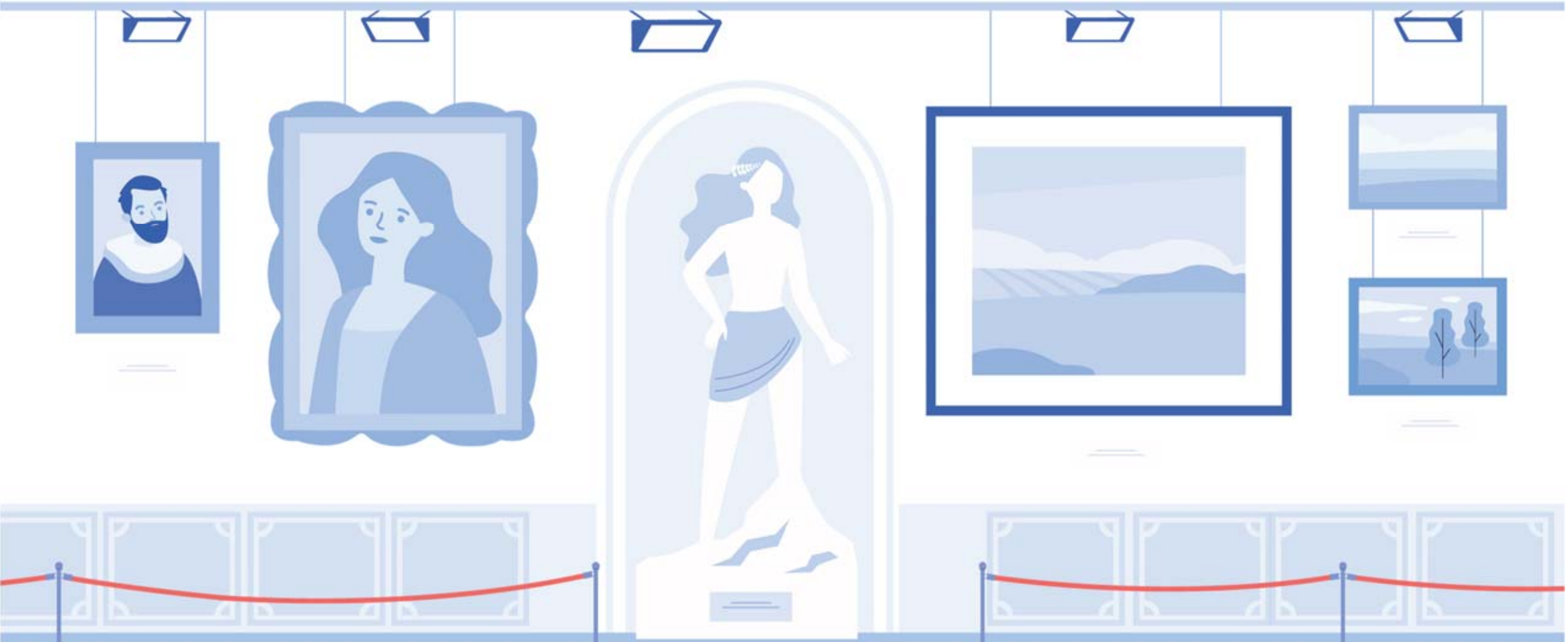
Ref. Ares(2025)5193634 - 30/06/2025

SIMIACCI

Deliverable 4.1

Most common sources of pollutants in GLAMs & Assessment of main challenges for an efficient IAQ control



Nature of the deliverable		
R	Document, report	X
DEM	Demonstrator, pilot, prototype	
DMP	Data Management Plan	
OTHER	Software, technical diagram, etc	

Dissemination level		
PU	Public (*fully open*)	X
SEN	Sensitive (*limited under the conditions of the Grant Agreement*)	
EU Cl	EU Classified (*eu-restricted, eu-confidential, eu-secret under Decision 2015/444*)	

Deliverable No.	**D4.1**
Dissemination level	**PU**
Work Package	**4**
Task	**4.1**
Lead beneficiary	**CNRS-CRC**
Contributing beneficiaries	ABK, DM, DTU, ISTD, MNHN, MMP, NTM, RDL
Main authors	**A-L Dupont (CNRS-CRC), I Fouskari (DTU) B Lavédrine (MNHN), A. Al Mohtar (ISTD), M Pamplona (DM), M Pinto (ISTD), M Roth (DM), M Qin (DTU), B Vinther-Hansen (RDL), N Wallaszkovits (ABK)**
Due date of deliverable	30/06/2025 (M6)
Actual submission date	27/06/2025 (M6)

Quality procedure			
Date	Version	Reviewers	Comments
27/06/2025	1	N/A	CNRS – main author

Acknowledgements

This report is part of the deliverables from the project SIMIACCI, which has received funding from the European Union's Horizon Europe research and innovation program under grant agreement N° 101178095. More information on the project can be found at www.simiacci.eu.

Document’s objective and executive summary

Volatile organic compounds (VOCs), nitrogen oxides (NOx), hydrogen sulfide (H_2S), and other gases present in the indoor air of Galleries, Libraries, Archives, and Museums (GLAMs) pose significant threat to the long-term preservation of Cultural Heritage (CH) artefacts and collections. Primarily based on literature, D4.1 gathers up-to-date information on the most common sources of pollutants in GLAMs, their impact on the artefacts, and their monitoring/analysis.

The state-of-the-art scientific knowledge on these pollutants concentration indoors, their known impact on artefacts, and the recommendations for acceptable concentrations are summarized in the first part of the report. A comprehensive survey conducted by WP4 within a large group of indoor air quality (IAQ) specialists in GLAMs sheds light on the current recommendations and guidelines concerning key airborne pollutants in GLAMs. It aims at providing an objective assessment of the main barriers encountered for an efficient IAQ control in GLAMs. Besides pollutants, temperature (T) and relative humidity (RH) also have a considerable impact on the preservation, yet new trends are emerging in the CH conservation community towards a relaxation of the strict T/RH benchmark values, in view of most needed energy savings and low carbon footprint, while preserving the IAQ. These new trends are investigated as well.

The second part of the report gathers the available sorbent materials and technologies (passive and active) on the market and used in GLAMs for IAQ control. Monitoring solutions for IAQ are varied (sensors, dosimeters, colour strips and tests), and their pros and cons are given in the third part of the report. This report will provide the SIMIACCI consortium with the current perception of IAQ management and mitigation in GLAMs. It will also provide input to other work packages of the project to adjust the exploitation strategy and the communication actions to the targeted groups of interest.

Table of contents

Funded by
the European Union

1. IAQ in GLAMs

1.1 Gaseous pollutants

Unlike outdoor pollution, where dispersion reduces concentration levels, indoor pollutants often accumulate in closed environments (e.g. display cases with low air exchange rate and cabinets), leading to prolonged exposure and thereby increasing the risk of causing Cultural Heritage materials degradation. Therefore, Indoor spaces such as GLAMs are highly vulnerable to airborne pollutants.

Airborne pollutants such as gases or particles can be classified according to their boiling points (World Health Organization (WHO), though a more practical approach relies on retention times of individual compounds after gas chromatography separation. Using the latter approach, compounds appearing between hexane (C6) and hexadecane (C16) on a lightly polar gas chromatographic column fall under volatile organic compounds (VOCs). Those before hexane (C6) are very volatile organic compounds (VVOCs), while those beyond hexadecane (C16) belong to the semi-volatile organic compounds (SVOCs) category.

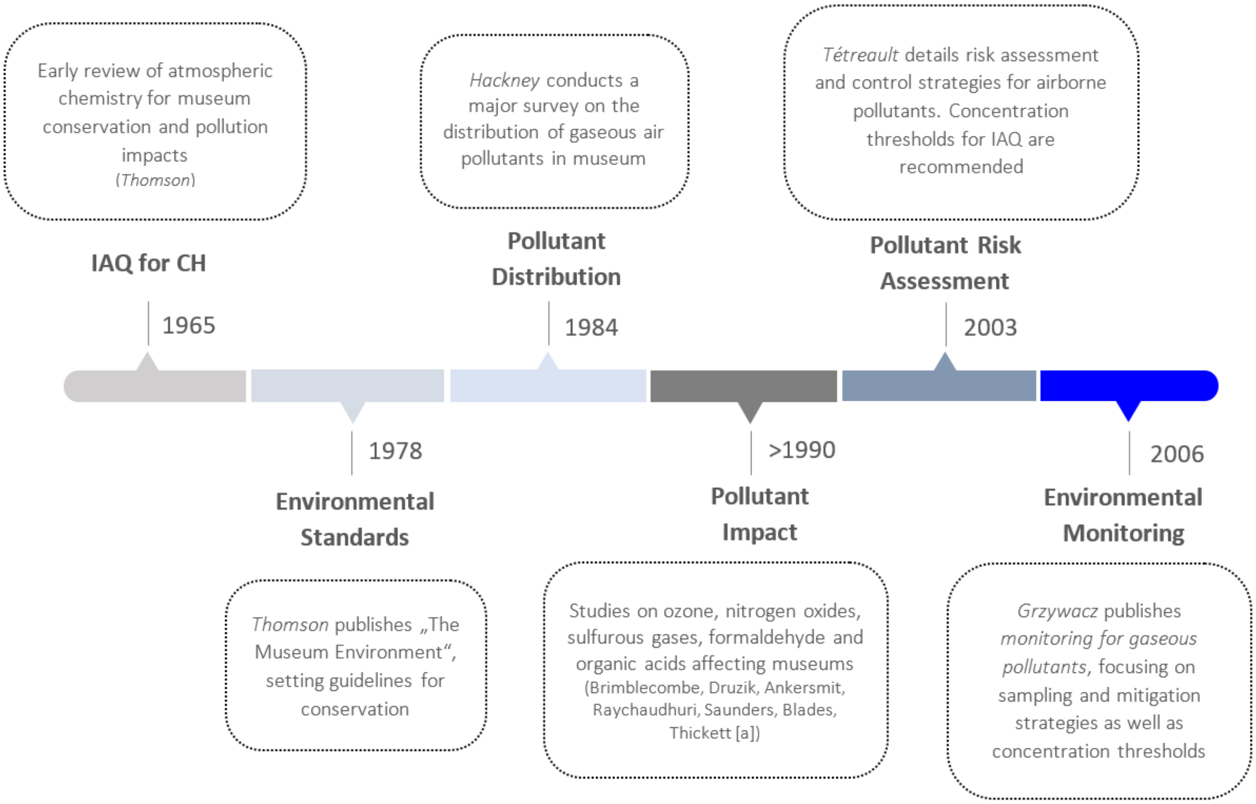
The most common gaseous pollutants affecting indoor environments include nitrogen oxides (NO_x), organic acids, formaldehyde, reduced sulfur gases (such as H_2S), ozone (O_3), and sulfur dioxide (SO_2). These pollutants originate from various sources, including building materials, furniture, adhesives, sealants, cleaning agents, and fuel combustion. Once present indoors, they can interact with CH materials, leading to fading, embrittlement, discoloration, and chemical degradation, with environmental factors like temperature and relative humidity influencing their impact[1].

