Analytical Methods

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue



Cite this: *Anal. Methods*, 2025, **17**, 3357

# Heritage science applications of ambient mass spectrometry

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An overview of the applications of the ambient mass spectrometry techniques Desorption Electrospray Ionisation (DESI) and Direct Analysis in Real Time (DART) in the field of cultural heritage is given. These techniques were first used for heritage science studies in the 2010s, but did not become common in the field until recent years. Investigation of the composition of objects, the analysis of surface residues and material degradation are discussed alongside the use of data obtained by DESI and DART for planning better conservation interventions. Heritage science studies using other ambient mass spectrometry techniques such as Paper Spray mass spectrometry (PS)-MS, Surface Acoustic Wave Nebulisation (SAWN)-MS, and Laser Ablation Electrospray Ionisation (LAESI)-MS are also briefly described. The analysis of a variety of artefacts and materials including paper, wood, oil paintings and pottery are included, and potential future developments in the field are explored, highlighting the current exciting expansion of the application of ambient mass spectrometry techniques to heritage science questions.

Received 4th February 2025
Accepted 24th March 2025

DOI: 10.1039/d5ay00193e

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## 1 Introduction

### 1.1 Ambient mass spectrometry techniques

The development of ambient ionisation mass spectrometry (ambient MS) techniques in the early 2000s opened the field of mass spectrometry (MS) to a whole new range of applications.[1] The pioneering methods of desorption electrospray ionisation (DESI)[2] and direct analysis in real time (DART)[3] were the first two ambient MS techniques to be described in literature, and are now the most established in this field.[4,5] Many more techniques have been published since, leading to a broader definition of ambient MS to include techniques with minimal sample preparation alongside those dealing with unprocessed samples.[1,6,7]

The common characteristic of all ambient MS methods is the ability to carry out ionisation at atmospheric pressure, allowing for the direct analysis of samples in their open, native environment outside the mass spectrometer, with no, or minimal, pre-treatment of the specimens.[1] Existing methods can be separated into representative classes based on the specific ionisation technique used, the three main ones being, liquid extraction, plasma based desorption and laser ablation.[1,7,8] This review primarily covers studies conducted using DESI and DART, but specific applications of other techniques that are less commonly used in heritage science, such as Paper Spray mass spectrometry (PS)-MS,[9] Surface Acoustic Wave Nebulisation (SAWN)-MS,[10] and Laser Ablation Electrospray Ionisation (LAESI)-MS,[11] are also included.

DESI is a spray-based liquid extraction technique: a charged solvent spray is directed at a sample, forming a thin solvent film on its surface, where the extraction/desorption of the analyte molecules occurs. Microdroplets containing the analytes are formed in a splashing process, and are subsequently ejected towards the mass spectrometer for analysis (Fig. 1).[8,12–14] Recent advances in the field include the use of DESI in mass spectrometry imaging (DESI-MSI),[15,16] and the development of high resolution nanospray sources (nano-DESI).[16,17]

In contrast, DART is a plasma-based desorption technique: a carrier gas, usually helium, is exposed to a corona discharge needle, creating excited gas atoms that stream out of the source to ionise molecules from the sample, placed in-between the source and the mass spectrometer (Fig. 2).[1,5] DART analysis is limited by the small gap between the source and MS inlet, but modification to place the source and the MS inlet at an angle to each other above the sample surface can circumvent this.[18]

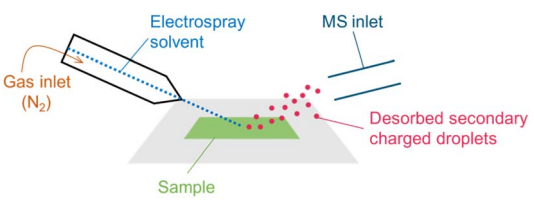


Fig. 1 Schematic representation of a DESI-MS source.

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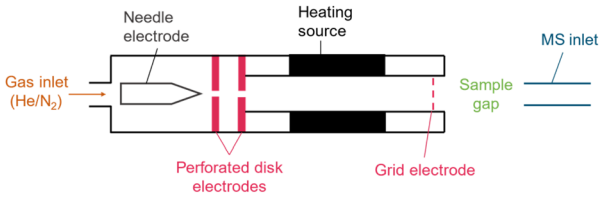


Fig. 2 Schematic representation of a DART-MS source.



When choosing between ambient MS techniques, practical considerations include sensitivity of the object under study towards the desorption and ionisation method employed, and the way the object is introduced into the desorption stream. Thus, if the object under investigation is thermally-sensitive, such as certain types of textiles and paper, DESI would be the more suitable technique to use. While for objects such as manuscripts that are more likely to be adversely affected by exposure to solvents, DART might provide the better choice. For introduction into the desorption stream, most DART instruments are limited to a small sample gap, meaning that the technique is more suitable for fragments or smaller objects, while larger objects require the larger, and often more customisable, stage of a DESI instrument. Nonetheless, overall DESI and DART have many advantages and limitations in common, and can be used interchangeably for most types of heritage objects.

### 1.2 Challenges in heritage science

When investigating the composition of historical artefacts there are several challenges to consider. Of major concern is the very small sample size available, as the objects investigated are of cultural importance and need to be preserved. Furthermore, processing or extraction of a sample should be minimised to retain valuable contextual information. Finally, analysis frequently provides complex mixtures, including degraded organic materials and the potential presence of contaminants from handling and storage conditions.[19] Analytical techniques currently used in heritage science for the characterisation of dyestuffs are either micro-destructive and require the extraction of a sample from the original objects, as is the case for ultra high performance liquid chromatography (UHPLC),[20] or are non-invasive but considerably less specific, as is the case for other spectroscopic techniques such as FORS, hyperspectral imaging and Raman.[21–23]

Ambient MS methods have been used in a wide range of applications, from forensic analysis, environmental control, and agricultural studies to biomedical applications and reaction monitoring.[1,8] They are rapid, direct, minimally invasive, and require only minute samples for analysis, making them ideal for implementation on valuable historical and archaeological artefacts.[24–26] Used in conjunction with tandem mass spectrometry ($MS^n$), they can also provide detailed information allowing the specific identification of components within complex mixtures.

