A REVIEW ON EFFECTIVE METHODS USED FOR CULTURAL HERITAGE STUDIES*

CRISTINA MIRCEA,
IOAN GABRIEL MIRCEA
Babes-Bolyai University, Cluj-Napoca

O analiză a metodelor eficiente utilizate în studiile privind patrimoniul cultural

REZUMAT

Prezenta trecere în revistă își propune să ofere o imagine actualizată a studiilor efectuate în domeniul cercetării patrimoniului cultural în ultimii ani. Tehnicile analitice clasice (microscopie, spectroscopie, analiză izotopică și analiză biologică) care au fost utilizate pentru investigații în ultimele decenii sunt prezentate în versiunile lor actualizate, respectând toate cerințele standard pentru cercetarea științifică nevătămătoare. Cele mai recente progrese tehnologice sunt corelate cu cele apărute în domenii adiacente, cum ar fi informatica, care dispune de tehnologii ușor adaptabile la știința patrimoniului, care nu pot decât să îmbunătățească cercetarea și conservarea acestuia. Perspectivele în acest domeniu științific evoluează spre invazivitatea minimă a tehnicilor aplicate de investigare, conservare și protejare, armonizate cu colectarea uniformă a datelor și interpretarea rezultatelor în context global.

Cuvinte-cheie: conservarea patrimoniului cultural, stadiul actual al dezvoltării tehnicii, tehnici de investigație multidisciplinare moderne, investigații automate asupra patrimoniului, tehnici non-invazive
Key words: cultural heritage conservation, current state-of-art, up-to-date multidisciplinary investigation techniques, automated heritage investigations, non-invasive techniques

Introduction

Cultural heritage refers to the totality of material, artistic and symbolic goods handed down from the past through each culture to all humankind[1]. The cultural heritage elements are divided into two large categories tangible and intangible.

The tangible cultural heritage consists of movable items such as paintings, sculptures, coins, and manuscripts, and unmovable elements such as buildings, monuments, and archaeological sites. The intangible cultural heritage is represented by oral, artistic, or ritual traditions[2].

Heritage can have a variety of uses, including existential, ideological, commercial, and educational ones, and usually brings together a variety of historical operators, developers, planners, and the public involved in the preservation, development, management, and culture capitalisation[3].

* Acknowledgements This work was supported by UBB-TeMATIC Art P_40_374, project co-financed by FEDR through Competitiveness Operational Programme 2014-2020.
[1] UNESCO 1989.
[2] Jokilehto 2011, pp. 6-8.
[3] Nilson Thorell 2018, pp. 13-18.

The conservation process of the cultural heritage assures the protection and increases the value of cultural items while emphasising their historical importance. Standardised methodological procedures, designed and applied, improve the investigation, research, preservation, and restoration of the heritage[4]. The diagnostic and conservation strategies implemented on the items belonging to cultural heritage became interdisciplinary in the past decades. The primary focus of the scientific studies became gaining as much information as possible on the degradation process without damaging the analysed artefacts[5]. The early sampling and preservative methods applied to cultural heritage characterisation were invasive, implying alterations brought to the integrity of the analysed cultural heritage item. The micro-invasive technique appeared next and evolved into non-invasive one as the surface of the altered material decreased until it fully maintained its integrity[6]. Moreover, *in situ* investigation and preservation practices gain ground to the detriment of the *ex situ* ones concerning cultural heritage management and begin to be considered appropriate in more environmental sites ranging from aquatic to overland[7].

Investigation and research techniques

The primary investigation of cultural heritage usually aims to determine the composition of the analysed items and their structural properties, such as chemical, physical, mineralogical consistency, and age[8]. In addition to the inorganic characterisation, biology studies are also conducted, targeting the microorganisms' communities associated with the heritage elements[9]. The most frequently used investigation techniques are presented in the next section.

Spectroscopy techniques

Artioli defined spectroscopy as the study of the interaction between electromagnetic radiation (or particles) and matter, and spectrometry as the experimental measurement of these interactions[10]. The incident radiation varies in frequencies from radio waves to gamma rays. Interpreting the absorption/emission of the radiation between energy levels is correlated with the physical nature of the energy ranges used for sample excitation[11]. The electromagnetic radiation in the infrared to X-ray spectrum assures atomic discrimination of elements present in a sample. More complex chemical interactions in connection to the molecular are obtained in the ultraviolet-

[4] Spiridon, Sandu 2015, pp. 43-52.
[5] Georgopoulos 2017, pp. 186-199.
[6] Artioli 2010, pp. 34-37.
[7] Richards, McKinnon 2009, pp. 17-31; Madariaga 2021, pp. 1-22.
[8] Artioli 2010, pp. 34-37.
[9] Petraretti *et al.* 2021, pp. 1-12; Ding *et al.* 2022, pp. 1-10.
[10] Artioli 2010, pp. 34-37.
[11] Wollrab 2016, pp. 17-19.

infrared range, while alpha, beta, and gamma particle radiation are used as nuclear spectroscopy techniques[12].