While VOCs such as acetic acid, formaldehyde and formic acid are particularly relevant in preventive conservation due to their corrosive and deteriorative effects, NO_x and H_2S belong to a different classification as inorganic gaseous pollutants. Nitrogen oxides (NO and NO_2) often enter indoor spaces from outdoor sources, contributing to secondary chemical reactions that alter air quality. They can also derive from primary sources such as from objects made of cellulose nitrate. Hydrogen sulfide (H_2S), linked to industrial emissions and degradation processes as well as off-gassing vulcanized rubber poses a notable risk due to its high reactivity, particularly with metals like silver[2,3].

1.1.1 *Development of Pollutant Research in Museum Environments*

The study of gaseous pollutants in museum environments has evolved significantly over the years, driven by advancements in conservation science, pollutant monitoring, and air quality management. Understanding how research, risk assessments, and technological developments have shaped current best practices provides an important context for mitigating pollutant-related damage. Figure 1 highlights past key milestones in the field, tracing the progression of air quality research in GLAMs and the development of monitoring tools and strategies.

Funded by the European Union



Early review of atmospheric chemistry for museum conservation and pollution impacts (*Thomson*)

Thomson publishes „The Museum Environment“, setting guidelines for conservation

Hackney conducts a major survey on the distribution of gaseous air pollutants in museum

Studies on ozone, nitrogen oxides, sulfurous gases, formaldehyde and organic acids affecting museums (Brimblecombe, Druzik, Ankersmit, Raychaudhuri, Saunders, Blades, Thickett [a])

Tétreault details risk assessment and control strategies for airborne pollutants. Concentration thresholds for IAQ are recommended

Grzywacz publishes *monitoring for gaseous pollutants*, focusing on sampling and mitigation strategies as well as concentration thresholds

Figure 1. Timeline of past milestones in the research of IAQ in museum environments. [a] further important publications: Ankersmit et al. 2005, Franey et al. 1985, Grosjean et al. 1988, Whitmore and Crass 1988, Williams et al. 1992, Grzywacz and Tennent 1994, Brokerhof et al. 1996, Dupont and Tétreault 2000). Other literature used for this figure: Thomson 1965, Thomson 1978, Hackney 1984, Brimblecombe et al. 1992, Brimblecombe 1994, Druzik 1990, Raychaudhuri et al. 2000, Saunders 2000, Blades et al. 2000, Thickett 1997, Tétreault 2003, Grzywacz 2006.

1.1.2 *EU-Funded Projects and Scholarly Reviews (1997–2025)*

Several EU-projects focused on the topic of IAQ in GLAMs (Figure 2), contributing to a broader understanding of air quality management in cultural heritage environments as well as developing new sorbents and devices in order to control IAQ. To our knowledge, the first project to address indoor air quality for cultural heritage protection started with the AMECP-Project in 1993. From there on, numerous projects followed. In a way, the SIMIACCI project picks up where these projects left. In that respect, it is important to understand the rationale and the achievements of the different projects as well as the challenges encountered when it comes to market solutions. The Annex B to SEN report D4.2 (Specifications for the adsorbent materials to be developed) gathers several person-to-person interviews that were conducted during the months of April and May 2025 with the coordinators and WP leaders of some of these projects to identify the main barriers and challenges for effective IAQ management in GLAMs.

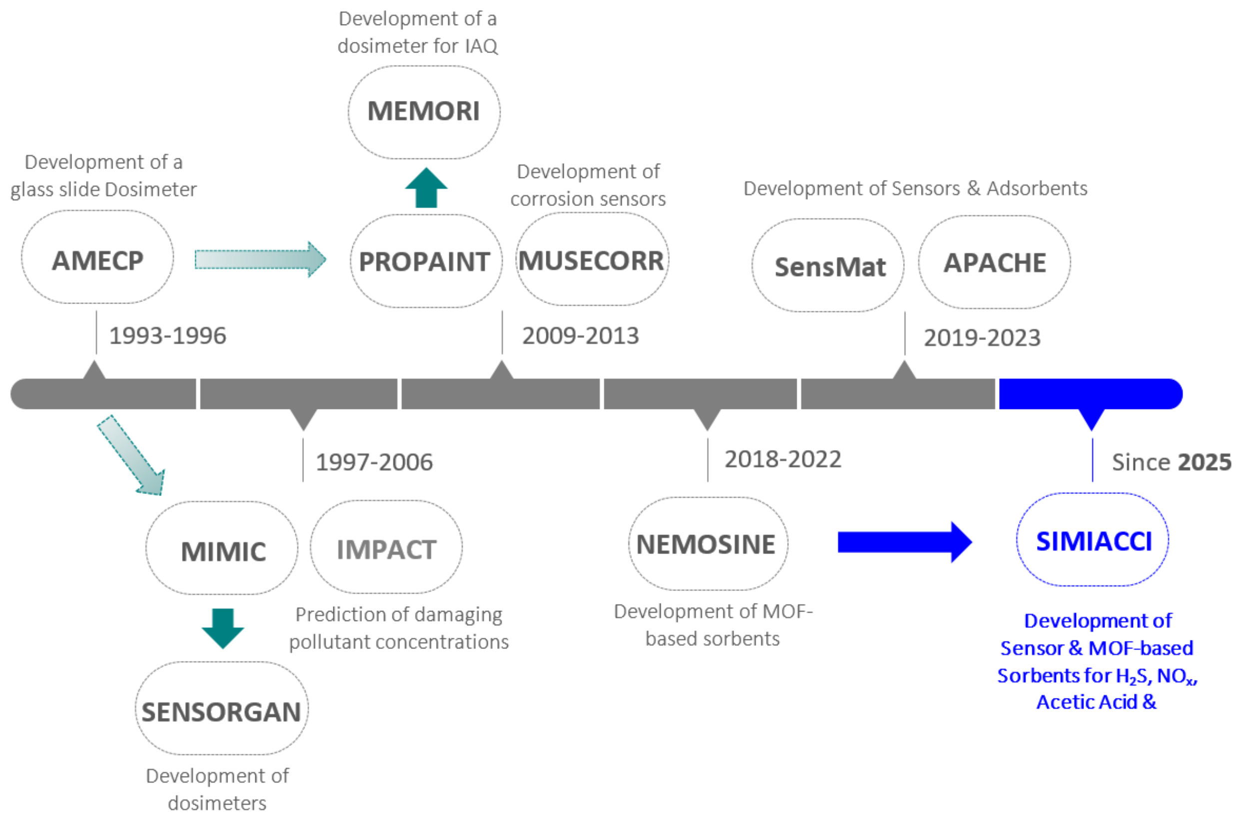


Figure 2. Overview of European research projects (1993–2025) related to indoor air quality in museum environments

Several reviews have examined pollutants and their control in GLAM environments. In 2019, Elyse Canosa and Sara Norrehed (Swedish National Heritage Board) provided a very detailed overview of both historical and contemporary approaches to pollutant mitigation[1]. This chapter draws significantly from their findings, offering only a concise discussion of the most common pollutants, particularly those relevant to SIMIACCI. Readers seeking a more in-depth information on pollutant types, their sources, and their effects on cultural heritage materials are encouraged to consult it. Two other very important reviews on this matter have been published in 2021 by Chiantore and Poli[4] and in 2025 by Vergelli et al. [5].

1.1.3 *Sources of pollutants*

Organic and inorganic pollutants can be introduced from external environmental sources and subsequently accumulate within GLAMs. However, in these spaces, the primary contributors to pollutant emissions are indoor sources. Understanding pollutant sources, their interaction with cultural heritage materials, and the best strategies for IAQ management is essential for long-term preservation. SIMIACCI essentially focusses on the four most common pollutants, namely: nitrogen oxides, hydrogen sulfide as well as formaldehyde and acetic acid.

To effectively manage indoor air quality (IAQ) in GLAMs, it is crucial to not only identify key pollutants but also understand their behaviour within indoor spaces. While threshold concentration levels help reduce deterioration risks, pollutant dynamics are influenced by various environmental interactions. One valuable approach to assessing these dynamics is the indoor/outdoor (I/O) ratio, which provides insight into whether contaminants originate externally or are predominantly emitted indoors. By analysing this ratio, researchers can better evaluate pollutant infiltration and accumulation, informing targeted conservation strategies. The

I/O-ratio is a simple yet valuable metric for assessing air quality. It helps to determine whether outdoor pollutants are infiltrating a building or if indoor materials are generating harmful contaminants. The ratio is calculated by dividing the average indoor pollutant concentrations by the corresponding outdoor air quality measurements over the same period[6,7]. Although useful, the I/O ratio must be interpreted carefully, as indoor pollutant levels can sometimes exceed outdoor levels due to complex atmospheric interactions[8]. More advanced I/O models incorporate factors such as air exchange rate and pollutant deposition velocity, offering refined insights into pollutant behaviour [6, 9]. For instance, the steady-state I/O ratio proposed by Weschler et al. is particularly useful for studying pollutants such as ozone, sulfur dioxide, and nitrogen dioxide, and it has been applied in research on air quality in museum environments[10].