While there are many advantages to the use of ambient MS, there are also limitations arising from the presence of background noise due to environmental contaminants, including personal hygiene volatiles (such as BTAC-228 ($m/z$ 368)), common plasticisers (such as phthalates ($m/z$ 279, 391)),[25] and frequently used laboratory chemicals (such as PPG ($m/z$ 309) and PEG ($m/z$ 327)). Another limitation is the lower reproducibility of ambient MS techniques compared to other MS techniques, due to the common reliance on home-built sources and on highly sensitive instrumental factors (such as geometrical parameters) for obtaining analyte signal. The inherent heterogeneity in surface samples also reduces reproducibility, as does the presence of surface contamination, including amino acids and lipids from improper sample handling and environmental build-up on object surfaces.

## 2 Ambient MS applications in heritage science

While the routine uses of MS techniques to analyse paintings, early synthetic dyes and organic pigments has been covered in depth,[27–29] this review focuses on recently reported applications of pioneering ambient MS techniques such as DESI and DART, to the field of heritage science. These applications include: (i) investigations into the material composition of artefacts, as well as any organic residues found on them (Sections 2.1 and 2.2); (ii) the study of degradation and ageing processes (Section 2.3); and (iii) understanding past conservation interventions and monitoring the status of objects on display (Sections 2.4 and 2.5). Progress in each of these areas and the role played by the application of ambient MS techniques to a range of materials, are discussed.

### 2.1 Material composition

One of the first applications of ambient MS in heritage science was the 2011 study by Adams of the composition of 16 reference paper samples.[26] This study was pioneering in its use of DART-MS for paper analysis, not only in the field of preservation and cultural heritage, but also for studies in forensics and the wider scientific community. Subsequent studies have focused on determining the materials used in the construction of historic objects, ranging from artworks, to textiles and furnishings.

**2.1.1 Paintings and artworks.** The detailed study of layers on paintings is important as it gives insight into the age of a painting and originality of the materials present, guides conservation treatments, and furthers our understanding of particular methods, such as gilding. In contrast to liquid or gas chromatography mass spectrometry, which allow for identification from bulk materials only, cross-sectional imaging can be performed using time-of-flight secondary ion mass spectrometry (ToF-SIMS).[30] ToF-SIMS also has the great advantage that it can be used to analyse and map both organic and inorganic components. However, this technique is operated under vacuum, and hence imaging is restricted in size and requires sampling. The potential for ambient MS techniques to provide information about materials from specific layers has been recognised for some time.[19] But it is only comparatively recently that their application to the composition analysis of polychrome artworks has been fulfilled.

In particular, DART-MS has found use as a rapid screening technique, prior to further investigation by GC-MS, for the characterisation of rock art painting from the Las Charcas caves, in Cuba.[24] While in the first example of DESI-MS applied

 

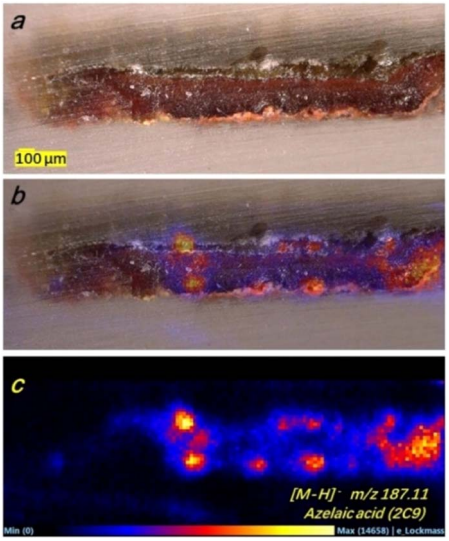


Fig. 3 (a) Optical image of gilded wall painting cross-section, (c) DESI-MS distribution of azelaic acid ($m/z = 187.11$) within the cross-section, and (b) overlay of image (a) and (c) to show the presence of azelaic acid, a marker for drying oil, in both the upper and lower layer. Reproduced with permission from ref. 32 © 2020 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Fig. 4 DESI-MS set-up for sampling of historical dye samples. Reproduced from ref. 12 under CC-BY 4.0 license conditions† doi: https://doi.org/10.1021/acs.analchem.2c03281.

to cross-section analysis, modern materials and lipid-containing binding media in a model matrix were distinguished using the positive ion distributions of each. This distribution of ions was then used to determine the lipid-binding media in a 17th century painting.[31] However, the successful analytical differentiation of oil and egg tempera (which show the same key positive ions), as well as distinguishing these from other common binding media, such as beeswax and resins, is yet to be resolved.[31]

DESI imaging has also been used to show how dicarboxylic acids are distributed underneath the tin foil and in the minium ($Pb_3O_4$) substrate in gilded wall paintings from the Kizil Grottoes (Fig. 3). These results confirmed how drying oil was not only used as mordant but was also added to the minium to act as the binding medium.[32]

**2.1.2 Textiles and dyestuffs.** The colouring of textiles for use in garments and furnishings, and to indicate status and wealth, has been used by humans for millennia. The identification of the dyestuffs employed in this process is important in dating an historical piece, can give valuable context about local customs and trading practices, and may inform its conservation and display. But there are significant challenges to the use of ambient MS techniques for dyestuff analysis, due to the wide array of chemical classes of dyestuff, the presence of structural isomers that may be difficult to identify on the basis of mass alone, and the way in which dyestuffs are bound to the substrate through chemical or ionic interactions, or using a mordant.