X-ray fluorescence spectroscopy (XRF)

The elemental composition of materials can be determined using XRF, as a non-destructive analytical technique. The secondary X-ray emitted by a sample when excited by a primary X-ray source is measured by XRF analysers to determine the chemical elements present[13]. Each chemical element in a sample produces a unique fingerprint of fluorescent X-rays, making XRF spectroscopy ideal for qualitative and quantitative material composition analysis[14].

XRF was one of the primary investigation methods used for the elemental characterisation of cultural heritage items[15]. The technique was lately applied, *in situ*, non-invasively, to unmovable cultural heritage consisting of archaeological excavation sites[16], stone monuments[17], and wall paintings[18].

The movable heritage was also analysed through XRF, being determined the composition of archaeological teeth and bones[19], rock materials[20], coins[21], historical metal objects[22], easel paintings[23], manuscripts and parchments[24].

XRF offers scientific possibilities of gaining information on the chemical structure in a non-destructive way, in the field, *in situ*, with portable XRF analysers, and obtaining standardised data collections, results, and X-ray maps that can be automatically processed[25]. On the other hand, the technique has its limitations on detection limits, precision, and accuracy[26] and its usage in *in situ* data collection. Sometimes micro-invasive sampling methods are needed for more precise measurements adding to *in situ* analysis more possibilities like the in-field and *ex-situ* ones[27].

New technologies of XRF were developed to improve detection and

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[12] Van Loon 2012, pp. 1-22.
[13] Hall 1960, pp. 29-35.
[14] Fitton 1997, pp. 224-237.
[15] Hall 1960, pp. 29-35.
[16] Save *et al.* 2020, pp. 203-218;Williams *et al.* 2020, pp. 1145-1163; Odelli *et al.* 2021, pp. 1-17.
[17] Uchida *et al.* 2016, pp. 1-17; Uchida *et al.* 2021, pp. 1-9; Bevins *et al.* 2022, pp. 1-30.
[18] Marcaida *et al.* 2017, pp. 3853-3860; Mauran *et al.* 2019, pp. 4123-4145; Cortea *et al.* 2021, pp. 1-19.
[19] Watkins *et al.* 2017, pp. 384-394; Thurzo *et al.* 2022, pp. 1-31.
[20] Vidal-Solano *et al.* 2020, pp. 1-7.
[21] Arias *et al.* 2016, pp. 281-284; Antipenko *et al.* 2020, pp. 19-25.
[22] Mozgai *et al.* 2021, pp. 1-20.
[23] De Viguerie *et al.* 2009, pp. 2015-2020; Mazzinghi *et al.* 2021, pp. 1-13.
[24] Targowski *et al.* 2015, pp. 167-177; de Viguerie *et al.* 2018, pp. 1-13.
[25] Odelli *et al.* 2021, pp. 1-17.
[26] Hunt and Speakman 2015, pp. 626-638; Nørgaard 2017, pp. 101-122; Chen *et al.* 2019, pp. 311-318.
[27] Williams *et al.* 2020, pp. 1145-1163.

maneuverability. Energy Dispersive X-Ray Fluorescence (EDXRF) was designed to analyse groups of elements, and the analysers became more easily to be handled while containing no moving parts[28]. Total Reflection X-ray Fluorescence (TXRF) allows the illumination of a sample with a reflected beam. This way of sample illumination reduces absorption and scattering in the sample matrix in contrast to the classical XRF based on an X-ray beam that causes elements in the sample to emit light at their characteristic energies[29]. Wavelength Dispersive X-ray Fluorescence (WDXRF) offers high resolution and low background spectra for precise elemental concentration assessment, using crystals that disperse the fluorescence spectrum into specific wavelengths of each element present in the samples[30]. Macro X-ray Fluorescence (MA-XRF) generates elemental distribution maps of a scanned area of an object, promoting fast results interpretations[31]. Micro X-ray Fluorescence (µXRF) assures the elemental examination of a sample through decreased excitation beam size[32].

Particle Induced X-ray Emission (PIXE)

In contrast to XRF, PIXE measures the X-rays emitted from a sample due to high-energy ion bombardment. Several excitation beams produce X-rays with energies characteristic to the target elements[33]. The method is particularly used for cultural heritage investigations on art objects, characterizing especially pigments, ceramics, metal, and jewellery[34]. The technique was proven to have its limitations in elemental characterisation[35], especially in paint samples, but it usually complements other investigative techniques[36].

