V-S, Marinček M. Surface modification during Nd: YAG (1064 nm) pulsed laser cleaning of organic fibrous materials. Appl Surf Sci. 2003;207(1–4):236–45.

22. Castillejo M, Martín M, Oujja M, Rebollar E, Domingo C, García-Ramos JV, et al. Effect of wavelength on the laser cleaning of polychromes on wood. J Cult Herit. 2003;4(3):243–9.

23. Kautek W. Laser cleaning of paper and other organic materials. Technology. 2008;2:2.

24. De Cruz A, Andreotti A, Ceccarini A, Colombini MP. Laser cleaning of works of art: evaluation of the thermal stress induced by Er: YAG laser. Appl Phys B. 2014;117(2):533–41.

25. Bertasa M, Ricci C, Scarcella A, Zenucchini F, Pellis G, Croveri P, et al. Overcoming challenges in street art murals conservation: a comparative study on cleaning approach and methodology. Coatings. 2020;10(11):1019.

26. Pouli P. Laser cleaning on stonework: principles, case studies, and future prospects. In: Francesca G, Pagona NM, editors. Conserving stone heritage. Springer; 2022. p. 75–100.

27. Torrisi A, Torrisi L. Pulsed laser cleaning (PLC) applied to samples in cultural heritage field. Radiat Eff Defects Solids. 2022. https://doi.org/10.1080/10420150.2022.2049780.

28. Chillè C, Agresti J, Ciofini D, Mencaglia A, Osticioli I, Siano S. Measurement of temperature gradients during Er: YAG laser irradiation of poly (vinyl alcohol). J Phys Conf Ser. 2022. https://doi.org/10.1088/1742-6596/2204/1/012071.

29. Bertasa M, Korenberg C. Successes and challenges in laser cleaning metal artefacts: a review. J Cult Herit. 2022;53:100–17.

30. Asmus JF. Laser divestment for natural history museum collections. J Cult Herit. 2000;1:S259–62.

31. Asmus JF, Abraham M. Laser dusting of delicate objects. Optical methods for arts and archaeology. Inter Soc Opt Photonics. 2005. https://doi.org/10.1117/12.612461.

32. Pacaud G, Lemaire J. Le nettoyage au laser d'un jaunissement observable sur des plumes blanches ayant subi un traitement par laser yag de désincrustation. La Lettre de l'OCIM. 2000;67:21–32.

33. Dignard C, Lai W-F, Binnie N, Young G, Abraham M, Scheerer S. Cleaning of soiled white feathers using the Nd: YAG laser and traditional methods. In: Dickmann Klaus, Fotakis Costas, Asmus John F, editors. Lasers in the conservation of artworks. Springer; 2005. p. 227–35.

34. Karantoni E, Ekaterini M. The influence of cleaning methods on feather structure: a comparative study CAC 31st annual conference and workshop. Jasper: Canada; 2005.

35. Pandozy S, Rivière C, Brunori M, Nepote F, Rivalta A, Santamaria U, et al. Sperimentazione sull'uso del laser per la pulitura delle piume presenti nella Collezione Etnologica dei Musei Vaticani. APLAR 5 Applicazioni laser nel restauro, Musei Vaticani: Nardini Editore; 2015.

36. L.P. Gnaccolini, G. Rossignoli, Mantello cerimoniale tupinambá fine del XVI - inizio del XVII secolo Restituzioni. Tesori d'arte Restaur., 18th ed. Marsilio - Intesa San Paolo. http://www.restituzioni.com/opere/mantello-cerimoniale-tupinamb/. 2018;529–537.

37. Colantonio C, Lanteri L, Ciccola A, Serafini I, Postorino P, Censorii E, et al. Imaging diagnostics coupled with non-invasive and micro-invasive analyses for the restoration of ethnographic artifacts from French Polynesia. Heritage. 2022;5(1):215–32.

38. Ciofini D, Rossignoli G, Tosini I, Lanterna G, Siano S. Laser ablation treatment of soiled featherworks: the first validation study. J Cult Herit. 2022;56:118–29.

39. Solajic MR, Cooper M, Seddon T, et al. Multidisciplinary investigation of the Amazonian feather work from the ethnographic collection at the national museum and galleries on Merseyside colourful feathers. In: Wright M, editor., et al., The conservation of fur feather and skin. London: Archetype; 2000. p. 69–78.

