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SCIENTIFIC RESEARCH

Nascent oxygen innovation in art conservation: Cold atmospheric pressure plasma-generated monoatomic oxygen for the non-contact cleaning of works of art

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Abstract

The climate crisis and unsustainable living increasingly threaten tangible cultural heritage around the world, including through the deposition of carbon-

INTRODUCTION

Challenges in cleaning sensitive object surfaces from carbon-based contaminants

The sustainable preservation of tangible cultural heritage is inherently linked to the UN's sustainability goals (SDG 11.4), but the conservation field currently lacks empowering green technologies, especially in cleaning treatments. Conservators, equipped only with contact methods, increasingly encounter sensitive surfaces where soiling cannot be removed at all. Carbon-based contaminants (CBC) constitute a significant portion of soiling materials (soot, organic compounds, organic aerosols, particulate matter, tobacco smoke deposits, handprints, bacteria and fungi, conservation materials, pesticides, food, vandalism materials, etc.) and are a major factor in the deterioration of tangible cultural heritage assets. Among the typical CBC, soot from fire and wildfires can swiftly cause catastrophic soiling damage to an entire collection. Developing effective fire-damage remedies is an acknowledged priority. Wildfires as well as arson relating to social unrest are becoming ever more frequent and will be further exacerbated by the climate crisis, forewarning us of future challenges. The available "wet" and "dry" contact cleaning methods used to remove CBC risk abrading the surface and transporting contaminants into the porous substrate, displacing loose fragments, swelling and shrinking the paint, and facilitating the migration of leachable components. Contact cleaning is particularly problematic with sensitive object surfaces (SOS), such as porous mineral materials (plaster, alabaster), friable media (pastels, modern paints), woven and nonwoven materials (unprimed canvases, textile, paper), animal-sourced materials (feathers, silk, ivory), plastics, and modern experimental media, and further complicated by challenging geometries and intricate topographies. Moreover, Indigenous communities consider the use of organic solvents unacceptable on sacred objects. Alternative methods, such as particle or CO_2 snow blasting, may displace loose paint particulates and cause micro-pitting, making them unsuitable for physically vulnerable SOS. Laser methods offer valuable non-contact alternatives but have limitations in treating SOS (Pouli et al. 2012). For example, laser is inherently directional in its action, which can be problematic for irregular porous surfaces, as ghosting of the CBC may remain. The available plasma sources were designed for different purposes. Moreover, the high temperatures and UV (100–400 nm) or

based contaminants from pollution, transport, fires, and vandalism. Many fragile porous art materials cannot tolerate "wet" or "dry" contact cleaning methods, which often use organic solvents and chemicals with adverse health and environmental impacts. A radically different approach to cleaning is the use of cold plasma-generated nascent (atomic) oxygen (AO) to remove contaminants in a non-contact, solvent-free process. The AO approach was pioneered by B. Banks and S. Miller at the National Aeronautics and Space Administration and its advancement was explored in this study in tests conducted at the Low Earth Orbit Facility at the European Space Agency. This novel atmospheric pressure AO technology for non-contact cleaning, as developed in the MOXY and PlasmArt projects,[1] is discussed.

VUV (10–200 nm) radiation can be destructive to many cultural heritage materials (Voltolina et al. 2016).

From space to art: Towards new non-contact cleaning systems using AO

The advancement of nascent or atomic oxygen (AO) technology may offer a breakthrough in the removal of CBC using a non-contact process. AO, consisting of a single oxygen atom, is a space-environment material found naturally at altitudes of 80–1000 km, where it is produced photochemically through the influence of solar radiation on O_2. AO is highly unstable and reactive, and in space it has a kinetic energy of approximately 5eV. AO is a major erosion factor for spacecraft materials (Banks 2013) and during the past thirty years, both the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have investigated AO interactions with aerospace materials and developed AO simulation systems. That work has provided a foundation for AO technology in conservation. AO innovations in this setting started with the pioneering work of NASA scientists Sharon Miller and Bruce Banks in the 1990s, in their attempt to remove lipstick defacement from the early, hand-painted Andy Warhol painting *Bathtub* (1961), displayed at the Andy Warhol Museum, in Pittsburgh, PA (USA) (Banks et al. 1999). The scientists later tested the use of AO on smoke- and fire-damaged art materials, such as plaster, sandstone, textiles, paper, and paintings (Banks et al. 2003, Miller et al. 2004).