Optical emission spectroscopy

Optical emission spectroscopy (OES) is a spectroscopic technique that analyses the wavelengths of photons released by atoms as they transition from an excited to a lower energy state. According to its electronic structure, each element emits a distinct set of discrete wavelengths, and the elemental composition of a sample may be established by detecting these wavelengths[37].

Ultraviolet-Visible-Near Infrared spectroscopy (UV-VIS-NIR)

UV – VIS - NIR spectroscopy is a non-destructive, non-contact optical

[28] Gajić-Kvaščev *et al.* 2012, pp. 1-9; Rovetta *et al.* 2018, pp. 159-170; Ruschioni *et al.* 2022, pp. 1-15.
[29] Coccato *et al.* 2016, pp. 1-10; García-Florentino *et al.* 2018, pp. 18-25.
[30] Georgakopoulou *et al.* 2017, pp. 186-199; Franci 2020, pp. 314-322.
[31] Saverwyns *et al.* 2018, pp. 139-147; Mazzinghi *et al.* 2021, pp. 1-13.
[32] Capobianco *et al.* 2020, pp. 1-17.
[33] Desnica *et al.* 2007, pp. 393-400.
[34] Rizzutto, Tabacniks 2017, pp. 383-396.
[35] Lazic *et al.* 2018, pp. 1-14.
[36] Duh *et al.* 2018, pp. 96-99; Dujmušić *et al.* 2020, pp. 53-58.
[37] Van Loon 2012, pp. 1-22.

characterisation technique used to measure reflectance, absorbance, and transmittance of liquids and solids at wavelength ranges between 100 and 1400 nm[38]. Lately, the range was extended and Short Wave Infrared (SWIR) is frequently also taken into account, within 1400-3000nm[39]. The UV-VIS-NIR-SWIR is usually used for pigments characterisation being frequently encountered for the analysis of canvas[40], wood[41], and mural paintings[42] but also on cinematographic films, archaeological bones, and copper-based corrosion products[43].

Atomic spectroscopy

Atomic spectroscopy consists of three techniques: Atomic Absorption Spectroscopy (AAS), Atomic Emission Spectroscopy (AES), and mass spectroscopy[44]. The methods make use of small amounts of samples for the analysis, being micro-destructive, that usually take place in dedicated laboratories[45]. AAS provides a quantitative analysis of chemical elements using the atomic absorption of light by free metal ions in the gaseous state. Several chemical elements can be determined by vaporising a solution or a solid sample. Atoms in the ground state absorb light and reach an excited state. The concentration of the elements can be determined based on the amount of energy absorbed compared to standards[46]. The method was the most frequently used in cultural heritage investigations for pigment characterisation[47] with the initial technique upgraded to more easy-to-use versions like Graphite Furnace Atomic Absorption Spectroscopy (GFAAS)[48].

Laser-Induced Breakdown Spectroscopy (LIBS) is an atomic emission spectroscopy technique that uses a targeted laser pulse to atomise samples by forming plasma. Rapid sample analysis is possible due to the employment of a high-power laser. The ablation of surface atoms produces a high-temperature short-living plasma when the intersection laser sample occurs. Electrons in atoms' outer orbitals get energised at high temperatures. The excited electrons travel to lower orbitals when they cool, producing photons. The detection limits of this approach are determined by several variables, including plasma excitation

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[38] Artioli 2010, pp. 34-37.
[39] Baronti *et al.* 1998, pp. 1299-1309.
[40] Pronti *et al.* 2019, pp. 2275-2286.
[41] Sandak *et al.* 2021, pp. 1-15.
[42] Romani *et al.* 2020, pp. 1-10.
[43] Catelli *et al.* 2020, pp. 1-10.
[44] Bings *et al.* 2010, pp. 4653-4681.
[45] Ricca *et al.* 2021a, pp. 1-14.
[46] Artioli 2010, pp. 34-37.
[47] Moretto *et al.* 2011, pp. 384-391.
[48] Tripković *et al.* 2022, pp. 3607-3618.

temperature, light collection window, and transition line strength[49]. Usually, LIBS was traditionally used for the analysis of paintings, ceramics, and stones, but new substrates such as biological materials and textiles begin to be analysed[50]. The technique develops toward noninvasiveness, microscopic spatial resolution, in-depth analysis, feasibility, and field studies, for overland and underwater submerged samples[51].

Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) is a mass spectrometry technology that uses plasma for sample ionisation. A quadrupole mass spectrometer directs and separates the individually charged ions generated by argon plasma from the elemental species in the sample. The ions separated by variable mass-to-charge ratios are analysed by the detector. This approach has a substantially higher analysis efficiency than traditional AAS and lower detection limits. ICP-MS can also distinguish between isotopes of the same element[52]. The technique was most frequently used for glass[53] and non-ferrous metal samples elemental characterisation[54].