Nitrogen Oxides (NO_x)

NO_x includes nitrogen dioxide (NO_2) and nitrous oxide (NO), primarily generated by fuel combustion, fertilizers, and lightning. Indoors, NO_2 is emitted from deteriorating cellulose nitrate[11, 12, 13]. NO_2 reacts with water to form nitric acid, which accelerates fading in artists' colorants on textiles and causes acidification of cellulose paper [13, 14, 15]. Atmospheric NO_x levels rose during the industrial revolution but began decreasing in the US and Europe after the 1980s due to air pollution regulations[16].

Hydrogen Sulfide (H_2S)

Hydrogen sulfide is a reduced sulfur gas that corrodes metal-based materials such as silver, copper, bronze, and lead pigments, and degrades paper. Found both indoors and outdoors, H_2S is emitted from fuel combustion, petroleum processing, marshes, some adhesives and rubber materials[3]. It causes visible deterioration in silver photographs[17], paper[18], and paintings[19]. It is highly toxic and exhibits a characteristic smell at ppb-concentrations. Objects sensitive to H_2S, like silver artefacts, can show signs of deterioration even at ppt levels[20].

Formaldehyde (HCHO)

Formaldehyde is a very volatile organic compound (VVOC) and can be emitted from carpet, wood, paints, adhesives, tobacco smoke, vehicle exhaust, and ozone-generating air purifiers[16]. Formaldehyde oxidizes to form formic acid, which accelerates corrosion in lead materials, leading to the formation of lead formate. Unlike formaldehyde, formic acid is very aggressive to cellulose-based materials like paper[21]. Sodium-rich glass objects also develop sodium formate deposits from exposure to formic acid[22]. Formaldehyde presence in museums is a concern for both artefact preservation and human health.

Acetic Acid (AcOH)

Acetic acid affects metals (especially lead), calcareous materials (shell, limestone, fossils), glass, cellulose and cellulose acetate. The corrosion of lead-rich metals is linked to acetic acid emissions[23], while discoloration of pigments is another effect[24]. Paper degradation is intensified by acetic acid exposure[21, 25]. Lead converts to lead acetate or lead formate when interacting with acetic acid[26]. Organic acids from deteriorating cellulose acetate, wood products, and adhesives contribute to museum air quality issues[27]. Acetic acid off gassing from wood increases with humidity and temperature, making climate control a crucial factor in pollutant mitigation[22].

Other Pollutants

Various airborne substances contribute to museum object deterioration through chemical interactions. Sulfur dioxide (SO_2) reacts with water to form sulfuric acid, which erodes calcium carbonate-based materials like marble, limestone, and frescoes[16, 28]. Ozone (O_3), produced by UV radiation, vehicle emissions, and electronic equipment, accelerates fading, embrittlement, and oxidation in artworks[14, 29]. Hydrogen chloride (HCl) corrodes metals such as silver and copper[30], while ammonia (NH_3), emitted from cleaning products, concrete, and paints, reacts with sulfates or nitrates to form damaging white surface deposits[16]. Peroxides, from smog, rubber, wood, and oil-based paints, cause discoloration in photographic prints and pigments[31]. Piperidinol derivatives, found in adhesives, have been linked to unexpected deterioration in display cases and collection objects, forming crystalline deposits on surfaces[4, 32, 33].

The primary sources of gaseous pollutants within GLAMs originate largely from organic materials, including the exhibits materials themselves, materials used in display cases, visitors, cleaning agents, etc. Table. 1 provides a comprehensive summary of the most common pollutant sources and their potential impact on cultural heritage, subdivided by the specific materials affected.

Table. 1. List of most common pollutants occurring in GLAMs, their origin and possible effects on cultural heritage (CH) (Tétreault 2021, Canosa et al. 2019, Horie 2010, Schieweck et al. 2009, Shashoua 2008, Grzywacz 2006, Blades 2000)

Abbreviations: PVC: Polyvinyl chloride; PU: Polyurethane; PS: Polystyrene; SBR: Styrene-butadiene rubber; PET: Polyethylene Terephthalate; PBT: Polybutylene Terephthalate; PMMA: Polymethyl Methacrylate; PAA: Polyacrylate; NR: Natural rubber.

Pollutant	**Common sources**		**Effects on CH**	
	indoor	**outdoor**	**Material**	**Effect**
Acetic Acid (AcOH)	• wooden objects • laminated materials • paints • adhesives • cellulose acetate degradation • sealants • paper degradation	• wooden objects	• metal • shell, fossils, lime-stone • cellulose • cellulose acetate • enamel • glass • pigments	→ corrosion (Pb, Zn, Cd, Mg, Cu-alloys) → deterioration, efflorescence → embrittlement → accelerated chemical deterioration rate → corrosion/deterioration → corrosion/deterioration → alteration of Cu-and Pb-based pigments
Formaldehyde (HCHO)	• wooden objects • resins • fiberglass • photocopiers • textiles • PVC • laminates • natural history wet specimen collections • adhesives • paints	• wooden objects • photochemical processes • combustion of organic material (e.g. wild-fires) • tobacco smoke	• animal hides • leather • parchment • hide glue • dyes • pigments • textiles • metal	→ embrittlement → embrittlement → embrittlement → embrittlement → fading → fading → deterioration → corrosion of Pb at RH>75%
Nitrogen Oxides (NO_x)	• cellulose nitrate degradation • photocopiers	• biological processes • fuel combustion • tobacco smoke	• metals • textiles • pigments • photographs • plastics • rubber	→ corrosion → dye fading → embrittlement → deterioration → deterioration → discoloration → embrittlement

Funded by the European Union

Pollutant	Common sources		Effects on CH	
	indoor	**outdoor**	**Material**	**Effect**
Hydrogen sulfide (H_2S)	• wool • silk • felt • vulcanized rubber • pyrite collections • waterlogged wood. organic material • arc-welding activities • polysulfide-based sealants	• fuel combustion • coal combustion • biological processes • marshes, ocean • petroleum & pulp industries • vehicle exhaust • volcanos	• metal (Ag, Cu) • photographs • leather • pigments • stone	→ corrosion → tarnishing → "silver mirroring" → redox spots → discoloration → "red rot" → Pb-pigment darkening → deterioration
Sulfur dioxide (SO_2)	• pulp/paper production • fuels (heating) • vulcanized rubber	• fuel combustion • biological activity	• metal • dyes • paper • textiles • photographs • leather • $CaCO_3$ • paper • glass • proteins (e.g. in hide glue etc.)	→ corrosion (also H_2SO_4) → Fading → Embrittlement → Embrittlement → Deterioration → "red-rot", weakening → Deterioration → acidification (also H_2SO_4) → corrosion, discoloration → deterioration /embrittlement
Formic Acid (HCOOH)	• formaldehyde ox. • oil paint • wooden objects • adhesives • sealants • paper degradation	• formaldehyde oxidation • wooden objects	• metal (Zn, Pb, Bronze) • shell, fossils, limestone • cellulose	→ corrosion → deterioration, efflorescence → → embrittlement
Ozone (O_3)	• photocopiers • laser printers • electrostatic particle filters • UV-light sources • insect electrocutes • electronic air cleaners	• smog	• rubber • dyes • pigments • photographs • paper/books • textiles • cellulose • inkjet print • metals	→ embrittlement (ozonolysis) → fading → fading → deterioration → embrittlement, yellowing → embrittlement, cracking → embrittlement → fading → corrosion
Amines **1. Ammonia (NH_3)**	• silicone sealants • emulsion adhesives • emulsion paints • cleaning products	• concrete • excrements • fertilizer • underground bacterial activity • inorganic	• ebonite • cellulose nitrate • metals	→ blemishes → efflorescence → corrosion, tarnishing

Funded by the European Union

Pollutant	Common sources		Effects on CH	
	indoor	outdoor	Material	Effect
		process industry		
2. Cyclohexylamine (CHA) **2.1 Diethylamino ethanol (DEAE)** **2.2 Octadecylamine (ODA)**	• corrosion inhibitor		• paintings • metals (Cu, Ag, Bronze	→ blemishes → corrosion
3. Piperidinol-derivatives	• light stabilizer in polymeric products such as sealants			→ crystalline depo-sits on material surfaces
Fatty acids (RCOOH) R: aliphatic chain (saturated or unsaturated)	• burning candles • adhesives • cooking • human metabolism • microbiological activities • skin, furs, insect collections • plastics • oil-based paint • wooden objects • paper	• vehicle exhaust • biological processes	• paintings • sculptures • glass • paper • photographs	→ blemishes → blemishes → ghost images → yellowing → yellowing
Reduced sulfur gases **1. Carbon disulfide (CS_2)**	• polysulfide-based sealants • fungal growth	• fungal growth • rotting organic matter in the oceans, soils and marshes	• metal (Ag, Cu, Cu-alloys) • photography • pigments	→ corrosion → discoloration → Pb-pigment darkening
2. Carbonyl sulfide (OCS)	• wool degradation • oxidation of CS_2	• coal combustion • coastal ocean, soils and wetlands		
Plasticizers (e.g. Phthalates, Adipates, Citrates, Polyether-based, Phosphoric esters, Camphor)	Polymers such as: PVC, PU, PS, SBR, PET, PBT, PMMA, PAA, Epoxy resins, CN, CA, vulcanized rubber (NR) (origin: object itself, sealants, adhesives, coatings, flooring)		the polymer itself and in composite objects (i.e. made of several materials as different plastics or made of plastic and metal) it can affect the materials in close contact with the damaged plastic surface	embrittlement yellowing efflorescence

1.1.4 *Guidelines*

Materials degradation in CH collections is influenced by a variety of environmental factors, including airborne pollutants, humidity, temperature and fluctuations thereof, as well as exposure to light. Due to the complex interplay of these elements, defining universal preservation standards remains challenging. To minimize their harmful effects, threshold concentration levels for pollutants have been established. While acceptable limits vary depending on material sensitivity, even low levels of pollutants can contribute to irreversible deterioration over time.