INNOVATION IN NON-CONTACT DRY-CLEANING USING ATMOSPHERIC PLASMA-GENERATED NASCENT OXYGEN

The concept of nascent (atomic) oxygen

To develop AO technology for conservation, the initial threshold challenge is to produce and deliver it to the artwork surface at atmospheric pressure conditions. AO is extremely short-lived on the ground (a few milliseconds). At about 250 km altitude, AO exists without instant recombination since only about 10^9 atoms are found in 1 cm^3 (de Rooij 2010). This is an infinitely small number, as the air we breathe contains approximately 1.6×10^{19} oxygen atoms per 1 cm^3. NASA and ESA have typically conducted AO experiments using low-pressure chambers, where AO is produced using a radio frequency (RF) field or laser detonation. Other methods were summarized by Kleiman (Kleiman et al. 2003). However, the low-pressure approach is impractical for conservation because of the size and cost of the system, the lack of access to the object during treatment, and the fact that the vacuum itself can be disruptive to art materials. In an alternative atmospheric approach, AO is produced and then used instantaneously. This process was first proposed by BruceBanks and Sharon Miller (Banks et al. 1999) in the treatment of the Warhol painting, in which atmospheric AO was formed by flowing O_2 in He gas through a high-voltage (5–7 kV), low-current (5–6 mA) DC arc. The AO was directed to the surface and removed the lipstick defacement (3.5 × 3.3 cm) in an incremental process (3.5 hours). Treatment included a second phase to remove the residuum, using a Groom Stick dry-cleaning material.[2] However, after this application and follow-up tests at NASA, the first AO proof-of-concept was not used for further studies in conservation and was disassembled. Thus, the AO concept

was hatched long ahead of its time, but it took decades for it to resurface in a new context (Markevičius et al. 2017) and evolve into a full-scale R&D project in 2022. In addition to the use of non-contact AO to remove CBC from the problematic porous and fragile surfaces listed above, AO can replace traditional sterilization methods, eliminating microorganisms and spores and preventing their reactivation. The by-products of AO cleaning are volatile species, such as CO, CO_2, and H_2O, resulting from the controlled oxidation of soiling, such that the process is both ecological and sustainable (Hill 1999).

However, given the challenges in the practical application of AO in conservation, as previously mentioned, a new AO technology, tailored for conservation, is needed to produce and use AO simultaneously (Figure 1). In our approach, a tailored system achieving target AO fluencies of around 10^{21} m^{-3} is obtained by flowing O_2 in He (0.1–10 v% O_2) using an RF field at 13.56 MHz. The pulsed modulated RF field at the frequency range of 2–100 MHz is distinct from the DC used by NASA. Specifically, in our method, AO is produced by electron impact dissociation splitting of molecular oxygen into excited $O(^1D)$ and ground state $O(^3p)$, which in the next step forms the excited state oxygen $O(^1D)$ *[A]* and O_2, and in the final step $O(^3p)$ and O_2 *[B]*. The process is described by Equation (1):

$$O_2+e^- \rightarrow 2O+e^- \text{ (or) } O_2+e^- \rightarrow O(^1D) + O(^3p) + e^- \textit{ [A] } O(^1D) + O_2 \rightarrow O(^3p) + O_2 \textit{ [B]} \quad (1)$$

O_2^+ and probably O_2^- ions are also formed in the effluent and participate in $O(^3p)$ production. Ground state oxygen (O^3p) is the essential active material in the cleaning process. Upon meeting the surface, AO reacts instantly with carbon/organic soiling, producing volatile by-products such as CO, CO_2, and H_2O vapors. In a plasma-generated process, high oxygen atom fluence (atoms/area) and flux (number of atoms/area/time) with a small soft-edged active spot (2–5 mm) can be expected to result in a relatively fast cleaning process similar to that of the Banks-Miller AO system (~5 mm^2/30 s), with sufficient clearance from the surface (5–10 mm), and at temperatures tested as safe for treated surfaces. The cleaning action