Raman Spectroscopy

Raman spectroscopy uses samples' irradiation with a monochromatic laser beam to measure the inelastic scattering of light when it interacts with vibrating molecules. The dispersed light with a frequency differing from the incident energy determines a specific spectrum. Raman spectrophotometers can be coupled with an optical microscope to obtain Raman microscopy as an analysis technique[55]. Customarily Raman spectrophotometers/microscopes are benchtop instruments facilitating small samples or loose fragments analysis. Handheld devices were designed to be simple to operate and well suited for in situ/in-field surveys. A handheld Raman probe also makes it difficult to set the power intensity to a suitable level at a sample. The lack of the microscope objective makes it harder for the analyst to inspect and choose the right target region[56]. Usually, Raman Spectroscopy is associated with other analytical techniques and used to analyse objects such as paper or parchment[57], pigments[58], painted objects[59], natural and synthetic textile[60], jewellery[61], ceramics and porcelain[62] and metal objects[63].

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49 No, A. M. C. T. B., and Analytical Methods Committee 2019, pp. 5833-5836.
50 Detalle Bai 2022, pp. 1-23.
51 Anglos 2019, pp. 1-14; Gaudiuso 2021, pp. 209-251.
52 Giussani *et al.* 2009, pp. 6-21.
53 Then-Obłuska, Wagner 2019, pp. 856-873; Křížová *et al.* 2020, pp. 1-14.
54 Ham-Meert *et al.* 2019, pp. 3375-3388; Vaníčková *et al.* 2019, pp. 2923-2936.
55 Casadio *et al.* 2017, pp. 161-211.
56 No, A. M. C. T. B., and Analytical Methods Committee 2015, pp. 4844-4847.
57 Chiriu *et al.* 2017, pp. 70-81.
58 Saviello *et al.* 2019, pp. 1-9.
59 Hibberts *et al.* 2016, pp. 1-14; Brooke *et al.* 2020, pp. 1148-1161.

Fourier-Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy employs the exposure of the sample to infrared light, which transfers substantially less energy and does not promote atomic excitation processes. However, it will generate molecular vibrations (heat transfer), which will impact the chemical structure of the sample components[64]. Functional groups in molecules absorb light when exposed to infrared radiation, generating dipole moment shifts due to vibrational energy levels shifting from the ground state to the excited state. The degree of vibrational freedom of the molecules determines the number of light absorption peaks, as the peaks' intensity is determined by changes in the dipole moment and energy level transitions[65]. As a result, FTIR spectroscopy has become a commonly utilised technique for examining artworks and historical items[66].

X-Ray Diffraction (XRD)

XRD can be used to identify crystalline materials. The component atoms in the ions or molecules of crystalline materials are arranged in ordered three-dimensional crystal lattices. In contrast, solid materials can be amorphous because their elements have no organisation as crystalline lattices. Interference is a phenomenon that can occur when X-rays interact with ordered materials. As a result of this interaction, a diffraction pattern emerges with lines of varying intensities. The diffraction patterns acquired by XRD reveal information about the material's interior structure[67]. The same developmental perspectives apply to the XRD, as well as to the other spectroscopy techniques for cultural heritage investigations, with concern to their in situ, non-destructive, and combined usage for easier to perform and more precise determinations of the historical materials[68].

Isotope Analysis Techniques

Atoms of chemical elements can have different masses. The variants are called isotopes. The isotope distribution of a given chemical element is almost uniform in the lithosphere and atmosphere. The variations are due either to the isotopic fractionation that occurs when the physical bonds of different resistances are broken; or radioactive decay, whereby an unstable isotope decays spontaneously and eventually results in a stable isotope. The first mechanism

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[60] Kavkler *et al.* 2018, pp. 110-123; Celis *et al.* 2021, pp. 1-11.
[61] Barone *et al.* 2016, pp. 1420-1431.
[62] Colomban 2004, pp. 841-848; Carter *et al.* 2017, pp. 1-8; Colomban *et al.* 2022, pp. 233-259.
[63] Veneranda *et al.* 2016, pp. 2-13; Henrik-Klemens *et al.* 2021, pp. 1-11.
[64] Prati *et al.* 2017, pp. 129-160.
[65] Bell *et al.* 2019, pp. 1-18.
[66] Yan *et al.* 2019, pp. 586-591; Liu, Kazarian 2022, pp. 1777-1797.
[67] Cotte *et al.* 2022, pp. 1-21.
[68] Lutterotti *et al.* 2016, pp. 423-430; Hiley *et al.* 2022, pp. 1-13.

refers to stable non-radiogenic isotopes, important for light chemicals. In nature, most chemical elements have two or more isotopes. Each element's multiple isotopes have the same number of protons (Z) but not the same number of neutrons (N) or mass (M = Z + N)[69].