Various CCIs and nations have developed concentration thresholds for pollutants to protect cultural heritage materials. While an internationally unified standard has not yet been established, many CCIs have either set their own thresholds or adopted recommendations primarily from the CCI[16] and/or the GCI[7] (Figure 3). The diagrams in Figure 3 show a great variability in thresholds that are recommended, especially considering the maximum values. Generally, the recommendations/thresholds for paper and paper-based objects are lower than for the other collections. It is noteworthy that the definition of "sensitive material" is not described in detail in the literature other than being materials that are especially sensitive towards the specific pollutant (e.g. silver towards H_2S, and often the example of ''dyes'' is given).These guidelines have been regularly updated to reflect new research and advancements in environmental monitoring. Pollutant concentration data is commonly expressed in gravimetric ($\mu g\ m^{-3}$) or volumetric (ppm, ppb, ppt) units (Table 2). The latter vary with temperature and pressure, making conversions necessary when standard conditions are assumed.

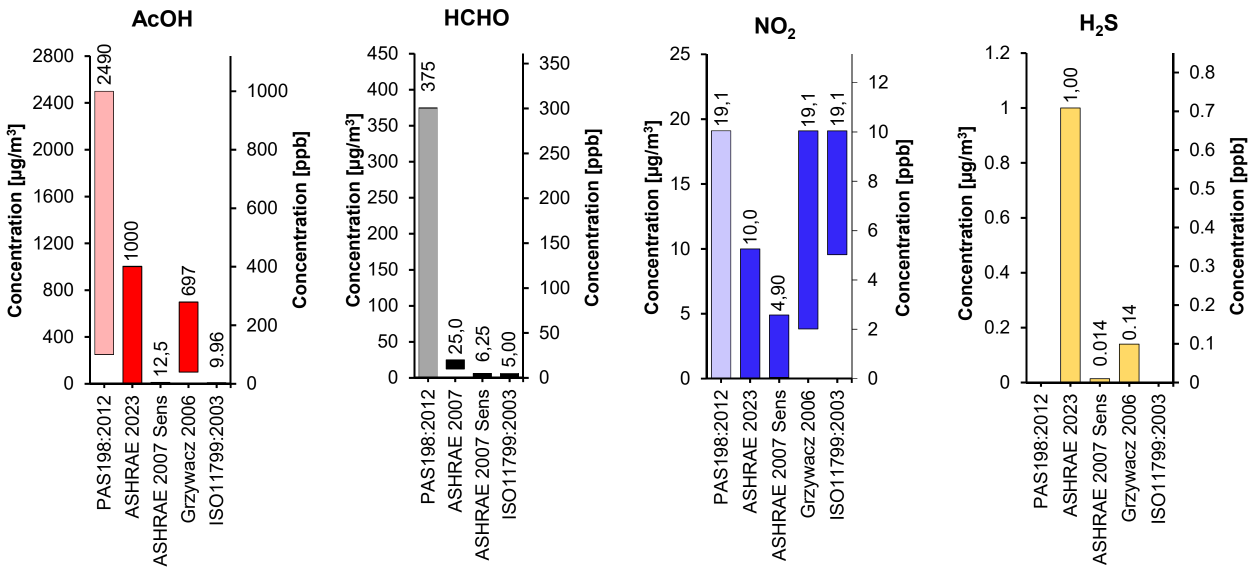


Figure 3. diagrams of the concentration thresholds/recommendations for the four main pollutants to be investigated in SIMIACCI. More detailed information can be found in Table 2. Gravimetric concentration values have been converted using the following multiplication factors: acetic acid: ppb x 2.49; formaldehyde: ppb x 1.25; Nitrogen dioxide: ppb x 1.91; hydrogen sulfide: ppb x 1.41.

Table 2. Concentration thresholds (gravimetric units) of the most common gas pollutants in GLAMs. [a]: NO2: values reported based on NO; [b]: values for NO2, H2S, AcOH, O3 from ASHRAE2023, values for Formaldehyde and SO2 in ASHRAE2007 are cited from Grzywacz 2006, value for Formic Acid from: ASHRAE2007; [c]: values cited in ASHRAE 2007 sens are taken from Grzywacz 2006.

Concentration in $\mu g/m^3$ (ppb)	**Acetic acid** (AcOH)	**Formaldehyde** (HCHO)	**Nitrogen dioxide** (NO_2)	**Hydrogen sulfide** (H_2S)
ASHRAE2007/2023[b]	**<1000** (<402)	**12,5-25** (10-20)	**<10** (<5,24)	**<1** (0,71)
ASHRAE2007 Sens[c]	**<12,45** (5)	**0,13-6,25** (0,1-5)	**0,1-4,97** (0,05-2,6)	**<0,014** (0,01)
Grzywacz 2006	**99,6-697** (40-280)	**12,5-25** (10-20)	**3,82-19,1** (2-10)	**<0,141** (0,1)
PD5454:2012[d]	**<100** (<40,2)	-	**19,1** (10)	-
PAS198:2012[a]	**249-2490** (100-1000)	**375** (300)	**19,1** (10)	-
ISO11799:2003	**<9,96** (<4)	**<5** (4)	**9,55-19,1** (5-10)	-

Building upon established pollutant concentration guidelines, Jean Tétreault formulated a theoretical framework for assessing the correlation between environmental contamination and material degradation. This framework is grounded in the concepts of No Observed Adverse Effect Level (NOAEL) and Lowest Observed Adverse Effect Level (LOAEL). NOAEL represents the maximum pollutant concentration at which no detectable deterioration occurs under specified environmental conditions, serving as a reference threshold for preservation efforts. Conversely, LOAEL defines the concentration at which the initial measurable signs of material degradation emerge, providing critical insight into pollutant sensitivity thresholds for cultural heritage conservation[16]. Using these concepts allows conservators to set preservation targets for CH collections and act upon the indoor environment and micro-environments to meet these targets.

1.2 Temperature and relative humidity

Temperature and humidity are decisive factors in the preservation of cultural heritage. A proper environment helps prevent deterioration and damage to artefacts, ensuring their longevity for future generations. Even if SIMIACCI does not tackle directly the hygrothermal issues in CCIs, the recommendations and standards applied are reviewed below.

Temperature plays a significant role in chemical reactions that can lead to the degradation of materials. High temperatures accelerate these reactions, causing materials like paper, textiles, and wood to become brittle and discolored. Conversely, low temperatures can slow down these processes, but extreme cold can also cause physical damage to some materials. A practical rule of thumb for the benefits of lower temperatures is that each 5°C reduction doubles the lifetime of chemically unstable objects.

Relative humidity (RH) must be kept under a certain level to prevent mold growth and managed carefully to avoid material deformation. High RH can lead to accelerated degradation of organic materials such as acid paper and textiles. Low RH, on the other hand, can cause materials to dry out and become brittle.

Generally, the set values of temperature and humidity are more important than their variation regarding chemical degradation. However, fluctuations in humidity can cause expansion and contraction in materials, leading to physical stress and potential damage.

For many materials, increased relative humidity will increase the damage caused by atmospheric pollutants as reported in MEMORI EC project[1].

1.2.1 *Standards and guidelines*

Typically, GLAMs aim for a temperature below 22°C and a relative humidity of 30 – 60 % to balance the preservation requirements of various materials.

Table 3 and Table 4 are extracted from the British guideline PAS 198:2012 (*Specification for managing environmental conditions for cultural collections*) and, later on, republished in EN 16893:2018 (*Conservation of Cultural Heritage - Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections*). A visual overview of the relative risk of damage and deterioration for most materials due to temperature and humidity is given. Alongside is given the relative energy demand associated with maintaining specific temperature and humidity ranges.