With its reliance on ionisation by excited gaseous ions, DART-MS is well suited to the analysis of lower molecular weight species that are both volatile and thermally stable. DART-MS is now well-established in the field of dye analysis, with its first reported use in cultural heritage dating back to 2011.[33] The Armitage group led the development of its use for the analysis of dyes on a variety of substrates for more than a decade.[33–36] In recent years, DART-MS has been used successfully to identify natural colourant components, including alizarin, purpurin and lucidin, from textile fragments dating to 740 BCE, found in the tomb Tumulus MM at Gordion, in Turkey.[37] Whilst work on pre-Columbian Andean textiles has highlighted the particular sensitivity of DART-MS for indigoids, with peaks for the regioisomers indigotin and indirubin at $m/z$ 262.07 for $[M]^-$ in negative mode, or $m/z$ 263.08 for $[M + H]^+$ in positive mode, often dominating the spectra obtained.[36] However, carminic acid and other glycosides are not easily detected by DART-MS, presumably because they are not as easily desorbed from the textile surface by heat.[36]

In contrast, while the potential application of DESI-MS for the identification of textile dyes in heritage science has been recognised for some time,[28] as it is commonly used to detect dyes and inks in other fields,[38] early attempts to implement its use failed to obtain stable signals.[39] It was not until 2023, that Sandström *et al.* successfully realised the use of DESI-MS for the identification of both early synthetic and natural textile dyes.[12,15] Using a 3D-printed stage, a DESI source was connected to a FT-ICR-MS instrument to allow the *in situ* analysis of 14 early synthetic dyestuffs on reference samples of wool and silk (Fig. 4).[12] The effects of varying the spray angle and solvent flow were demonstrated using water sensitive paper, and the optimised conditions were used to identify dyes from several chemical families found in fabric swatches present in Lehne's handbook dating from 1893 (Fig. 5).[12] In extending this work to the analysis of natural product dyestuffs, it was found that, as with other ambient MS techniques, the dye application process (direct, mordant, vat) has a large impact on the ionisation efficiency of DESI-MS.[15] Enabling $x,y$-positioning of the ionisation

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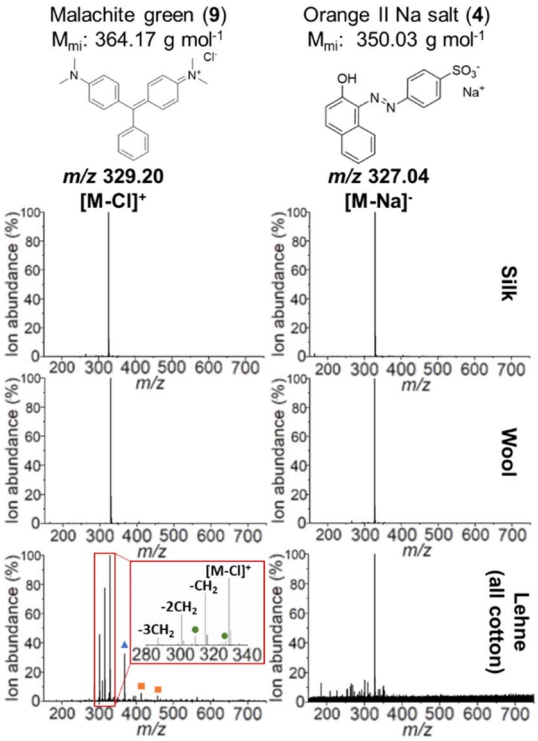


Fig. 5 DESI-MS spectra of triphenylmethane malachite green ([M − Cl]$^+$ (*m*/*z* 329.20)), and azo dye orange II sodium salt ([M − Na]$^-$ (*m*/*z* 327.04)) dyed on silk (top row), on wool (centre row) and from historical samples in Lehne's handbook (1893). Marked with a blue triangle is *m*/*z* 368.43 (BTAC-228), green circle is *m*/*z* 309.21 (PPG) and *m*/*z* 327.18 (PEG). An orange square marks phthalates at *m*/*z* 301.07, 413.26, 429.24, and 457.27. The Lehne sample spectra for triphenylmethane malachite green include a zoomed-in inset to show the degradation products and synthetic byproducts of the dyestuffs. Sum of two mass spectra shown. Adapted from ref. 12 under CC-BY 4.0 license conditions† doi: https://doi.org/10.1021/acs.analchem.2c03281.

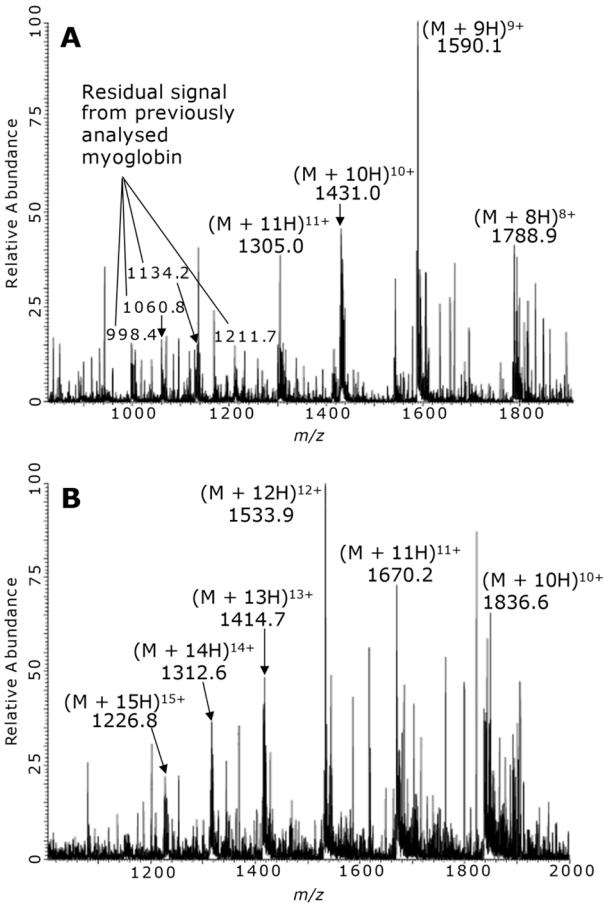


Fig. 6 DESI-MS spectra of (A) myoglobin (16 950 Da), and (B) β-lactoglobulin A (18 300 Da) on a flint substrate (250 pmol of each protein applied to substrate). Adapted from ref. 45 with permission from Elsevier.

source relative to the object under analysis, has been used to produce ambient MS imaging of synthetic rhodamine dyes.[15,40]

Combining this approach with nanospray-DESI successfully revealed the use of early synthetic dyes including rhoduline blue, malachite green and auramine O in the printing of traditional Chinese patterns in printed fabrics found in the Palace Museum in Beijing.[16] Differentiation in the *z*-dimension has even been achieved in ink analysis by using a nanospray-DESI source and an extended acquisition time to observe the changes in ionisation patterns with time, where the later spectra correspond to the elution of inks at a greater depth.[41]

Where sampling is possible, an alternative ambient MS technique, SAWN-MS, has been shown to be a highly effective means of generating electrospray-like gaseous ions from textile dyes with minimal sample preparation on minute samples.[42] Albeit, as with other ambient MS techniques, without the additional information provided by chromatography.