Neutron Activation Analysis (NAA) is a universally acknowledged technology in art forensics, archaeology, and anthropology with multiple applications. NAA uses decay characteristics ranging from distinctive decay radiation to characteristic time decay as a unique analytical signature for identifying elemental or isotopic components in samples. Neutron activation permits isotope analyses as well as information regarding elemental abundances[70].

In cultural heritage analysis, stable isotopes are frequently used to answer issues about previous diets[71], past food practices[72], subsistence economies[73], and populations' mobility[74], processes and manufacturing techniques of historical objects[75], and the origin of a variety of materials[76].

Radiocarbon dating

The radioactive decay of 14C is used in radiocarbon dating. It is known that the half-life of 14C is constant and unaffected by environmental variables. Its use is restricted to biological materials that are exposed to CO2 exchange with the atmosphere[77]. Radiocarbon dating is frequently used for cultural heritage elements age estimation referring to archaeological bones and mummified remains[78], canvas paintings and pigments[79], manuscripts and parchements[80].

Imaging techniques

In the study of cultural heritage elements, imaging techniques are crucial, facilitating the collection, analysis, and display of visual data recovered from macro to atomic scale for investigated items. The simplest and most popular imaging method is photography, most frequently used in cataloguing, increasing

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[69] Nord, Billström 2018, pp. 1-13.
[70] Wiescher, Manukyan 2020, pp. 138-139.
[71] Wißing *et al.* 2019, pp. 1-12.
[72] Miller *et al.* 2020, pp. 1-16.
[73] Cheung *et al.* 2019, pp. 1-27.
[74] Ortega *et al.* 2021, pp. 1-12.
[75] Doherty *et al.* 2021, pp. 1-12.
[76] Von Holstein *et al.* 2016, pp. 1-27.
[77] Wiescher, Manukyan 2020, pp. 138-139.
[78] Higham *et al.* 2010, pp. 653-670; Richardin *et al.* 2013, pp. 345-352; Panzer *et al.* 2014, pp. 1-11; Di Maida *et al.* 2019, pp. 1-19.
[79] Hendriks *et al.* 2018, pp. 207-218; Hendriks *et al.* 2019, pp. 13210-13214; Hendriks *et al.* 2020, pp. 7674-7682.
[80] Bonani *et al.* 1992, pp. 843-849; Omayio *et al.* 2022, pp. 1-30.

public access, education, and marketing cultural heritage artefacts. The levels for photographic imaging fall into the main categories: aerial photography, diagnostics of architectural sites, and single-object imaging[81]. Aerial photography and diagnostics of architectural sites facilitate the imaging and mapping of the locations of vast archaeological sites and objects and possible in situ conservation strategies adaptation[82]. Single-object imaging refers to the exact contour identification and visualisation of the shape of particular archaeological artefacts *in situ*[83] and establishing its integrity and possible reconstruction for cataloguing and inventory[84].

Imaging can also be done at the mesoscopic, microscopic, or atomic levels. The capacity to investigate the object's surface or internal structure distinguishes modern imaging techniques. The penetration of electrons, X-rays, or neutrons through an object is used to expose its internal structure. The main visualising methods are reflectography, microscopy, radiography, and tomography[85]. Reflectography involves UV, visible, and infrared light reflection to retrieve information from the surface of various objects[86]. Microscopy, varying from optical microscopy to electron microscopy, scanning, and transmission, allows surface characterisation but also can determine electron diffraction, which offers crystallographic information about materials[87]. The ability to see into the internal structure of objects is possible with radiography. Two-dimensional radiography pictures generate three-dimensional models known as computed tomography[88].

A particular imaging-related technique is Light Detection And Ranging (LiDAR), which allows the creation of highly detailed digital terrain models (DTMs) that reveal low-relief topographic elements[89]. These models have the potential to supplement archaeological field research by creating visual imagery that may be utilised to discover indications of ancient anthropogenic activity. It is especially beneficial in difficult-to-reach places and densely vegetated areas, where manual surveys are challenging to organise and conduct. Furthermore, because LiDAR technology is non-invasive, initial surveys may be carried out without affecting or destroying the landscape's integrity or any characteristics it may contain[90].

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[81] Wiescher, Manukyan 2020, pp. 138-139.
[82] Verhoeven 2009, pp. 233-249; Markiewicz 2022, pp. 1-8.
[83] Verschoof-van der Vaart, Lambers 2022, pp. 15-31.
[84] Rasheed Nordin 2020, pp. 883-894; Cerasoni *et al.* 2022, pp. 1-6.
[85] Wiescher, Manukyan 2020, pp. 138-139.
[86] Miguel *et al.* 2022, pp. 286-296.
[87] Balzano *et al.* 2022, pp. 1-17.
[88] Albertin *et al.* 2019, pp. 2028-2038.
[89] Schindling, Gibbes 2014, pp. 411-423.
[90] Balsi *et al.* 2021, pp. 1-10; Fernández-Lozano *et al.* 2022, pp. 1-6.