Table 3. Relative risk of damage due to improper temperature (PAS 198:2012)

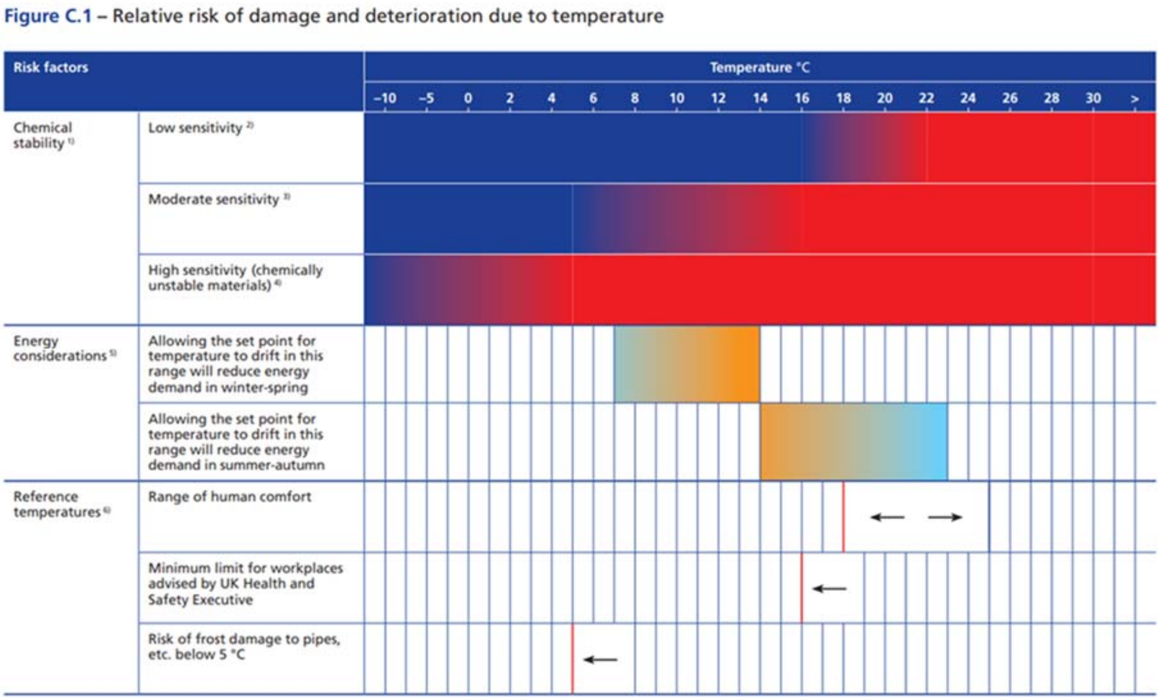


Figure C.1 – Relative risk of damage and deterioration due to temperature

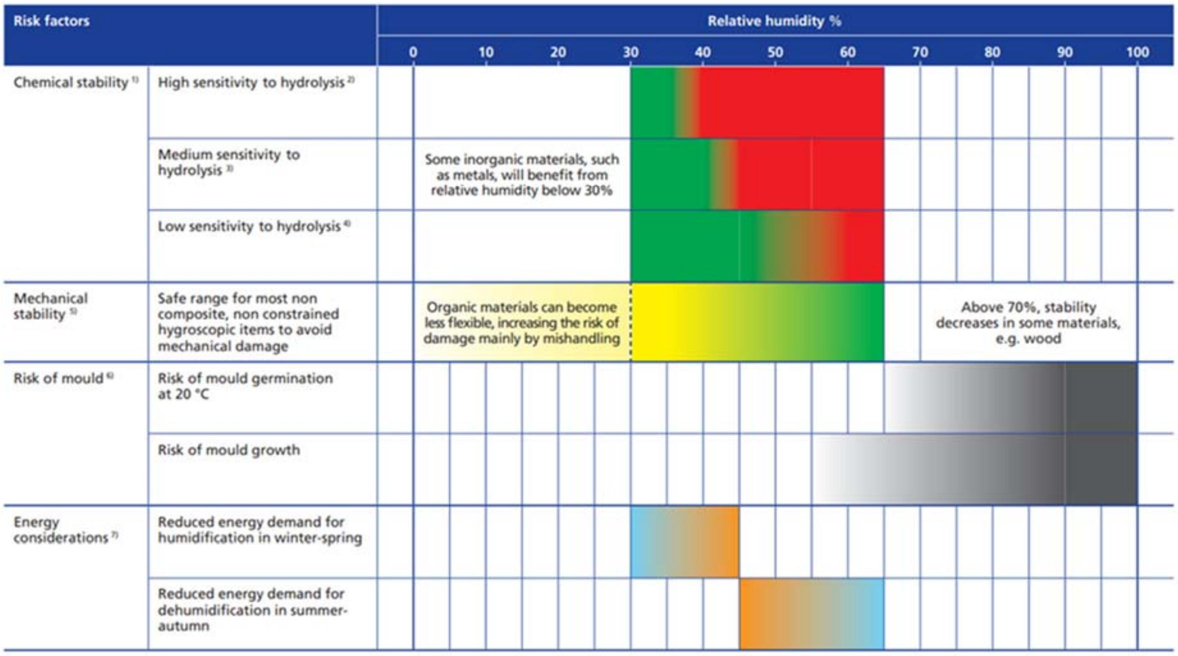
Risk factors		Temperature °C: −10	−5	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	>
Chemical stability 1)	Low sensitivity 2)																			
	Moderate sensitivity 3)																			
	High sensitivity (chemically unstable materials) 4)																			
Energy considerations 5)	Allowing the set point for temperature to drift in this range will reduce energy demand in winter-spring																			
	Allowing the set point for temperature to drift in this range will reduce energy demand in summer-autumn																			
Reference temperatures 6)	Range of human comfort													← →						
	Minimum limit for workplaces advised by UK Health and Safety Executive											←								
	Risk of frost damage to pipes, etc. below 5 °C						←													

---

[1] All hyperlinks link to web pages accessed 19.05.2025 through 15.06.2025

Table 4. ***Relative risk*** *of damage due to improper RH (PAS 198:2012)*

Figure D.1 – Relative risk of damage and deterioration due to relative humidity



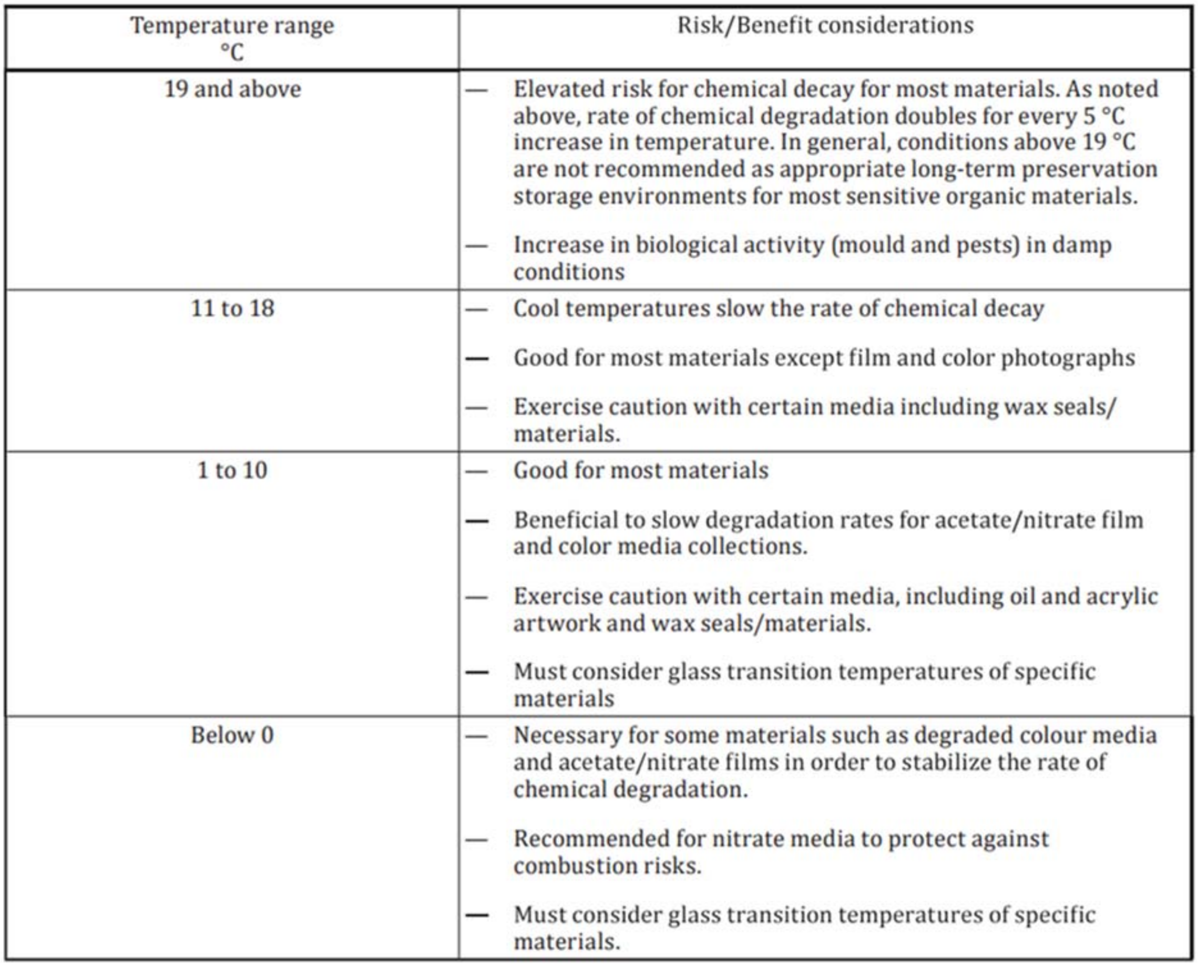
Risk factors		Relative humidity %
Chemical stability 1)	High sensitivity to hydrolysis 2)	
	Medium sensitivity to hydrolysis 3)	Some inorganic materials, such as metals, will benefit from relative humidity below 30%
	Low sensitivity to hydrolysis 4)	
Mechanical stability 5)	Safe range for most non composite, non constrained hygroscopic items to avoid mechanical damage	Organic materials can become less flexible, increasing the risk of damage mainly by mishandling Above 70%, stability decreases in some materials, e.g. wood
Risk of mould 6)	Risk of mould germination at 20 °C	
	Risk of mould growth	
Energy considerations 7)	Reduced energy demand for humidification in winter-spring	
	Reduced energy demand for dehumidification in summer-autumn	

Some materials may have special environmental requirements. Below are two general tables from ISO 11799:2024 (Annex) -Information and documentation - Requirements for the storage of archival and library documents illustrating the effect of temperature and humidity on a broad range of sensitive archive and library materials (Table 5 and

Table 6). These recommendations are applicable also to other materials. For library and archival materials, there has been a recent trend moving away from very specific recommendations for each material to a more general understanding seen in the development from ISO 11799:2003 to ISO 11799:2024 (Document storage requirements for archive and library materials).