### 2.2 Organic residues analysis

The detection and study of organic residues in artworks, archaeological artefacts and paleontological samples can provide us with information on manufacturing processes, available technology and cultural practices of historical societies that would otherwise be unknown, especially in the field of archaeology.[43] Outcomes from studies of this kind not only further our understanding of heritage objects and their use, but also inform us on how to best treat such pieces. For these reasons, the study of organic residues on heritage objects, in particular proteins, have been of interest for many years, with the first attempts dating back to the start of the twentieth century.[44]

**2.2.1 Peptides and proteins.** Initial studies have demonstrated that DESI-MS can be used for the detection and identification of both peptides and intact proteins at low concentrations (50–250 pmol) and on various substrates (Fig. 6).[45] Analysis on porous materials such as pottery is still a challenge as DESI is a surface analysis technique, but it could nonetheless be very useful on other artefacts, particularly for the analysis of visible surface residues.[45,46] When looking at residues, it is important to consider how the sampling location on the object can affect the result; so experimental planning is critical, not only from a scientific point of view but also considering the historical and cultural background of the

 

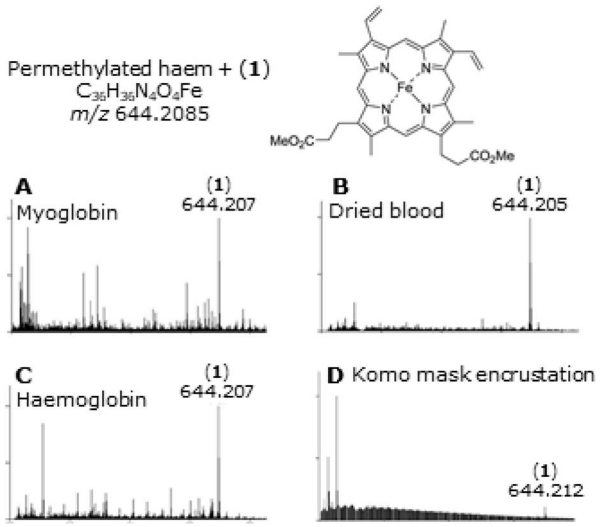


Fig. 7 DART-TOF spectra for (A) myoglobin, (B) dried blood, (C) haemoglobin, and (D) coating on the Komo mask (DIA 74.229), showing the presence of the permethylated haem ion. Adapted from ref. 46 with permission from the Royal Society of Chemistry.

artefact.[43] Analysis *via* DESI-MS has the advantage of allowing the mapping of a specific analytes' distribution across a surface and the comparison of data from different areas on the same object, all without needing to extract or destroy the material.[45]

The characterisation of blood encrusted on an African Komo mask by Fraser *et al.* shows how DART-MS can be used as a rapid and simple method for detecting haem-containing proteins (Fig. 7).[46] Identification of the source of this protein as blood was supported by further analysis using X-ray fluorescence (XRF), FTIR and Raman spectroscopy, as well as optical microscopy and tetramethylbenzidine tests.[46] Whilst the animal species that the blood originated from could not be specified by DART-MS; a proteomics approach could give further insight into the use and nature of such complex objects.[47]

**2.2.2 Small molecules.** With a successful track record of application in the fields of forensics and pesticide control, DART-MS is also an attractive approach for the analysis of minute traces of residues.[5,48] It has been used to analyse organic residues on ceramic vessels from Cerro Baúl, in southern Peru, to identify the botanic sources used in the brewing process of ritual alcoholic beverage *chicha*.[49] While the use of *Schinus molle* (Peruvian pepper) in *chicha* had previously been suggested based on circumstantial evidence, this was confirmed by the presence of compounds characteristic of *molle* in the pores of ceramic vessels using DART-MS analysis. Six triterpenoid compounds were successfully identified as the main biomarkers for *Schinus molle* (Fig. 8), along with the presence of the phenylpropanoid safrole.[49]

In 2019 a modified DART-MS system was used for the analysis of surfaces on a broken ceremonial hat from the Tlingit tribe of Alaska (Fig. 9).[50] Due to flow dynamics, flat surfaces yielded higher intensity absolute signals than measurements taken tangentially to curved surfaces, but all sampling areas provided useful data for determining the original structure of

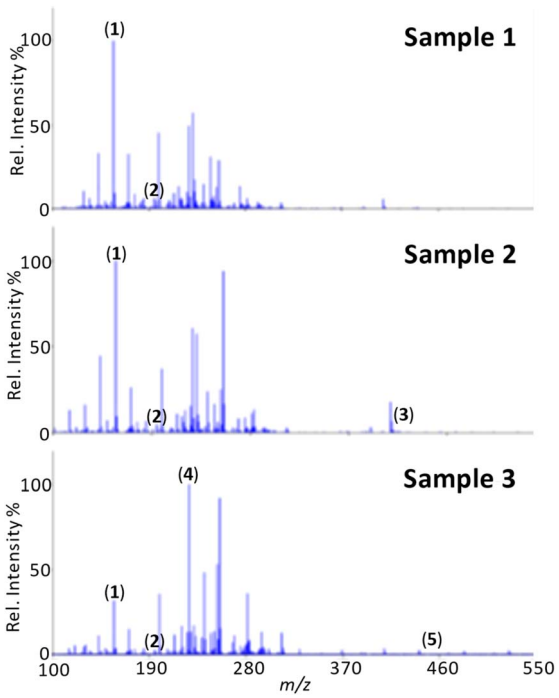


Fig. 8 (a) Example DART-MS spectra of some of the ceramic residue samples from the Cerro Baúl brewery. Sample 1 corresponds to sample 1233, Sample 2 corresponds to sample 1221, and Sample 3 corresponds to sample 1110. (1) Nonanoic acid-H (*m/z* 157.123), (2) β-spathulene/teredenene/terebanene-H (*m/z* 201.166), (3) simiarenol-H (*m/z* 425.372), (4) tetradecanoic acid-H (*m/z* 227.203), and (5) moronic acid-H (*m/z* 453.345). Adapted from ref. 49 under CC-BY 4.0 license conditions† doi: https://doi.org/10.3390/su11082333.

the object.[50] A study of the distribution of nicotine on the object's surface confirmed that the hat and the cylinder were connected at the flat top, and the majority of the exposure to tobacco took place when the hat was still intact and in use.