Biological investigation techniques

All the above-mentioned analytical techniques for cultural heritage investigation allow chemical composition evaluation revealing information on the object's origin or production components, manufacturing technique and time of production, and its authenticity[91]. Biological approaches complement the physicochemical strategies and contribute to the characterisation of the items with bio-origin (fibers, parchment) or the entities causing changes and deterioration as bacteria, fungi, or insects[92]. The most studied investigated items consist of varnishes[93], paintings[94], archaeological objects[95], binding media[96], paper-based documents[97], parchments[98], marbles[99], and frescoes[100], as well as various objects made of leather[101], fabric[102], stone[103], ceramics[104] and glass[105], wood[106], and metal[107].

Most of the recent studies on biological investigations use up-to-date investigative techniques correlated to the *omics* era, such as genomics, transcriptomics, proteomics, and metabolomics[108]. Both genomics and transcriptomics are the beneficiaries of the technological progress regarding nucleic acid processing, from the extraction techniques to the sequencing ones, with Next Generation Sequencing (NGS) and Third Generation Sequencing (TGS) being the fundamental promoters[109]. Metagenomics offers information on the taxonomy of microorganisms' communities. DNA molecules retrieved from living cells, viable but not culturable cells, and dead cells are analysed together. Complimentary metatranscriptomics gives information on genes expressed in a specific environment, allowing only active species to be identified[110]. Together

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[91] Mari, Filippidis 2020, pp. 1-19.
[92] Piñar *et al.* 2020b, pp. 1-22; Stefano *et al.* 2021, pp. 1-6.
[93] Piñar *et al.* 2020a, pp. 1-10.
[94] Caselli *et al.* 2018, pp. 1-18; Dubrovskii *et al.* 2022, pp. 1-15.
[95] Vinciguerra *et al.* 2016, pp. 341-348; Bonicelli *et al.* 2022, pp. 1285-1298.
[96] Vilanova, Porcar 2020, pp. 435-441.
[97] Pinzari, Gutarowska 2021, pp. 79-116.
[98] Fiddyment *et al.* 2019, pp. 1-10; Rosenbloom 2021, pp. 336-338.
[99] Sazanova *et al.* 2021, pp. 1-19; Checcucci *et al.* 2022, pp. 1-10.
[100] Cennamo, De Luca 2022, pp. 1-6; Zucconi *et al.* 2022, pp. 1-31.
[101] Vyskočilová *et al.* 2022, pp. 483-499.
[102] Szulc *et al.* 2021, pp. 1-12.
[103] De Leo *et al.* 2022, pp. 1-20; Wu *et al.* 2022, pp. 1-17.
[104] Romani *et al.* 2021, pp. 1-14.
[105] Corrêa Pinto et al. 2019, pp. 106-113.
[106] Wagner *et al.* 2018, pp. 1138-1154.
[107] Mari, Filippidis 2020, pp. 1-19; Giriyan *et al.* 2021, pp. 417-439.
[108] Marvasi *et al.* 2019, pp. 1-7; Marvasi *et al.* 2021, pp. 1-2.
[109] Athanasopoulou *et al.* 2021, pp. 1-22; Branysova *et al.* 2022, pp. 245-260; Liu *et al.* 2022, pp. 1-9.
[110] Branysova *et al.* 2022, pp. 245-260.

with metatranscriptomics, metaproteomics and metabolomics offer information on the functional activity potential of the microorganisms' communities associated with cultural heritage items by analysing proteins[111] as well as various metabolic compounds[112].

Bicodicology is a newly defined discipline correlated to the biological information stored in parchments, evolving due to the omics development[113]. According to Fiddyment et al., the obtained biological data on parchment documents offer a holistic view of their production, livestock economies, handling, conservation, and historical usage of the object[114].

Preservation, Conservation and Restoration techniques

Ageing, improper handling, pollution, temperature, light, bacteria, fungi or insects, and other variables can change the colour of an object and induce cracks, chemical reactions, or layer separation, which can cause damage to cultural heritage items[115].

Preservation of cultural heritage refers to keeping unimpaired community artefacts and customs against forces that seek to alter or destroy them. From the preservation perspective, intangible cultural items become as crucial as tangible ones[116]. On preservation, the current research trends minimise the invasiveness of the investigative utilised techniques for every object integrity assessment. More and more methods are developed for their usage *in situ* and in a standardised manner[117]. Imagistics play a crucial role in preservation, using surface spectroscopic maps, digital 3D models, 3D scanning, and photographic documentation for appropriate handling and usage. Virtual reality technology can provide the tools for the 3D reconstruction of historical items of various dimensions[118]. Landmarks, archaeological sites, towns, or single objects that no longer exist or have their integrity altered can be projected. Even though technical capabilities are rapidly expanding, the focus is primarily on building virtual museums and displays, with archaeological sites and excavations following[119].