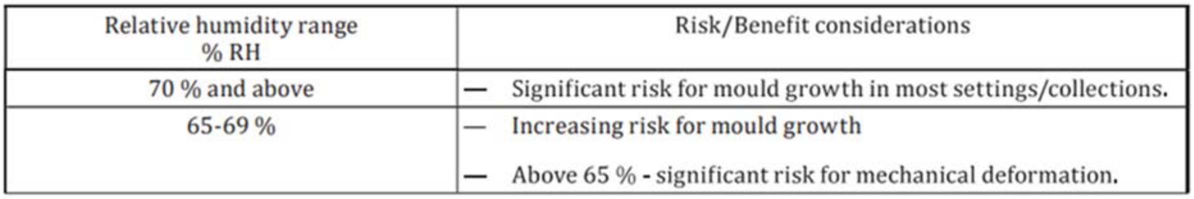
The standard EN 15757:2010 (Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials) focuses on relative humidity and the mechanical damage to organic, hygroscopic materials. It does not suggest a universal safe range for RH but defines a target range for each object or collection based on a statistical evaluation of historical climate conditions. A range of 10% RH on both sides of the annual average is considered safe.

Table 5. Table B.1 (Temperature ranges for long-term preservation and storage) in [ISO 11799:2024]

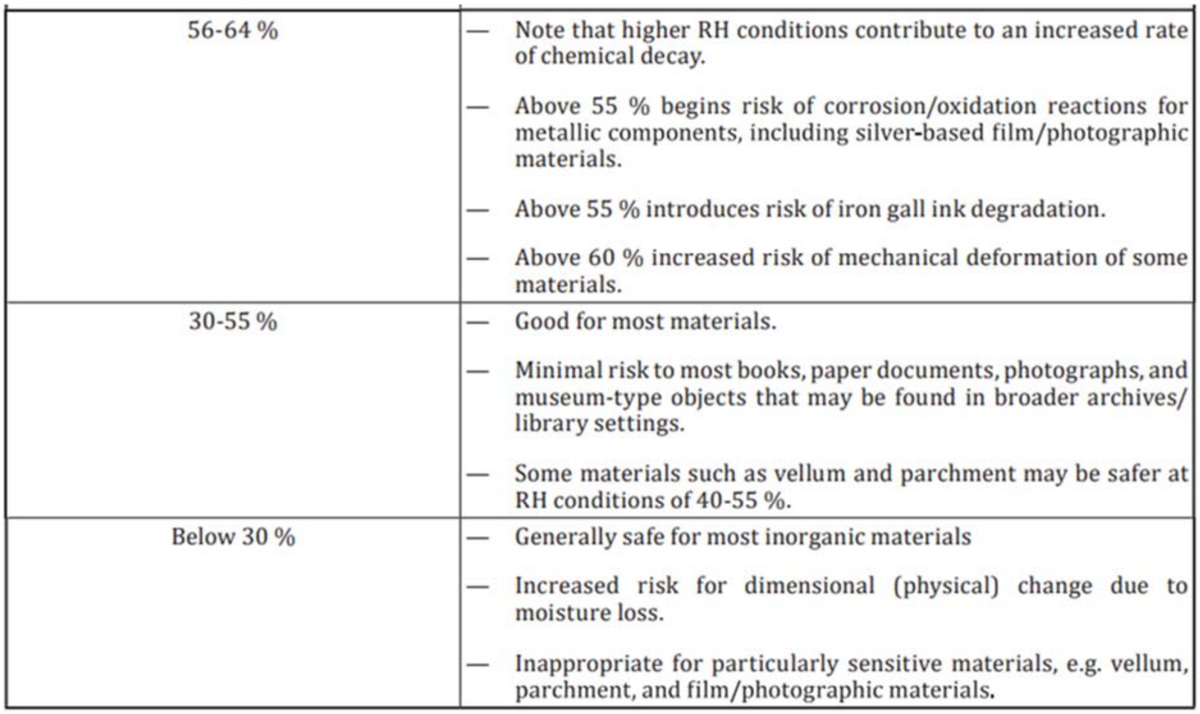


Temperature range °C	Risk/Benefit considerations
19 and above	— Elevated risk for chemical decay for most materials. As noted above, rate of chemical degradation doubles for every 5 °C increase in temperature. In general, conditions above 19 °C are not recommended as appropriate long-term preservation storage environments for most sensitive organic materials. — Increase in biological activity (mould and pests) in damp conditions
11 to 18	— Cool temperatures slow the rate of chemical decay — Good for most materials except film and color photographs — Exercise caution with certain media including wax seals/ materials.
1 to 10	— Good for most materials — Beneficial to slow degradation rates for acetate/nitrate film and color media collections. — Exercise caution with certain media, including oil and acrylic artwork and wax seals/materials. — Must consider glass transition temperatures of specific materials
Below 0	— Necessary for some materials such as degraded colour media and acetate/nitrate films in order to stabilize the rate of chemical degradation. — Recommended for nitrate media to protect against combustion risks. — Must consider glass transition temperatures of specific materials.

Table 6. Table B.2 (Relative humidity ranges for long-term preservation and storage) in [ISO 11799:2024]



Relative humidity range % RH	Risk/Benefit considerations
70 % and above	— Significant risk for mould growth in most settings/collections.
65-69 %	— Increasing risk for mould growth — Above 65 % - significant risk for mechanical deformation.



56-64 %	— Note that higher RH conditions contribute to an increased rate of chemical decay. — Above 55 % begins risk of corrosion/oxidation reactions for metallic components, including silver-based film/photographic materials. — Above 55 % introduces risk of iron gall ink degradation. — Above 60 % increased risk of mechanical deformation of some materials.
30-55 %	— Good for most materials. — Minimal risk to most books, paper documents, photographs, and museum-type objects that may be found in broader archives/library settings. — Some materials such as vellum and parchment may be safer at RH conditions of 40-55 %.
Below 30 %	— Generally safe for most inorganic materials — Increased risk for dimensional (physical) change due to moisture loss. — Inappropriate for particularly sensitive materials, e.g. vellum, parchment, and film/photographic materials.

1.2.2 *Strategies*

Depending on which material is to be preserved, more or less strict regulation of temperature and humidity may be required. The ASHRAE Handbook[34] defines six groups of climate control ranging from precision control (AA) to prevention of dampness (D). For decades this classification has guided museums to determine an appropriate level of environmental control based on the specific needs of their collections.

The need for maintaining a specific climate often requires a heat, ventilation and air conditioning system (HVAC) coming with high-energy demand. On average, museums use 343 kWh/m²a in operation; the median is 273 kWh/m²a [35]. The use of energy depends on climate zone, set points for temperature and humidity, over-pressure, air exchange rate, air filtration etc.

In temperate climate zones low energy storage becomes more widespread. They are built to keep a seasonal variation in temperature (8-16°C) and can provide a humidity range between 40-60 % RH with a small amount of dehumidification during summer. They typically use less than 3 kWh/m³/year[36]. These systems rely on passive measures such as thermal insulation and airtight construction to minimize energy consumption.

1.2.3 *Relaxation trends for indoor climate*

In recent years research has shown that CH collections can tolerate greater variations in RH than previously thought, as reflected in the Bizot Green Protocol[37] and the joint declaration by IIC and ICOM-CC[38]. The best available technology for HVAC systems has influenced the setting of standards and guidelines towards "best possible" level. Consequently, HVAC systems have operated with a single set point allowing only minimal variations. Nowadays, research and field and laboratory experience has shown that most materials perform well within the range of 40-60% +/- 10 % RH. Therefore, guidelines for climate control in museums have shifted to allowing greater fluctuations without compromising quality of preservation and CH materials lifespan. This paradigm shift can save significant amounts of energy in operating ventilation systems. Many GLAMs in Europe have adapted to the Bizot Protocol, which emphasizes the importance of protecting art objects responsibly while reducing energy consumption and carbon emissions.

2. IAQ control in GLAMs

The preservation of cultural heritage objects requires more than just pollutant detection; it also demands effective control measures to reduce the exposure of the artefacts to harmful indoor pollutants. A comprehensive survey of 115 European cultural heritage sites, conducted through the MEMORI EC project, identified air pollution as the third most significant cause of damage to museum objects, following inadequate humidity and temperature regulation. Among environmental factors, only these factors contribute more frequently to visible deterioration within two years. Thus, to safeguard the integrity of the artworks, the monitoring and control of air quality is essential in GLAMs.

2.1 IAQ versus IEQ

IAQ in GLAMs is primarily managed to ensure human comfort and safety and often focusses primarily on the concentration of airborne particles and the level of CO_2 in the air[39,40]. To encompass all indoor conditions that allow a building to fulfill its intended function—including lighting, thermal comfort, ergonomics, and other environmental factors affecting occupants—the term Indoor Environmental Quality (IEQ) is more appropriate. Beyond human health and comfort, IEQ also influences the preservation of cultural artefacts[41]. This requires the treatment of incoming air to eliminate or significantly reduce external pollutants (such as sulfur dioxide, nitrogen oxides, ozone, and hydrogen sulfide) and internal pollutants (volatile organic compounds, VOCs), as well as particulate matters (PM)[42]. Filtration and air purification are effective strategies for enhancing IEQ by minimizing airborne contaminant concentrations via mechanical filtration, air purification technologies, and ventilation strategies, employing both active and passive approaches. These methods can serve as a valuable complement to, or even a partial replacement for, outdoor air ventilation. Active mitigation relying on filtration systems at the building or display-case level is more prevalent and cost-effective, though less predictable in performance compared to passive mitigation[43]. Figure 4 shows examples of standalone air purification devices.