### 2.3 Degradation and ageing processes

Assessing the deterioration status and understanding degradation processes is key to better conservation and restoration of cultural heritage artefacts, for this reason studies of deterioration mechanisms and markers in various materials are abundant in the literature.[26,51] Being able to determine the condition and degradation rate of materials is particularly important when dealing with objects for which long term preservation is a concern, as knowledge of the degradation processes allows for the design of effective conservation treatments, both for preventive interventions and in the aftermath of damaging events.[52,53]

Heritage objects are subject to deterioration due to several factors: aging of natural components, exposure to light and weathering, damaging events such as fires or floods, the action of microorganisms, flawed storage conditions, as well as handling, exhibiting and general use of the objects. Deterioration is usually assessed based on the detection of the products and derivatives from breakdown processes or by looking for structural changes in the polymer framework of materials such as paper and wood.[18,25,51–54] These studies are most commonly performed using techniques such as scanning electron

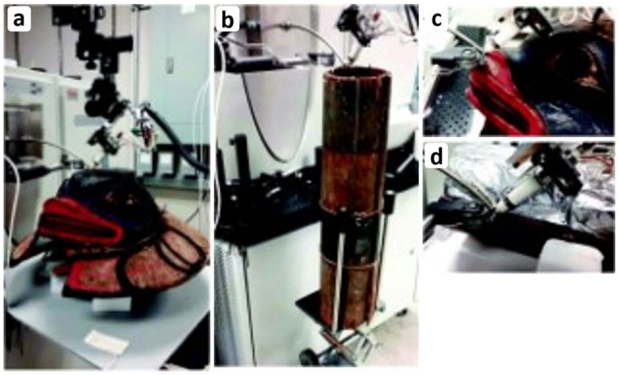


Fig. 9 DART set-up for sampling for selected surfaces on (a and c) hat and (b and d) cylinder from the Tlingit tribe of Alaska. Adapted from ref. 50 with permission from the Royal Society of Chemistry.

microscopy, FTIR and X-ray diffraction spectroscopy. However, these techniques often don't yield detailed enough information for the organic components without combination with MS or some other micro destructive technique.[51,55] Electrospray ionisation (ESI) MS has also proven a useful technique for tracking the hydrolytic breakdown products of cellulose. Soluble oligomers are produced from the cellulose chains by a series of hydrolysis reactions; these are then released from the amorphous phase of cellulose, becoming detectable on the paper surface.[53] The drawback of ESI-MS is that it is a destructive technique, and even though a single fibre is sufficient for analysis, this can cause problems when repeated sampling or investigation of different areas are needed.[53] Matrix assisted laser desorption/ionisation mass spectrometry imaging (MALDI-MSI) has also been applied to study degradation.[56] MALDI-MSI can be labelled as a non-destructive surface technique, but it requires the application of matrix onto the sample, which reduces the number of analyses that can subsequently be conducted on the sample. Ambient MS offers a minimally destructive, equally informative and faster alternative to these techniques.

**2.3.1 Paper and wood.** DESI-MS has been applied to works on paper to understand the deterioration processes of cellulose, both when studying degradation caused by natural aging, and by exposure to high temperatures and chemicals during a fire blaze.[52–54] DESI-MS was shown to be as sensitive and accurate as ESI-MS in detecting and tracking oligosaccharides produced during the artificial accelerated aging of unsized cotton paper (Fig. 10 and Table 1).[53] Whilst a study of the effect of fire exposure on burned rag paper books damaged during the 2004 fire of the Duchess Anna Amalia Library in Germany utilised DESI-MS for mapping polyaromatic hydrocarbons (PAHs) present on the surface of the burned paper.[52] PAHs are non-polar compounds that form and accumulate in the cellulose matrix after exposure to high temperatures. Different burned samples were analysed and the DESI-MS mapping showed that PAH concentration levels correlated with areas that had experienced higher thermal degradation (Fig. 11 and Table 1).[52] DESI-MS was particularly suitable for this study as the extremely fragile burned samples could be analysed under ambient

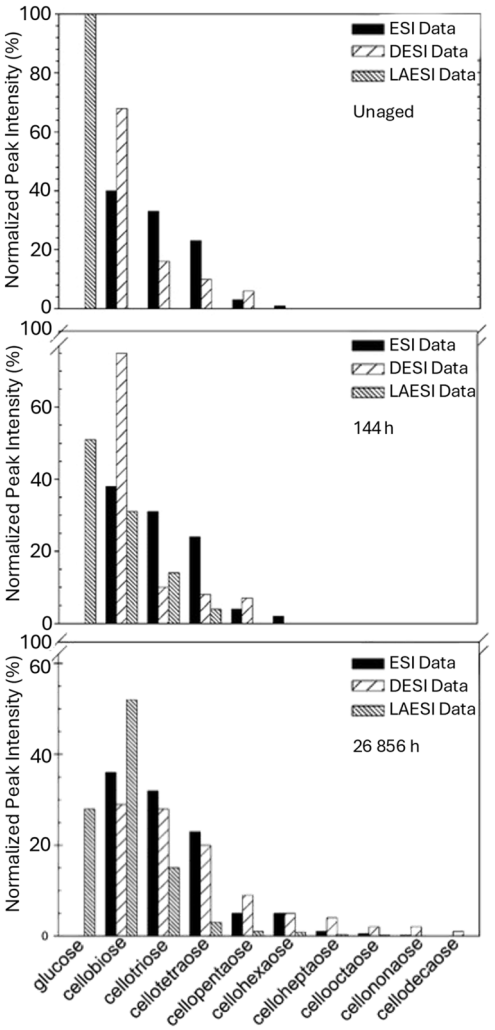


Fig. 10 Normalised total peak intensities of the oligosaccharides detected by ESI-, DESI-, and LAESI-Mass Spectrometry at different times during the artificial aging of paper. Adapted from ref. 53 with permission from the Royal Society of Chemistry.