Cultural heritage conservation refers to actions that can extend the life of cultural assets while increasing the transmission potential of the valuable legacy to the next generations. The goal in the realm of cultural property is to preserve

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[111] Dubrovskii *et al.* 2022, pp. 1-15.
[112] Gutarowska *et al.* 2015, pp. 1-13.
[113] Fiddyment *et al.* 2019, pp. 1-10; Rosenbloom 2021, pp. 336-338.
[114] Fiddyment *et al.* 2019, pp. 1-10; Tamburini *et al.* 2022.
[115] Mari, Filippidis 2020, pp. 1-19.
[116] Ogden 2007, pp. 275-287.
[117] Gallo *et al.* 2021, pp. 1-23; Cataldo *et al.* 2022, pp. 1-16; Gatti *et al.* 2022, pp. 1-14.
[118] Kargas *et al.* 2019, pp. 1799-1811.
[119] Liritzis *et al.* 2021, pp. 3635-3654; Parfenov *et al.* 2022, pp. 1-10.

the object's physical and cultural features so that its value persists and outlasts our finite lifespan[120]. Usually, conservation is associated with restoration redefining the new domain in cultural heritage science of conservation-restoration defined *as a set of measures and actions aiming at preserving the cultural heritage while conserving its significance, but also the access of the present and future generations*[121]. The ontological models for the conservation-restoration process formalise the information describing the analysed item (typology, form, dimensions, material constitution, etc.), its characteristics (origin, nature, factors), and the associated phenomena or events affecting the cultural object at a given moment (alteration, degradation, ageing, etc.). The information also refers to data (measurements, spectra interpretation) retrieved by scientific studies conducted on the cultural object (diagnosis, analysis, sampling, etc.) implemented through material resources (analytical instruments, diagnosis, sampling technique, etc.). Also important is the information about the types of interventions undertaken on the cultural object (conservation, restoration, preventive conservation, etc.) and the participants involved in the conservation-restoration process (conservators, restorers, scientific actors, etc.)[122].

The treatment and restoration techniques applied to cultural heritage can be chemical, physical, and biological and are used in various combinations to obtain the best possible outcome[123]. Cleaning is a crucial step in cultural heritage conservation. It must be a selective process that removes only the unwanted attached materials on the surface of the investigated items without affecting the objects' composition. The chemical cleaning of cultural heritage items was the first methodological applied attempt. Inappropriate solvent usage led to unwanted changes to the surface of art objects[124], manuscripts[125], archaeological objects[126] etc. In contrast to the improper removal due to chemical cleaning same materials (glues, adhesives, varnishes, protective coatings) were added to the surface of the analysed object in the attempt to increase its integrity[127].

Recent strategies utilise nanostructured fluids, gels and polymers, bio cleaning, and nanoparticles. Nanostructured fluids (NSFs) are colloidal systems that rely on surfactant characteristics. Surfactant molecules in water self-assemble to create micelles, which are nano-sized supramolecular aggregates

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[120] Stovel 1998, pp. 1-15.
[121] Kakali *et al*. 2007, pp. 128-139.
[122] Niang *et al.* 2015, pp. 157-160.
[123] Baglioni *et al.* 2021, pp. 1-20.
[124] Brajer 2009, pp. 1-28.
[125] Elnaggar *et al.* 2015, pp. 73-81.
[126] Ricca *et al.* 2021b, pp. 1-12. See also Rogerio-Candelera 2014, pp. 1-11.
[127] Baglioni *et al.* 2021, pp. 1-20.

with a hydrophobic core that may act as solubilisation sites for small hydrophobic compounds[128]. NSFs were successfully tested on cleaning monumental carvings[129], glass, marble, polystyrene[130], and varnish[131].

For gels and polymers, poly(vinyl alcohol)/poly(vinyl pyrrolidone) hydrogels, p (HEMA)/PVP hydrogels, and poly(hydroxyethyl methacrylate) semi-interpenetrated with linear chains of polyvinylpyrrolidone (pHEMA/PVP SIPNs) were successfully used for cleaning painting artworks[132], paper artworks[133], archaeological metals[134], and stone objects[135]. Some gels are combined with biocidal substances and contribute to removing the biological patina of heritage items[136].

Biocleaning implies using microbial biotechnologies to remove unwanted materials associated with cultural heritage[137]. The procedure was utilised for the desalination of granite pavement[138], nitrate removal from building materials[139], and black crust, nitrate, and sulfate decay agents removal from artworks[140]. On the other hand, the nanoparticles are frequently designed as biocides agents due to the applied coatings[141] or as nanomaterials that promote the consolidation of heritage items[142].