Figure 4. Example of an OBERA active air purification device using AC in a museum gallery

2.2 Elimination of particles matter

The removal of particle matter from indoor air as well as outdoor air of GLAMs is widely achieved in HVAC system by using HEPA filters and/or particulate air cleaners, such as V8 Air Cleaning Solutions or Camfil Particulate Air Cleaner. These systems can capture up to 99.9% of airborne particles. While particle filtration appears to be a must in museum HVAC systems, gas pollutant filtration is, by contrast, less commonly used and not always implemented in standard building filtration systems including GLAMs. In those cases, the IAQ is directly linked to the quality of the external air[44], with the additional factor of pollutants generated within the premises. Indoor air can be cleaned from gaseous pollutants through filtration and then recirculated: filtration systems vary, ranging from those integrated into the building's mechanical ventilation system to devices placed in individual rooms, which may be either fixed or portable. Several technologies for industrial air treatment have been developed, including gas scrubbing (dissolving pollutants in solutions), thermal oxidation (using heat to destroy pollutants present in the air), ionization and cold plasma (use electrical discharges to generate radicals and ions that break down or deactivate pollutants in the air or on surfaces), photocatalysis, sorbents[45] among others. The use of sorbents is regarded as one of the most promising technologies for treating volatile organic compounds (VOCs), thanks to their cost-effectiveness, operational flexibility, and low energy consumption. In fact, museums implement sorbents either through active systems integrated into HVAC units or passive systems within display cases or enclosures.

2.3 Sorbents selection, use and considerations

In GLAMs environments, preserving cultural heritage requires effective pollutant control to maintain a stable environment without compromising the integrity of the objects. Sorbents are materials capable of capturing gases or liquids through physical or chemical interactions. They are generally categorized into adsorbents, which bind molecules onto their surface, and absorbents, which integrate molecules into their structure (Figure 5). These materials are widely used for pollutant removal in air and water purification, and in museum environments, they help mitigate the presence of volatile organic compounds (VOCs), inorganic pollutants, and acidic gases. Sorbents can either be used actively or passively.

Active sorption operates by using forced air circulation, such as through HVAC systems or fans, to improve the rate of pollutant capture. These systems are ideal for large spaces like galleries, where the air is actively circulated, ensuring pollutants are removed more efficiently. Active sorption often works faster but requires more energy and maintenance due to the continuous airflow through the system.

Passive sorption, on the other hand, functions without requiring forced air circulation. It relies on the natural diffusion of pollutants into the sorbent material over time, making them more suitable for smaller, enclosed spaces, such as display cases or storage rooms, where air circulation is limited. The sorbents continuously adsorb pollutants but at a slower rate compared to active systems. Passive sorption is more energy-efficient and requires minimal maintenance, though the pollutant removal efficiency is generally lower compared to active sorption. However, in passive scenarios, the residence time between the pollutant and the sorbent is longer, which can enhance the removal efficiency for certain compounds. Table 7 gives an overview of the most important differences between active and passive sorption.

Table 7. Comparison of active vs passive sorption

Feature	Active Sorption	Passive Sorption
Air circulation	requires forced air systems (e.g. HVAC, fans)	relies on the natural diffusion of pollutants
Pollutant Removal Rate	faster due to active airflow	slower, continuous adsorption over time
Energy Requirement	requires power for the system	no power required
Maintenance	requires more frequent maintenance due to faster sorbent exhaustion	low maintenance, but sorbents need to be monitored for saturation
Cost	higher operational cost due to energy use and system complexity	lower operational cost, but sorbents may need replacing periodically
Suitability	ideal for larger, ventilated spaces and rapid pollutant removal	best for small, enclosed spaces like display cases and archives

Materials like activated carbon (AC), zeolites, molecular sieves, and archival cardboard have been extensively studied for their ability to trap pollutants in GLAMs environments. Table 10 gathers these sorbents, used in passive (as well as in active) systems, and their properties. AC, in particular, remains one of the most efficient passive sorbent, effectively reducing pollutant levels while maintaining a stable microclimate to date[46, 47, 48, 49]. However, AC has limitations, such as its relatively low capacity for certain pollutants, potential release of secondary pollutants, reduced effectiveness at higher humidity levels, and lack of selectivity, which can restrict its application in environments where targeted pollutant removal is needed[48, 50].

2.3.1 *A glimpse into Adsorption Mechanisms*

In order to make an informed decision regarding the optimal adsorbent for pollutant control in GLAMs, a comprehensive understanding of its physicochemical properties is essential.

Adsorption occurs when ions, atoms, or molecules adhere to a solid surface due to excess surface energy. Within the bulk of a material, the bonding requirements of atoms are fulfilled by surrounding atoms, ensuring stability. However, at the surface, unfulfilled bonding sites create excess energy that leads to adsorption, a process most commonly observed at liquid-solid and gas-solid interfaces[51] (Atkins 2018). Porous materials are widely used as adsorbents due to their high surface area, providing numerous adsorption sites. The Adsorption efficiency depends on multiple factors, including material composition (e.g. surface polarity), surface area, pore size distribution (Table 8), and environmental conditions such as temperature, humidity, and gas composition. By impregnating sorbents with a chemical, specific pollutants can be targeted while chemisorption is increased[52].

Physisorption, or physical adsorption (Figure 5), is the process where an adsorbate adheres to a solid surface via weak van-der-Waals forces, without forming strong chemical bonds or altering the adsorbate's chemical structure. This occurs on both the external and internal surfaces of porous adsorbents, enhancing their pollutant capture abilities. Key interactions include London dispersion forces, dipole-dipole interactions, hydrogen bonding, and π-π interactions (especially in carbon-based materials). Some mechanisms like ion exchange adsorption and capillary condensation are also considered physisorption when driven by non-covalent forces. Governed by weak interactions, physisorption is typically reversible; adsorbents can be regenerated by heating or reducing pressure. This makes them ideal for reusable applications, though their efficiency decreases at higher temperatures[53].

Chemisorption (Figure 5) occurs when an adsorbate forms covalent or ionic bonds with an adsorbent's surface, making the process largely irreversible[34]. It is highly specific, happening only when the surface chemistry allows for such bonding, which is advantageous for targeted pollutant removal[54]. Chemically treated adsorbents can enhance this selectivity further. Chemisorption permanently alters both the adsorbate and adsorbent, preventing regeneration, though the adsorbent's porous structure may still be used for physisorption. Chemisorption is generally more effective at higher temperatures and reaches equilibrium more slowly than physisorption due to higher activation energy requirements[34].

While chemisorption ensures stronger retention, physisorption is essential for reusable adsorption processes. Physisorption is faster and more suitable for applications needing rapid and reversible adsorption.

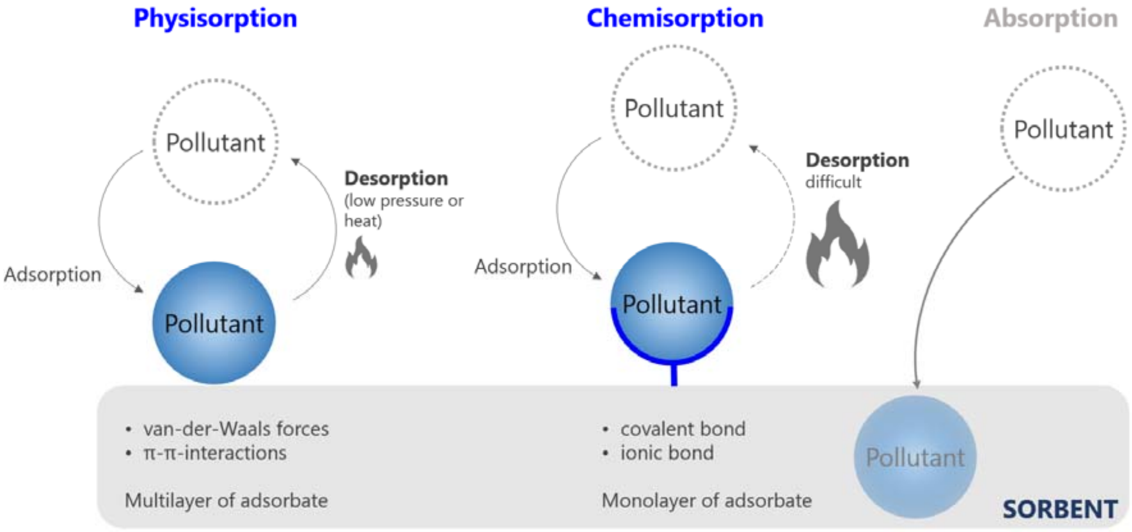


Figure 5. Schematic overview of physisorption and chemisorption (two adsorption processes) in contrast to absorption.

2.3.2 *Physicochemical properties of adsorbents*

The fundamental physicochemical characteristics that govern an adsorbent's performance include adsorption capacity, particle diameter, bulk density, porosity, specific surface area, and pore size distribution. These parameters collectively influence the material's ability to interact with adsorbates, affecting adsorption efficiency and selectivity. Table 8 gives a brief overview of the most important physicochemical properties of adsorbents.