conditions without the need for additional physical manipulation.[52]

DESI-MS has also been trialled for the detection of acetylated chromophores 2,5-dihydroxyacetophenone (AP-OAc), 2,5-dihydroxy-benzoquinone (BQ-pyr-OAc), and 5,8-dihydroxynaphthoquininone (NP-OAc), which contribute to the yellowing of aging paper (Table 1).[54] While both AP-OAc and NP-OAc could be detected by DESI, the limit of detection (in pmol $mm^{-2}$) for BQ-pyr-OAc was too high. Another ambient MS technique, PS-MS, where the solvent and voltage are applied through a piece of paper rather than a heated capillary, was found to be more versatile and sensitive for these specific chromophores and was therefore chosen for the rest of the study.[54] This limitation highlights the need and importance of adapting and optimising ambient MS techniques specifically for heritage applications, as results are limited when using the parameters set in other fields.

DART-MS has been used successfully to evaluate the deterioration state of wooden artefacts.[25] The relative abundances of

 

Table 1 Common degradation markers detected by Ambient MS

| Source | Process | Ions detected ($m/z$) | Ref. |
|---|---|---|---|
| Cotton paper | Cellulose decomposition | 365 ($[M + Na]^+$ cellobiose)<br>527 ($[M + Na]^+$ cellotriose)<br>689 ($[M + Na]^+$ cellotetrose) | 53 |
| | Paper yellowing[a] | 237 ($[M + H]^+$ 2,5-hydroxy acetophenone diacetate) | 54 |
| | Paper pyrolysis | 179 ($[M + H]^+$ phenanthrene, or anthracence)<br>203 ($[M + H]^+$ fluoranthene, or pyrene)<br>252 ($[M]^{\bullet+}$ benzo[*a*]pyrene benzo[*b*]fluoranthene, or benzo[*k*]fluoranthene)<br>279 ($[M + H]^+$ dibenzo[*a*,*h*]anthracene) | 52 |
| Wood | Cellulose decomposition | 228, 397, 684, 759 ($[M + H]^+$ hemicellulose fragments)<br>305, 648 ($[M + H]^+$ cellulose fragments) | 25 |
| | Lignin decomposition | 107, 137, 167, 180 ($[M + H]^+$ lignol fragments)<br>312, 316, 318, 328, 330, 342, 350, 530 ($[M]^{\bullet+}$ lignin dimers/trimers) | 25 |
| Synthetic dyestuffs | Demethylation<br>*e.g.* 372 ($[M - Cl]^+$ crystal violet) | 358 ($[M - Cl - CH_3 + H]^+$ loss of 1× methyl group)<br>344 ($[M - Cl - 2CH_3 + 2H]^+$ loss of 2× methyl groups) | 57 and 58 |
| | Debromination<br>*e.g.* 648 ($[M + H]^+$ eosin)[b] | 568 ($[M - Br + 2H]^+$ loss of 1× Br atom)[b]<br>490 ($[M - 2Br + 3H]^+$ loss of 2× Br atoms)[b] | 51 |
| Lipid binding media | Lipid oxidation | 187 ($[M - H]^-$ azelaic acid) | 31 |

[a] Paper surface derivatised with acetic acid/pyridine prior to MS. [b] Only most intense peak arising from bromine isotopes cited.

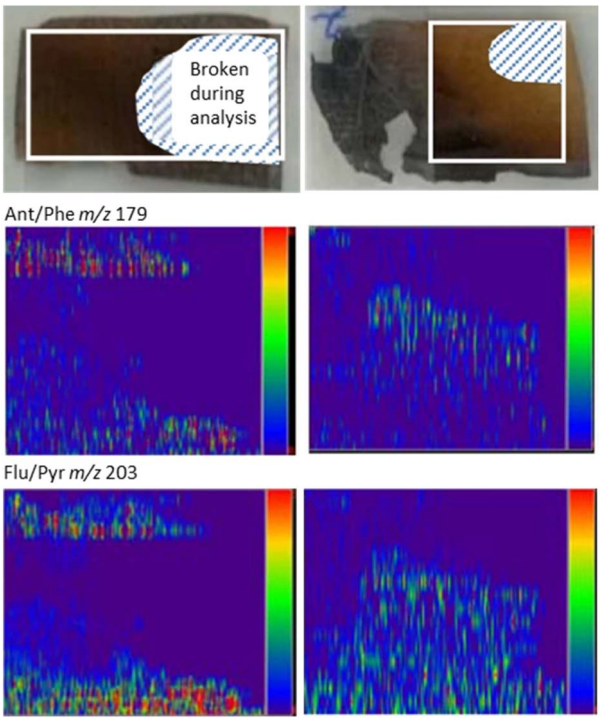


Fig. 11 Mapping of PAHs on the surface of burned paper by DESI-MS: Ant = anthracene, Phe = phenanthrene, Flu = fluoranthene, Pyr = pyrene. Adapted from ref. 52 under CC-BY 4.0 license conditions† doi: https://doi.org/10.1038/s41598-018-30424-7.

wood cell wall components detected (including monomeric lignols, lignin dimers, lignin trimers and oligosaccharides), allowed discrimination between severely decayed, moderately decayed and recent wood, using a partial least-squares discriminant analysis (PLS-DA) based chemometrics approach. This method could be applied to a range of historic woods, including *Castanopsis*, *Quercus*, *Idesia*, *Populus*, and *Cunninghamia* species.