Perspectives

Cultural heritage science evolved in the last years in connection with technological advances. The overall directions of evolution in this scientific domain converge on the automatisation of data acquisition, standardisation of data processing and analysis, obtaining comparable data with the ones already published, and results' interpretation in the most comprehensive possible way[143]. Computer science plays a crucial role and becomes more tested and applied in variable techniques suited for each cultural heritage challenge.

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[128] Baglioni *et al.* 2019, pp. 1-16.
[129] Alcalá *et al.* 2022, pp. 18-29.
[130] Baglioni *et al.* 2019, pp. 1-16.
[131] Pensabene Buemi *et al.* 2020, pp. 1-16.
[132] Domingues *et al.* 2013, pp. 2746-2755; Giorgi *et al.* 2013, pp. 303-306; Bonelli *et al.* 2019, pp. 339-348.
[133] Mazzuca *et al.* 2014, pp. 16519-16528.
[134] Giraud *et al.* 2021, pp. 73-83; Guaragnone *et al.* 2022, pp. 7471-7485.
[135] Han *et al.* 2021, pp. 1-11.
[136] Gabriele *et al.* 2022, pp. 1-17.
[137] Ranalli, Zanardini 2021, pp. 583-603.
[138] Bosch-Roig *et al.* 2021, pp. 1-18.
[139] Tomić *et al.* 2022, pp. 1-9.
[140] Bosch-Roig *et al.* 2015, pp. 1227-1241.
[141] Lázaro-Mass *et al.*, pp. 1-13; Abdel-Nasser *et al.* 2022, pp. 14-23; Wang *et al.* 2022, pp. 206-211.
[142] Valentini *et al.* 2022, pp. 93-108.
[143] Van den Bosch *et al.* 2009, pp. 129-138.

Building Information Modeling (BIM) is a modern approach used in architecture, engineering, and construction. It allows users to create virtual architectural models that can be linked to numerical data, words, photos, etc. Building components are described as “smart objects” specified by numerical parameters such as dimensions and embedded with other types of information like construction materials and qualities. The findings in BIM are easily transferable to the cultural heritage buildings generating a new subsection called Heritage Building Information Modeling (HBIM). HBIM offers the ability to construct a classification system for endangered heritage structures and to define how heritage legislation and regulations should be applied[144]. HBIM proposes new levels of interactivity between users and virtual environments capable of putting in touch with tangible and intangible values of ancient ruins. The development of new technologies in computer graphics, Virtual Reality (VR), and three-dimensional (3D) digital surveys allows 3D sketching and digital modelling based on new Scan-to-HBIM-to-VR standards, based on the conversion of point clouds into mathematical models and digital data[145]. HBIM proved its usefulness in defining new methodological guidelines for historical buildings for their protection and habitability[146]. New informative models for 4D management were defined to depict the evolution phases between pre-modern and industrial era techniques[147] and new heritage conservation, monitoring, and management techniques that suit various heritage elements[148].

Computer vision is more frequently applied in cultural heritage investigations. Usually is associated with robotics[149] or artificial intelligence algorithms, especially with machine learning techniques[150] for automatised data acquisition and processing. Point clouds are standardised units and consist of spatial collections of data points for 3D shapes or items. Cartesian coordinates are assigned to each point position. 3D scanners or photogrammetry software, which measure multiple points on the external surfaces of things surrounding them, produce point clouds[151]. Machine learning algorithms are expected to be also used for *omics* data interpretations in cultural heritage investigations as they tend to develop at the moment[152].

Other innovations take place in the digitalisation of heritage collections. Ideally, all the heritage goods will be accessible through digital media as more

[144] Aburamadan *et al.* 2021, pp. 3-14.
[145] Banfi 2020, pp. 16-33.
[146] Millán-Millán, Cabeza-Lainez 2022, pp. 1-17.
[147] Currà *et al.* 2022, pp. 1-29.
[148] Jia *et al.* 2022, pp. 1-21.
[149] Luxman *et al.* 2022, pp. 1-11.
[150] Arandjelović, Zachariou 2020, pp. 1-17.
[151] Aicardi *et al.* 2018, pp. 257-266.
[152] Chicco *et al.* 2020, pp. 1-3.

researchers contribute to the digitalisation process[153].

Conclusions

The advances in cultural heritage science are remarkable and are based on the classical investigation techniques updated to the present technological advances. The present and future advances are correlated with top-notch quality techniques applied in a multidisciplinary context. Each scientific entity implicated in heritage conservation helps the transmission of the heritage to the next generations in the most professional possible way, with minimal harm to the integrity of existing objects.

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