40. Fox DL. Feather carotenoids of an interspecific hybrid flamingo. Comp Biochem Physiol Part B: Comp Biochem. 1974;48(2):295–8.

41. Amat JA, Rendón MA. Flamingo coloration and its significance. In: Matthew JA, editor. Flamingos, behavior, biology, and relationship with humans. Nova Science Publishers; 2017. p. 77–95.

42. Veronelli M, Zerbi G, Stradi R. In situ resonance Raman spectra of carotenoids in bird's feathers. J Raman Spectrosc. 1995;26(8–9):683–92.

43. Stradi R. The colour of flight: carotenoids in bird plumage. Solei Gruppo Editoriale Informatico. 1998.

44. Koyama Y, Takatsuka I, Nakata M, Tasumi M. Raman and infrared spectra of the all-trans, 7-cis, 9-cis, 13-cis and 15-cis isomers of β-carotene: Key bands distinguishing stretched or terminal-bent configurations form central-bent configurations. J Raman Spectrosc. 1988;19(1):37–49.

45. de Oliveira LN, de Oliveira VE, Dávila S, Edwards HG, de Oliveira LFC. Raman spectroscopy as a tool for polyunsaturated compound characterization in gastropod and limnic terrestrial shell specimens. Spectrochim Acta Part A: Mol Biomol Spectrosc. 2013;114:541–6.

46. Tay EJ, Barnsley JE, Thomas DB, Gordon KC. Elucidating the resonance Raman spectra of psittacofulvins. Spectrochim Acta Part A Mol Biomol Spectrosc. 2021;262: 120146.

47. Choudhury AR. Textile preparation and dyeing. USA: Science publishers; 2006.

48. Brannt WT. The techno-chemical receipt book. Henry Carey Baird; 1919.

49. Freyer P, Wilts BD, Stavenga DG. Reflections on iridescent neck and breast feathers of the peacock, Pavo cristatus. J R Soc Interface Focus. 2019;9(1):20180043.

50. Rogalla S, Patil A, Dhinojwala A, Shawkey MD, D'Alba L. Enhanced photothermal absorption in iridescent feathers. J R Soc Interface. 2021;18(181):20210252.

51. Chen S-W, Lu J-Y, Tung P-H, Lin J-H, Chiesa M, Hung B-Y, et al. Study of laser actions by bird's feathers with photonic crystals. Sci Rep. 2021;11(1):2430.

52. Berthonneau J, Parent P, Grauby O, Ferry D, Laffon C, Colombini A, et al. Yellowing of laser-cleaned artworks: formation of residual hydrocarbon compounds after Nd: YAG laser cleaning of gypsum plates covered by lamp black. J Cult Herit. 2019;39:57–65.

53. Surmacki A. Preen waxes do not protect carotenoid plumage from bleaching by sunlight. Ibis. 2008;150(2):335–41.

54. Chiale MC, Rendón MA, Labaude S, Deville AS, Garrido-Fernández J, Pérez-Gálvez A, et al. The color of greater flamingo feathers fades when no cosmetics are applied. Ecol Evol. 2021;11(20):13773–9.

55. Krinsky NI, Yeum K-J. Carotenoid–radical interactions. Biochem Biophys Res Commun. 2003;305(3):754–60.

56. Sarna T, Swartz HA. The physical properties of melanins. In: James JN, Raymond EB, Vincent JH, Richard AK, William SO, Jean-Paul O, editors. The pigmentary system: physiology and pathophysiology. Blackwell Publishing Ltd; 2006. p. 311–41.

57. Taarnskov B, Pouli P, Bredal-Jørgensen J. Laser cleaning studies for the removal of tarnishing from silver and gilt silver threads in silk textiles. In: Roxana R, John FA, Marta C, Paraskevi P, Austin N, editors. Lasers in the conservation of artworks VIII. CRC Press; 2011. p. 8.

58. Brimblecombe P, Thickett D, Yoon YH. The cementation of coarse dust to indoor surfaces. J Cult Herit. 2009;10(3):410–4.

59. Kuzmichev A, Azarov V, Stefanenko I. The impact of dust particles on cultural heritage objects in the field of environmental mechanics. Appl Mech Mater. 2018. https://doi.org/10.4028/www.scientific.net/AMM.878.259.

60. Shah B, Hunter S, Adams S. When the dust settles: dust monitoring in exhibitions at the Victoria and Albert museum. Int Preserv News. 2011;53:24.

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