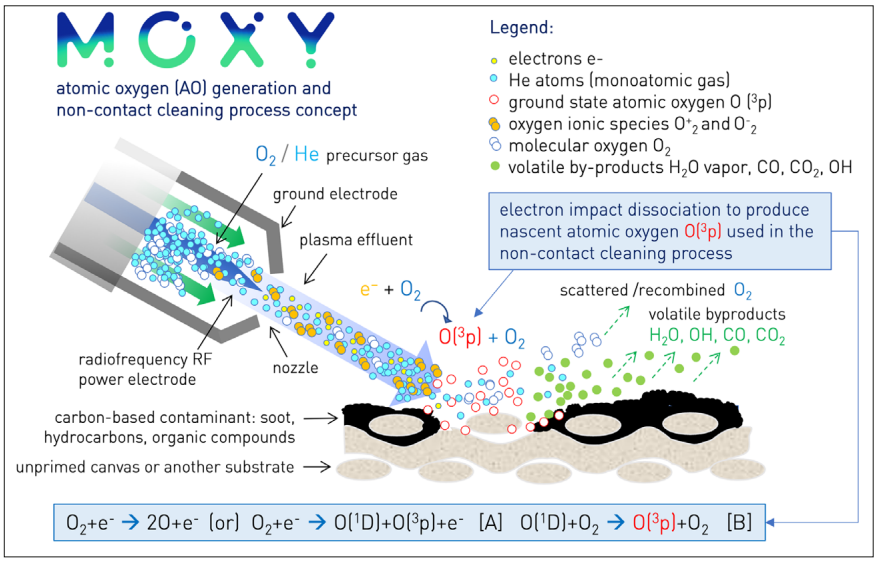

Figure 1. Schematics of the non-contact plasma-generated AO cleaning process of soot on canvas

stops immediately when the conservator halts AO generation or redirects the nozzle, as there is no retention of AO in the substrate. Nonetheless, tailoring AO for conservation at atmospheric pressure is challenging because the generator needs to produce high concentrations of AO at low energies (to avoid heat) while limiting the yield of ozone, nitrogen oxides, radical species, and UV-VUV radiation. In the atmospheric He/AO process, UV-VUV is typically formed by H* and H_2* excimers as they transition from the excited to the ground state and emit energetic resonant photons. In He/O plasma, UV-VUV dramatically decreases because the excimers are quenched by oxygen, and fewer are created because the electron energy decreases as a result of frequent collisions with other atoms (Popović et al. 2021). However, in atmospheric plasmas, a higher frequency of collisions results in higher energy levels, and the low-temperature process is more challenging. To tailor AO parameters for conservation, the He/O gas phase composition, pulsed operation, the waveform of applied voltage, and the geometry of the nozzle need to be finely tuned in a radically new AO generator design, which is among the objectives of the MOXY and PlasmArt projects.

Experimental: AO testing using the ESA's Low Earth Orbit Facility (LEOX) space simulator

To explore the effects of AO on conventional cultural heritage materials, two sets of 39 mock-ups (2 × 2 cm each), including plaster, limestone, acrylic paint, canvas, pastel, and paper, were prepared for testing with the ESA's environment simulator ESTEC TEC-QEE LEOX (Tighe 2010). The simulator consists of a vessel containing three compartments separated by an electro-pneumatic valve and a main chamber, with an orifice, where the samples are exposed to 99% AO under low-pressure conditions using CO_2 laser detonation (Figure 2a). The kinetic energy of the atoms was set at 5eV, similar to the space environment. The two sets of samples were soiled with typical contaminants, including soot and several commercial products commonly used for art vandalism (spray paint, ballpoint pen, markers, lipstick). One set was de-gassed for 72 hours in a vacuum chamber (background pressure 9 × 10^3 mbar) and aged in an isothermal chamber (ClimeEvent, Weisstechnik, C/270/70/15/M) for 14 days at 60°C/65% RH. The control set was left to age naturally in a dust-free environment. Time-of-flight mass spectrometry (TOF–MS) was performed to determine the ratio between AO and O_2. The first peak (0.2 ms) is induced by the photons emitted from the plasma and the second peak (0.3–0.5 ms) is the actual pulsed AO effluent (Figure 2b).

For the AO test, half of each sample was masked with aluminum foil before the samples were mounted in the LEOX sample holder, which has circular

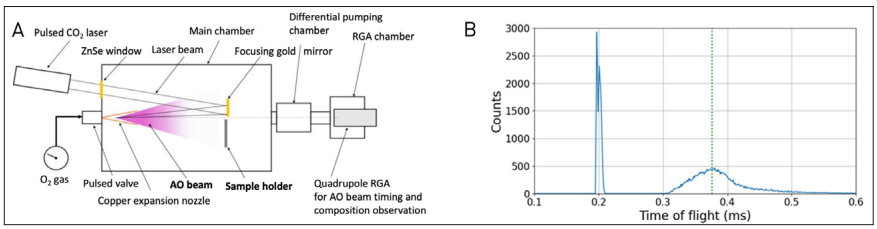

Figure 2. LEOX facility. (A) LEOX schematics, (B) AO spectra measured by time-of-flight mass spectrometry