**2.3.2 Inks and dyestuffs.** The well-known degradation products of some synthetic inks and dyestuffs may also be detected using ambient MS techniques. The early synthetic dye crystal violet, is known to age through the successive loss of methyl groups, to give methyl violet and tetramethylpararosaniline as its principal degradation products (Table 1). This degradation pathway has been proposed as a means to determine the relative age of inks.[57] Initially, the ambient ionisation technique SAWN-MS, was shown to detect this degradation process in textiles,[42] but this requires sampling. More recently, DESI-MS has been shown to provide a rapid, non-destructive and effective method to detect this degradation process.[58] Although these studies were conducted with forensics applications in mind,[58] the technique could be applied to historical manuscripts and documents; particularly those that have been subject to modifications and editing throughout time, or those for which authenticity could be questioned. In 2019, Alvarez-Martin *et al.* described the use of DART-MS for monitoring and studying the degradation of the synthetic dye eosin in oil paint for the first time (Table 1).[51] The MS results supported a debromination-based degradation pathway that is particularly prevalent in the presence of lead white, but the authors noted that this does not satisfactorily explain the observed decolouration of eosin upon exposure to light. Finally, in artworks, the detection of the dicarboxylic acid, azelaic acid, in lipid binding media by DESI-MS, may provide a marker of oxidation that allows the relative age of paint to be determined.[31]

**2.3.3 Biodeterioration.** When looking at degradation processes, it is important to also consider bio-deterioration caused by various organisms, including bacteria, moulds, lichens, and others. The activity of microorganisms on heritage objects can cause damage through varied mechanisms, an excellent overview of which is given by Gutarowska in a 2020 review.[59] Although proteomics-based approaches have been popular *e.g.* to identify paint binders (Section 2.2.1),[27] the application of omics approaches to the study of bio-deterioration in cultural heritage is a very new field, with only a few publications, none of which used ambient MS techniques.[59,60] However, since direct MS methods, including DESI and DART, are currently used for metabolomics research in fields such as health analysis, there is potential for future applications of these techniques for systemic analysis of bio-deterioration in cultural heritage.[59,61,62]

Overall, the application of DESI and DART can be useful in identifying degradation products in a variety of materials from paper and photographs, to textiles and paintings. However, the comparatively low sensitivity of these techniques means that they are less effective in studies which seek to identify unknown degradation markers and instead are more readily applied where degradation products are more clearly defined.

## 2.4 Conservation or analytical interventions

Being able to distinguish between older, original layers and modern ones enables conservators to make informed decisions about the removal of non-original material from an artwork. Removal of substances added during conservation interventions for example is not only done to restore an object to its original appearance and best preserve it for future generations, but is also necessary to be able to carry out further analysis such as carbon dating, which would otherwise yield false results.[63,64] Studies by ambient MS can be very useful for this, for example they can be easily used to obtain initial results rapidly, thus allowing better planning of further in-depth investigations.

**2.4.1 Cleaning and conservation.** DART-MS was used for the preliminary analysis of conserved painting samples originally found in Neolithic hypogea in Marne, France. Together with FTIR and GC-MS, DART-MS allowed the characterisation of resin, beeswax, and turpentine layers, which were added during previous conservation work.[64] Identifying the non-original materials present was necessary to be able to successfully remove them and be able to reliably carbon date the artworks, without the results being influenced by contamination.[64] The micro-destructive ambient MS technique SAWN-MS, has also been used to investigate the solvent-mediated extraction of fatty acids in bilayer oil paint models and the water sensitivity of 20th Century oil paints,[65,66] to determine optimum cleaning protocols by conservators. SAWN-MS was chosen in these applications, because sample throughput was accelerated by the minimal processing required.

**2.4.2 Analytical interventions.** Kissel *et al.* used DART-MS to verify that their newly proposed micro-sampling methodology for the analysis of red dyes on prints was minimally-invasive and not damaging to the sampling area, as they had predicted. The results confirmed that no detectable hydrogel residue was left on the paper after sampling.[67] However, visible discolouration and distortion can occur on the surface of heat-sensitive materials during DART analysis, due to the high temperature of the gas stream hitting it.[18] Newsome *et al.* successfully developed an experimental protocol to avoid heat damage upon DART-MS analysis of photographs, adding a time-controlled mechanical shutter. It is yet to be attempted, but this could be a useful method for assessing the degradation of photographs, based on chemical markers of dye colour shift.[18] An important theme discussed in this paper is signal decrease over time due to sample depletion; it is particularly important to think about this in experimental planning when analysing surface residues and markers as they are present in a finite amount, and their depletion speed is often also temperature dependant.[18]

These studies highlight the versatility of ambient MS techniques to aid both conservation and analytical intervention, with a view to maintaining or restoring artworks to the best possible condition (Table 2). In particular ambient MS can be used both before and after cleaning treatments. By identifying the nature of surface deposits, dirt and non-original layers, targeted and effective cleaning of artefacts can be planned and carried out. After treatment, the same techniques can be used to ensure both that all the undesired materials have been removed, and that no residues from the cleaning materials are left on the object.

## 2.5 Display of objects

Displayed artefacts are more vulnerable to deterioration than those held in storage facilities, as they are subject to the

Table 2 Potential applications of Ambient MS to aid conservation treatments

| | Application | Resulting strategy | Ref.[a] |
|---|---|---|---|
| Before treatment | Identify surface deposits | Optimise cleaning by targeting specific material | — |
| | Identify non-original layers | Optimise targeted removal of unwanted layers | 64 |
| During/after treatment | Confirm absence of surface deposits | Check effectiveness of cleaning intervention | — |
| | Identify cleaning materials residues *e.g.* gels | Prevent contamination or damage by cleaning processes | — |
| Preventive | Check for presence of toxic substances *e.g.* pesticides | Inform decisions on how to handle objects safely | — |

[a] References given where suggested strategy has already been implemented.