windows for AO exposure. Each sample was divided into quadrants: A (pristine), B (soiled), C (soiled-AO cleaned), and D (pristine-AO treated) (Figure 3a). Before AO treatment, a pre-test was carried out to measure the average flux and the spread in the AO flux across the sample plate and to establish a flux map of the plates. Thirty-nine fluence witnesses (Kapton HN) were mounted on the main and extended sample plates (same as the sample number) and exposed to the AO flux for 17 hours. The AO fluence was calculated using the mass loss of the Kapton witnesses, according to ESA procedure ESA-TECQEE-LAB-PR-006707. AO fluence (At/cm^2) was set from 1.07E+20 – 9.0E+2 (AO flux [At/cm^2·sec]) to 2.10E+15 – 7.21E+15. AO exposure times of 3.18, 14, 20.7, 46.5, and 54.9 hours were selected. The samples were regularly checked, and those that appeared visually clean were removed.

Mock-up characterization and assessment methods

Nine AO-treated samples were selected for assessment. They represented porous, friable materials that are difficult to clean using mechanical "dry" and "wet" cleaning methods, and which are at greater risk of contaminant diffusion deeper into the substrate (Table 1). The samples were examined visually and using optical microscopy, 3D Hirox scanning microscopy, scanning electron microscopy (SEM, JEOL JSM-6010PLUS),

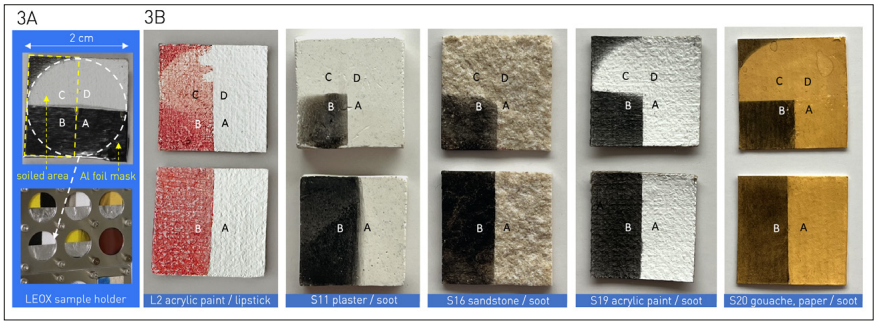

Figure 3. (a) Sample mounting for LEOX testing; AO treatment areas: (A) pristine, (B) contaminated, (C) contaminant removed with AO, (D) pristine AO-treated. (b) Examples of mockups cleaned at LEOX: acrylic paint on canvas / Boho glossy lipstick Desire 312 (contaminant L2) with two dry-cleaning tests. Mockups soiled with candle soot: plaster S11, sandstone S16, titanium white acrylic paint on canvas S19, natural yellow ochre gouache paint on paper S20. Bottom row: untreated control samples

Table 1. Samples cleaned with AO at the ESA LEOX facility: AO treatment parameters and time

#	Substrate	Contaminant	Fluence (At/cm^2)	Flux (At/cm^2·sec)	Time (hours)
S11	Plaster (gypsum)	Soot	1.84E + 20	3.67E + 15	14.0
S16	Sandstone	Soot	3.62E + 20	7.21E + 15	14.0
S19	Titanium white acrylic on canvas	Soot	5.01E + 20	2.99E + 15	46.6
S20	Paper, natural yellow ochre gouache	Soot	1.53E + 20	2.06E + 15	20.7
S26	Aged unprimed cotton canvas ca. 1977	Soot	6.10E + 20	3.64E + 15	45.5
S30	Pebeo cadmium yellow imitation oil paint (titanium white + yellow Py1)	Soot	6.84E + 20	4.09E + 15	46.5
S34	Fabriano Elle 220 g/m^2 paper	Schneider markers	7.21E + 20	2.06E + 15	54.9
L4	Titanium white acrylic on primed linen canvas	Boho Desiree 312 #1342560	2.49E + 21	7.10E + 15	54.9
S23	Titanium white acrylic on primed linen canvas	Maybelline NY 344 Coral Rise Lipstick #333836	1.14E + 21	6.82E + 15	46.5

Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR–ATR, Bruker Hyperion 3000), confocal laser microscopy (CLM, Keyence VK-X3000), gloss measurements (BYK Spectro2guide), and reflectance spectroscopy (Ava-Spec 2048L, deuterium halogen source AvaLight-DH-S-BAL, integrating sphere AvaSphere 30-REFL). The color change was compared using the CIEDE2000 (ΔE00) CIEL*a*b* color index (ASTM D2244-02).

RESULTS AND DISCUSSION

As observed with an unaided eye, CBC was effectively removed from all nine samples (Table 1), except white acrylic paint sample L2, soiled with lipstick containing titanium white and red iron oxides (Figure 3b).[3] As shown by FTIR–ATR, AO removed the lipstick's organic components (Figure 4d), which enabled the subsequent dry removal of the inorganic residuum (Figure 4e-2) using a soft rubber material (described below), based on NASA's two-phase approach to treating Andy Warhol's painting (Banks et al. 1999, Markevičius et al. 2023). In the soot-soiled samples viewed under a Hirox 3D scanning microscope, the surface appeared intact after AO cleaning, although at high magnification dispersed soot particles were found, except on plaster sample S11 (Figure 5). However, in actual treatment, this could be resolved by repeated focused AO application, since AO cleaning is an incremental process. AO was especially effective in removing soot from porous, fragile, and woven materials, such as unprimed cotton canvas (Figure 5, S26), plaster (Figure 5, S11), and sandstone (Figure 5, S16), which demonstrated the potential of novel non-contact dry-cleaning methods for porous and delicate fire-damaged cultural heritage materials.

Plaster sample S11, when examined with the unaided eye and under the microscope, appeared optimally cleaned of soot, confirmed by colorimetry

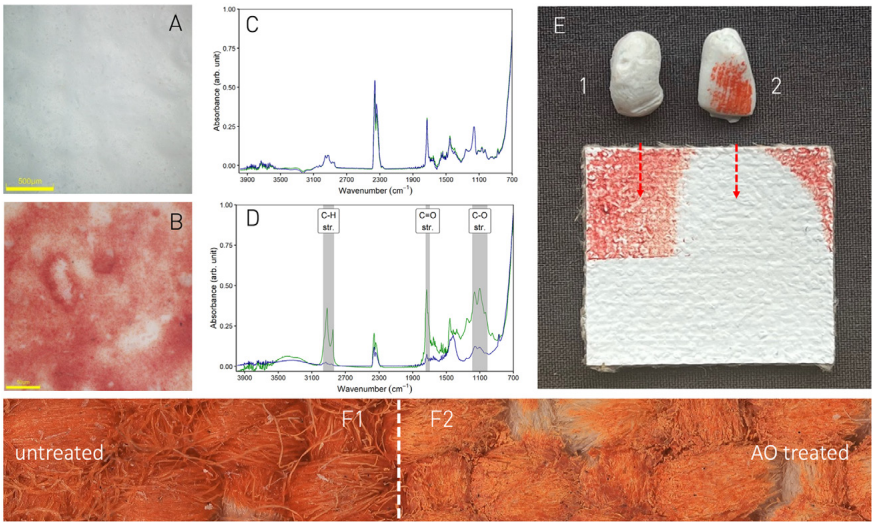

Figure 4. Reconstruction of the NASA treatment of the Andy Warhol painting on mock-up L2: titanium white acrylic paint on canvas contaminated with Boho glossy Desire 312 lipstick. (a) After lipstick removal; (b) lipstick contaminant; (c) FTIR–ATR spectra of acrylic paint before (blue) and after (green) treatment; (d) FTIR–ATR spectra of lipstick before (blue) and after AO treatment (green), showing the chemical changes in the lipstick composition; (e) two-step lipstick cleaning on sample L2: Groom Stick was ineffective in the untreated area (1) but effective in the AO-treated area (2); (f) 3D microscopy of Maybelline Coral Rise 344 lipstick on cotton duck canvas (sample S27) before AO treatment (F1) and the lipstick residuum after AO treatment (F2)