 

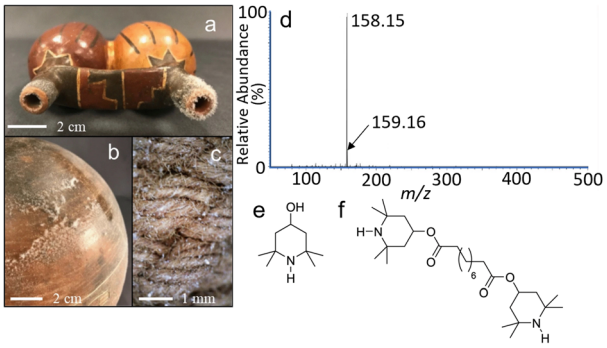


Fig. 12 Photographs of efflorescence on: (a) Nazca double spout ceramic vessel; (b) Paracas ceramic vessel; and (c) micrograph of efflorescence on cotton cordage knot of Inka quipu. (d) DART-MS spectrum of the efflorescence collected from a Pueblo bowl, showing ion peak at $m/z$ 158.1527 (TMP-ol + $H^+$). Chemical structures of (e) TMP-ol and (f) Tinuvin® 770, the adhesive component that TMP-ol derives from. Adapted from ref. 70 under CC-BY 4.0 license conditions† doi: https://doi.org/10.1186/s40494-020-00454-4.

environment of the museum or gallery. Continuous control of air quality and other factors in the exhibition environment and of the state of the objects is therefore of primary importance.[68] Volatile organic compounds (VOCs) in particular need to be monitored; these can be released into the environment by materials such as building constituents, technical equipment or furnishing present near the exhibit, creating indoor pollution. Some of the common VOCs that can cause problems for heritage objects are aldehydes (formaldehyde and acetaldehyde) and carboxylic acids (acetic acid and formic acid).[69] In the long run, these compounds can interact with the artefact materials, leading to degradation and formation of patinas or other fouling on the surfaces of objects.[68,69] On-site detection of VOCs is conducted using air sampling devices and sensors, but these are often not designed for heritage materials, meaning they are not sensitive enough, and can also be visually disruptive to the display, for this reason samples for laboratory analysis are commonly collected instead.[56,69]

Display cases and cabinets, originally designed to protect pieces from physical damage, can in some cases do more harm than good, as the airtight boxes allow VOCs to accumulate in the closed environment, reaching concentrations potentially harmful to the objects held within them.[56,68] This was seen for a series of artefacts displayed at the Smithsonian's National Museum of the American Indian in New York, the Rijksmuseum in Amsterdam, and the Boston Museum of Fine Arts, where

Table 3 Comparison of analytical techniques used in cultural heritage applications

| Technique | Analysis | | | Operation | Set-up | Species identified | | | | | Imaging capacity | Advantages | Limitations or drawbacks | Ref.[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-invasive | Non- | Destructive | | | Inorganic | Organic | $M_w$ <1,000 | $M_w$ >1,000 | $M_w$ >10,000 | | | | |
| **Spectroscopic techniques: Raman, FTIR, FORS, XRF** | ✓ | ✓ | | Ambient | Fixed | ✓ | ✓ | | | | Yes, from single spot to larger stitched images | *In situ* analysis, commercial instruments | Complex spectra hinder species-specific interpretation | 16, 19, 21, 22, 23 |
| **Mass spectrometry: TOF-SIMS, MALDI-MS** | | ✓ | ✓ | Vacuum | Fixed | ✓ | ✓ | ✓ | ✓ | ✓ | Yes, with high spatial resolution ~1–10 μm | High resolution imaging of a range of species | Limited to small samples, home-built instruments | 30 |
| **Hyphenated MS: GC-MS, LC-MS** | | | ✓ | Gas/liquid phase and vacuum | n/a | | ✓ | ✓ | ✓ | | No | Highly specific, quantifiable, sensitivity, commercial instruments | Sample preparation required | 16, 19, 20, 21, 27, 29, 35, 36, 56 |
| **Ambient MS: DESI-MS, DART-MS** | ✓ | | | Ambient | Adjustable | | ✓ | ✓ | ✓ | | Yes (DESI), but spatial resolution limited to ~100 μm. | *In situ* analysis, flexibility, range of species | Spatial resolution, home-built instruments | 12, 15, 17, 18, 31, 35, 36, 27, 40, 45, 50, 53, 56, 58 |

[a] Examples where the technique has already been successfully implemented for cultural heritage studies.

a crystalline efflorescence developed on items held in cases all made by the same manufacturer. The surface deposits were analysed with a variety of analytical techniques, including Raman spectroscopy, solid-phase microextraction gas chromatography and DART-MS.[56,70] The organic component of the efflorescence was successfully identified by DART-MS as 2,2,6,6-tetramethyl-4-piperidinol (TMP-ol), which was found to be emitted from the adhesive used in the construction of the cases (Fig. 12). Results from DART-MS were obtained in a fraction of the time and with minimal effort compared to the other techniques, thus proving DART's potential for the rapid, and sensitive analysis of VOCs and their products in exhibition case displays.[56]

## 3 Conclusions

In recent years there has been an emphasis on the application of ambient, *in situ* spectroscopic techniques to cultural heritage science, while the field of ambient mass spectrometry has remained relatively unexplored. This review highlights how ambient MS techniques, in particular DESI and DART, can be applied both for purposes of conservation and preservation of artefacts, and for investigation and research into the objects themselves and their use throughout time. The benefits provided by ambient MS methods (Table 3), including minimal sample preparation and almost negligible damage, have been shown to be useful for fragile artefacts, especially when methods are optimised for a particular material.

There are a variety of directions for future investigation within the field, in particular, the optimisation of existing ambient MS methods for application on different substrates, the development of new ambient MS techniques and innovative combinations of present methods (such as SIFT-MS[71,72] or DIP-MS[73] both deriving from DART-MS, or DESI-PIXE[74,75]) and the collection of data from a range of objects and subsequent creation of libraries and databases specific to heritage materials, to be used for reference and comparison. Imaging mode MS investigations, facilitating the mapping of components of interest and aiding reconstructions, are becoming increasingly key to better understanding the integrity of historical objects.[76] And whilst imaging can be conducted with DESI-MS,[77] further optimisation is required to make this technique routine in the heritage science field. Overall, the continuing development and implementation of ambient ionisation mass spectrometry techniques highlights their potential in heritage science to aid understanding of previously inaccessible objects.

## Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

## Author contributions

CV and ES wrote the manuscript. ANH, LGT and CLM read and edited the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We thank the Scottish Cultural Heritage Consortium AHRC CDP (AH/S00176X/1 Studentship to ES) for funding.

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