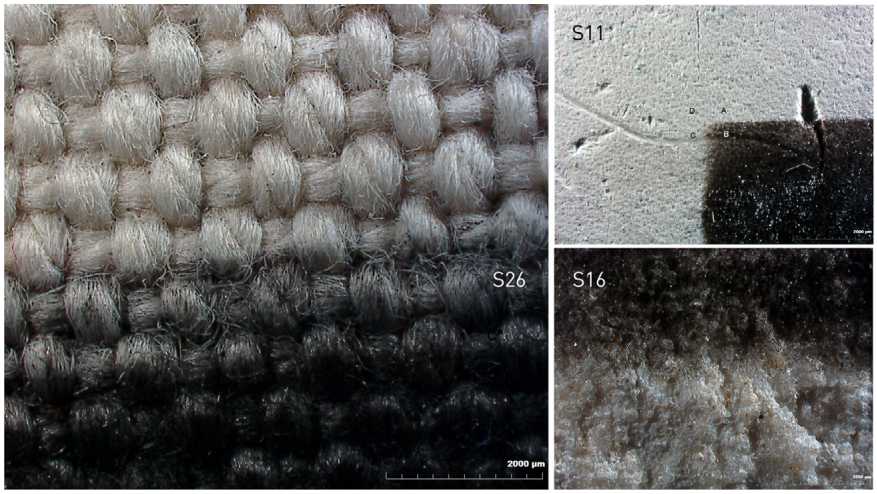

Figure 5. Soot half-removed from cotton canvas S26 (left), plaster S11, and sandstone S16 as observed under Hirox 3D microscopy. S11 area (a) pristine; (b) soot; (c) soot cleaned with AO; (d) pristine, treated with AO

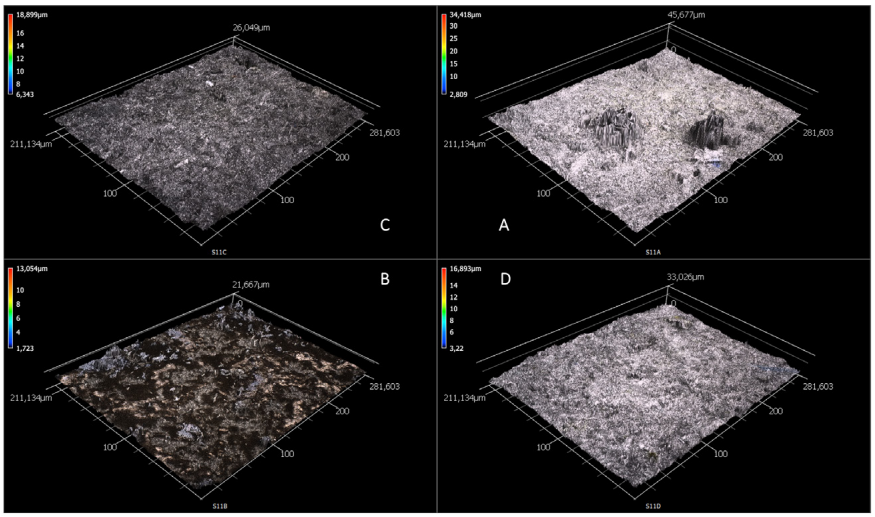

Figure 6. Plaster S11 sample roughness changes were examined using CLM. (a) pristine; (b) soot contaminant; (c) soot cleaned with AO; (d) pristine, treated with AO

and gloss measurements. However, at the micrometer scale, using CLM, changes in the micro-roughness were detected, but they were caused by the heat-deposited soot, not by the AO treatment. The micro-roughness was quantified by calculating the RΔq value.[4] The RΔq of plaster sample S11 in the pristine area (Figure 6a) was 1.150 µm, with a similar value for the pristine/AO treated area (Figure 6d) of 1.650 µm, indicating that AO did not affect micro-roughness. However, the contaminated area (Figure 6b) was smoother (RΔq 5.411 µm), as was the area where the contaminant was removed (Figure 6c, RΔq 5.412 µm), suggesting that both soot and heat affected the micro-roughness (Figure 6). Overall, there were no adverse effects on the AO-cleaned samples when visually inspected. When the color change was assessed with spectrocolorimetry (Figure 7a), the highest ΔE^*_{00} values were measured in the comparisons of pristine and soiled areas (A vs. B) and, conversely, between soiled and cleaned areas (B vs. C). The ΔE^*_{00} between pristine and cleaned areas (A vs. C) was around or below the perceivable ΔE threshold of 2.3 (Sharma and Bala 2003). In sample S26, a small amount of soot remained in the cotton fibers after cleaning (ΔE_{00} A vs. C: 3.9). In sample S30 (yellow oil paint/soot), the not-soiled area (D) was lighter after AO treatment (ΔE^*_{00} A vs. D: 3.4), but the color

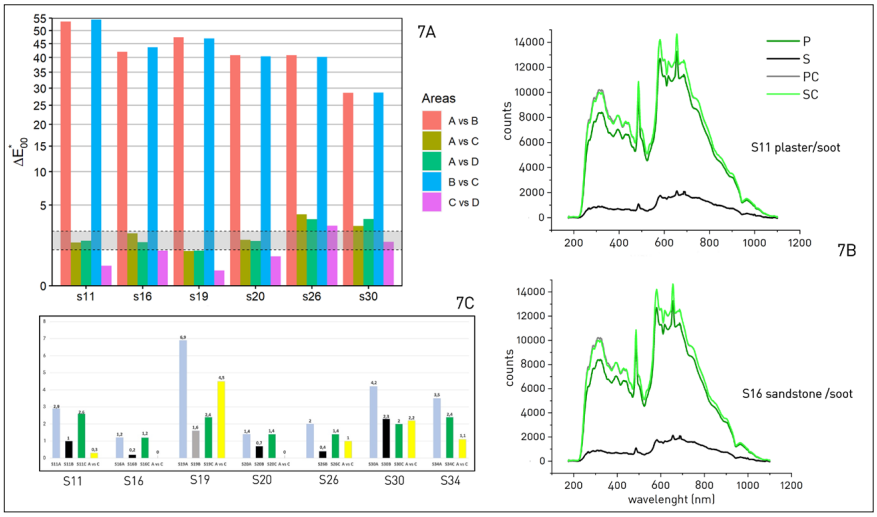

Figure 7. (a) Color measurements: the A vs. C bar (khaki) shows the ΔE^*_{00} between pristine and cleaned points. The dotted lines indicate the area between the upper ($\Delta E^*_{ab} \approx 2.3$) and lower ($\Delta E^*_{00} \approx 1.0$) limits on a just noticeable difference (JND) range of values. The *y*-axis is in square root scale to enhance readability. (b) Reflectance spectra of plaster S11 and sandstone S16: pristine (P), soiled (S), pristine-AO treated (PC), soiled AO-cleaned (SC). (c) Gloss measurements: the yellow bar shows the change between pristine, and AO-cleaned areas A vs. C

change in the soiled and then AO-cleaned area (ΔE^*_{00} A vs C: 2.7) was just slightly above the ΔE^*_{00} threshold of 2.3 (Sharma and Bala 2003, Miller and Druzik 2012). Assessments of the plaster S11 and sandstone S16 samples by reflectance spectroscopy showed significant absorption in the contaminated area (S: black), while the spectra of the soiled/cleaned (SC: green), pristine (P: dark green), and pristine/AO-treated (PC: gray) areas nearly coincided, indicating effective cleaning (Figure 7b). The gloss change in plaster sample S11 was 0.3 GU, but in other matte samples (sandstone S16, gouache S20) it was zero (Figure 7c: A vs. C, yellow bar). For sample S19 (acrylic paint), the AO-treated area became more matte (4.5 GU), but subsequent dry-cleaning with an eraser restored the sheen, an observation that requires further investigation. Gloss changes were observed in organic substrates, such as oil paint S20 (2.2 GU), cotton duck canvas (1 GU), and paper S34 (1.1 GU) (Figure 7c).

In the reconstruction of NASA's Warhol treatment, two contemporary lipsticks (Boho Desiree 312 #1342560 and Maybelline Coral Rise 344 #333836) were exposed to AO under low-pressure conditions, which made the lipsticks appear lighter but did not remove them. The lipsticks contained red iron oxides and titanium white, which are metal oxides typically unaffected by AO. However, the AO step was essential, as it converted the organic compounds in the lipstick into volatile species, leaving a loose powdery residuum on the surface. This enabled the gentle dry removal of the residual powder using a tacky natural rubber material in a second step, repeating NASA's methodology (Figure 4a, b, e); notably, dry-cleaning was ineffective in the untreated area (Figure 4e-1). Chemical surface changes of the acrylic paint substrate were investigated using FTIR–ATR. Matching FTIR–ATR spectra (Figure 4c) in the pristine (blue) and cleaned areas (green) showed effective cleaning without noticeable chemical changes to the substrate. FTIR–ATR spectra in the untreated lipstick area (green) and the AO-treated area (blue) showed chemical changes to the chemical composition of the lipstick (Figure 4d).[3] The reduction in the peak intensity

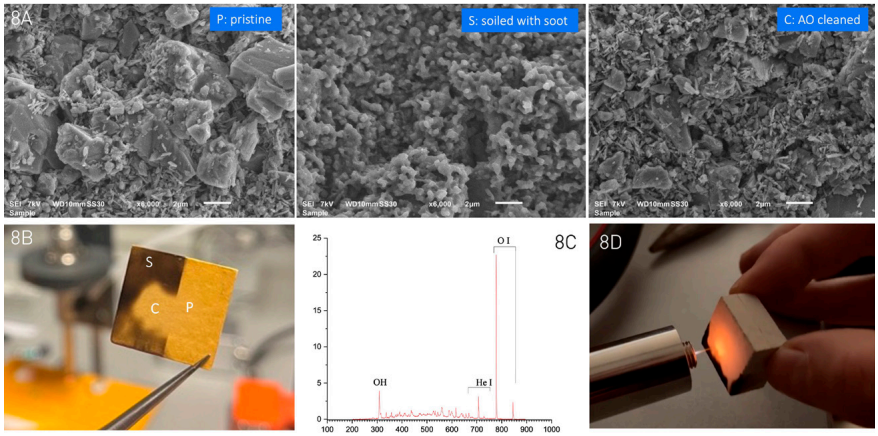

Figure 8. Testing with the atmospheric AO prototype. (a) SEM; (b) yellow ochre (Fe_2O_3-H_2O) gouache paint on paper: (A) pristine, (B) soiled with soot, and (C) cleaned. (c) Optical emission spectra show a high peak of excited atomic oxygen O (^1D), which is essential for the production of the ground state AO (O^3P). (d) AO generator tested on soot-soiled limestone sample

of C–H, C=O, and C–O stretching bands, related to esters and aliphatic compounds, indicated the removal of organic lipstick components by their conversion to volatile species.

The duration of the AO treatments at the ESA was relatively long (up to 54.9 hours), due to the design of the LEOX simulator. For applications in conservation, an atmospheric AO process will enable a relatively short exposure time, necessary in practical settings. The authors' development of such an AO system is currently in progress under the MOXY and PlasmArt projects (Figure 8). The AO prototype in development successfully removed soot from natural yellow ochre gouache on paper and the surface morphology of the substrate under SEM appeared intact after treatment (Figure 8a, b); testing on other cultural heritage materials is in progress. In the prototype (Figure 8d), AO is generated by flowing O_2 in a He gas (0.1 v.% O_2) using a RF field at 13.56 MHz, confirmed by high excited oxygen (O^1D) peak, measured by optical emissions spectroscopy (Omni-λ 750i monochromator and spectrograph with an Andor iStar 740 camera) (Figure 8c). During the first tests, AO efficiently removed paraffin soot from sandstone at approximately 5 mm^2/8 s (Figure 8d); however, the cleaning speed will vary depending on the mass, chemical composition, and reactivity of the contaminant, the substate characteristics, the parameters of the AO effluent, and the operational capacities of the AO generator, which is a work in progress.

CONCLUSION

Preliminary testing showed that AO offers a novel non-contact, non-abrasive, and solvent-free approach to cleaning SOS that does not raise health or environmental concerns and results in environmentally sustainable by-products. AO therefore holds promise as a cleaning method with a low carbon footprint as well as reduced waste and reliance on hazardous chemicals, taking into consideration the full life-cycle assessment from raw materials to utilization. As a non-contact, non-liquid approach, AO is an effective solution for SOS consisting of friable and porous materials. It is a volatile, non-thermal method, incrementally applied and delivered at atomic scale with low kinetic energy. It may thus be an effective solution

for reaching surfaces with irregular topographies, especially surfaces subjected to airborne contaminants such as convection and fire-born soot, environmental organic aerosols, and propellants in spray paints. Unlike liquid and traditional contact means, AO will not drive contaminants deeper into the substrate. Moreover, as an essential natural element, AO may be culturally accepted by Indigenous communities, which do not consent to the use of synthetic solvents on sacred objects. Investigations of hybrid methods combining AO, gels, laser, and pressurized microblasting are in progress. However, like any other conservation means or material, AO will not be suitable for every situation. The interaction of AO with art materials needs to be investigated and the full potential in conservation has yet to be realized. AO innovation is venturing into new territory and there are many questions to which there are no answers yet. However, this is often the path of innovations that eventually become transformative.

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NOTES

1 Green Atmospheric Plasma-Generated Monatomic Oxygen Technology for Restoration of the Works of Art (MOXY), Horizon Europe grant agreement: 101061336: 2022–2026; Art objects conservation by non-thermal plasma generated atomic oxygen beam (PlasmArt), Research Foundation – Flanders (FWO): 2022–2025.

2 Groom Stick: a tradename for tacky natural rubber, used for dry surface cleaning: https://cameo.mfa.org/wiki/Groom_Stick

3 Boho glossy lipstick Desire 312 (#1342560) composition: castor seed oil, hydrogenated olive oil stearyl esters, oleic/linoleic/linolenic polyglycerides, carnauba wax, candelilla wax, carmine (CI 75470), titanium dioxide (CI 77891), red iron oxides (CI 77491), fragrance, tocopherol. Boho Green, Lyon, France: https://www.bohocosmetics.com

4 Δq indicates the root mean square of the local tilt dZ/dX along the sampling length.

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