Table 8. Key physicochemical properties of adsorbents and their impact on adsorption performance[34]

Property	Description
Capacity	• amount of adsorbate collected per unit mass under specific conditions, such as temperature and partial pressure • equilibrium is reached when adsorption and desorption are balanced (saturation point) • varies based on adsorbate-adsorbent interactions and can be influenced by other gases, as well as the surface area, pore structure, and adsorbate properties
Particle Diameter	• affects adsorption kinetics and flow behaviour • smaller particles provide a greater surface-to-volume ratio, enhancing adsorption efficiency, but may enhance pressure drop in packed beds • larger particles may reduce adsorption rates.
Bulk Density	• determines the mass per unit volume of sorbent including pore volume and interparticle voids • impacts transport, handling and system design • high-density adsorbents store more adsorbate in confined spaces
Porosity	• percentage of void space • defines how much of the adsorbents volume is available for adsorption • influences molecular diffusion and adsorption efficiency • higher porosity improves accessibility to active sites
Surface Area	• total accessible area determines the adsorption performance • adsorbents with a high specific area (e.g. MOFs or activated carbon) provide more binding sites and improve uptake capacity
Pore Diameter	• controls the selectivity and accessibility for target molecules • microporous adsorbents (<2 nm) favour small molecules • mesoporous adsorbents (2–50 nm) and macroporous (>50 nm) structures accommodate larger molecules or facilitate faster diffusion
Removal efficiency	• key metric for evaluating the performance of adsorbent materials (and air-cleaning devices) • depends on the residence time
Residence time	• refers to the theoretical duration that an airborne pollutant remains in contact with the adsorbent before being removed, desorbed, degraded or otherwise removed as air moves through the filter structure. • a longer residence time generally allows more effective adsorption

2.4 Criteria for Sorbent Selection

2.4.1 *Cost and Regenerability*

Cost is a central consideration for most CCIs. Physisorbents like activated carbon and silica gel are generally low-cost and regenerable, making them economical for long-term use. By contrast, chemisorbents, including those impregnated with potassium permanganate or potassium hydroxide, are typically non-regenerable and must be replaced once exhausted, leading to higher recurring costs[16] (see section 2.9.2). Sorbents in granular or powder form are also more affordable than foam or textile forms, which may offer handling advantages but are not reusable and often release particulate dust.

2.4.2 *Sensitivity to humidity*

Humidity plays a dual role since it influences both the performance of sorbents and the microclimate of the enclosure (dsiplay case, cabinet or box). Silica gel is often used to stabilize RH but can reduce the effectiveness of other adsorbents when used together. Zeolites perform best under low humidity conditions as they are very hydrophilic, while silica gel and activated alumina adsorb water primarily at moderate to high RH. Nonpolar materials such as activated carbon are less affected by moderate RH but can still be compromised at high RH, as water may compete with target gases for adsorption sites[4, 55] .

2.4.3 *Selectivity, Pore Structure, and Composition*

The selectivity of a sorbent (its ability to adsorb preferentially specific compounds) is governed by several material properties, including pore size, polarity, and chemical composition. Materials with broad pore size distributions (e.g., activated carbon, silica gel) can adsorb a wider range of pollutants, which is advantageous when the air composition is unknown. However, this also increases the risk of undesired adsorption, such as plasticizer loss from cellulose acetate[56].

Somewhat selective materials like zeolites and molecular sieves, with uniform pore sizes, may be preferred for well-characterized environments. The polarity of the sorbent also plays a role: polar sorbents adsorb polar gases (e.g., acids), while nonpolar sorbents are more effective for nonpolar species[16]. Chemical modification or impregnation can improve selectivity; for example, impregnated activated carbon shows enhanced adsorption for acidic gases such as formic and acetic acid[1] (see section 2.9.2).

2.4.4 *Target Pollutants*

Key pollutants in museum environments include nitrogen oxides, hydrogen sulfide, acetic acid, formic acid and formaldehyde[7]. These were also the pollutants of concern that the questionnaire led by SIMIACCI with CCIs in April 2025 confirmed (Annex A). However, due to the complex and variable nature of indoor atmospheres, precise identification is often impractical. In such cases, general-purpose sorbents like activated carbon are used, though their effectiveness for certain of these pollutants may be limited. For example, non-impregnated activated carbon has a relatively weak affinity for formic acid[1].

2.4.5 *Breakthrough and Saturation*

Sorbents have a finite adsorption capacity. Once saturated, they can no longer effectively remove pollutants and may even release previously adsorbed substances back into the environment (breakthrough). Regular monitoring and timely replacement are essential to prevent this problem.

2.4.6 *Secondary Emissions*

Some sorbents, especially if not properly selected or maintained (not replaced or not regenerated in time), can themselves emit VOCs, from inherent impurities or because of chemical interactions with adsorbed pollutants. This risk highlights the importance of careful material selection and ongoing assessment of sorbent performance.

Because indoor pollutant concentrations in museums are considered typically low compared to outdoor concentration in highly polluted (industrial) areas, and visual indicators of sorbent exhaustion are lacking, regular IAQ monitoring is necessary to ensure ongoing effectiveness. Sorbents must be replaced regularly, and their placement in the target location should maximize pollutant contact while avoiding direct contact with sensitive objects or have an influence of the exhibition concept/aesthetics.

2.5 Determination of Sorbent Quantity and Lifetime

To help estimate the amount of sorbent needed in a museum enclosure, Tétreault [16,57] developed a quantitative model that considers both external pollutant infiltration and internal pollutant generation. The model calculates the required mass of sorbent based on several interrelated factors:

- External pollutant concentration (*i.e.* how much of a specific pollutant is present in the air outside the enclosure),
- The volume of air inside the enclosure, and
- The air exchange rate, which describes how often the air inside is replaced or mixed with external air, adjusted for the specific pollutant in question.

Note that the air exchange rate (AER) is a value of particular interest that is often calculated, for display cases for instance, when seeking to understand pollutants concentrations inside an enclosure[58].

In addition to external sources, the model proposed by Tétreault also accounts for internal pollutant emissions. These are calculated by multiplying the pollutant emission rate (per square meter of material surface) by the total exposed surface area of materials inside the enclosure that may off-gas pollutants.

All pollutant sources, both external and internal, are considered over a desired protection period, expressed in days. This defines how long the pollutant concentration inside the enclosure needs to be kept below a certain acceptable level. Finally, the total pollutant load is compared against the specific sorption capacity of the sorbent being used, that is, the amount of a given pollutant the material can adsorb per gram under defined conditions. This relationship determines how much sorbent is needed to ensure that the internal concentration of the pollutant remains below a defined acceptable limit.

The model assumes that the sorbent is evenly spread in a thin layer (ideally ≤ 2 cm) to maximize surface exposure, and that the pollutant concentration outside the enclosure is at least ten times greater than inside. This assumption is used primarily for modelling purposes and reflects a design goal to ensure that pollutant levels inside the enclosure remain significantly lower than those outside. It does not necessarily reflect actual concentration dynamics, especially in cases where internal sources dominate (*e.g.* in showcases or other enclosures). While the equation is very useful for CCIs as starting point for determining sorbent quantity, attention is required as real *in-loco* applications may still require adjustments based on case-specific variables and pollutant behaviour.

When environmental data is unavailable, CCIs may rely on manufacturer guidance, comparative case studies, or trial-and-error to estimate effective sorbent quantities.

Most sorbents have no intrinsic easy to visualise indicators of saturation, complicating efforts to determine their useful lifespan. Besides most silica gel that show colour changes upon hydration, other sorbents (*e.g.* zeolites, activated carbon) do not provide any visible information of saturation. As a result, pollutant or humidity monitoring tools are required to determine replacement timing. These include for instance tools such as hygrometers (for RH), passive air samplers, metal coupons or dosimeters such as the acid detector (AD) strips[1,7]. Institutions without monitoring tools may adopt pragmatic approaches, such as annual replacement routines or consulting with peer institutions. More detailed information of monitoring and analysis can be found in section 3.

2.6 Sorbent placement in enclosures

Effective placement of passive sorbents requires maximizing exposure to ambient air while minimizing risk to nearby objects. Ideal configurations include:

- Thin layers of sorbent material with large surface area exposure
- Some airflow, even passive convection or small fans, to promote contact with airborne pollutants
- Hidden compartments in display cases (*e.g.* trays above or below objects), provided there is airflow between compartments and display zones.

Other environmental surfaces, including case walls and even collection materials themselves, can act as secondary sorbents. However, this is often undesirable if sensitive materials, such as silver in hydrogen sulfide environments, begin absorbing pollutants. In such cases, localized sorbent placement (*e.g.* activated carbon cloth near the object) can be protective, though care must be taken to avoid contact with reactive or dusty materials (*e.g.* impregnated carbon filters containing KOH or $KMnO_4$; see section 2.9.2).

2.7 Passive sorption performance

In 2003, Tétreault provided a ranking on the performance of sorbents when used actively. However, passive sorption is driven by natural diffusion and therefore the performance of the sorbent when used passively is different. More recent studies have tested sorbents under passive conditions but not for all gases. In 2015 Grøntoft et al.[59] directly measured the mitigation of acetic and formic acid in museum showcases using passive deployment of activated carbon (granulate, cloth, foam) and found significant reductions (up to ~80%), but also noted that saturation and breakthrough can occur within weeks or months depending on pollutant load and air exchange. In 2020, Schieweck[48] confirms that while activated carbon remains the most effective general-purpose passive sorbent, the efficiency for NOx and HCHO is much lower under passive conditions than active ones.

2.8 Main Challenges and Insufficiencies of Using Passive Sorbents in GLAMs

Passive sorbents are widely used in GLAMs for their cost-effectiveness and ease of deployment, especially in display cases and enclosed storage. However, as detailed in the previous sections, several potential drawbacks and limitations should be considered:

- **Unpredictable performance**: The efficiency of passive sorbents can be difficult to predict. Unlike active filtration systems, passive sorbents rely on natural air diffusion, so pollutant removal rates can vary depending on case design, air exchange rate (AER), pollutant load, and environmental conditions;
- **Saturation and breakthrough**: Sorbents have a finite adsorption capacity. Once saturated, they can no longer effectively remove pollutants and may even begin to release previously adsorbed substances back into the environment, a phenomenon known as breakthrough. Regular monitoring and timely replacement are necessary to prevent this.
- **Secondary emissions**: Some sorbents, especially if not carefully selected or if of lower quality, can themselves become sources of VOCs. These emissions may occur both before and after exposure to

pollutants, either from impurities in the sorbent or as a result of chemical interactions with adsorbed substances. For example, certain foams embedded with metals or poorly processed charcoals have been shown to emit VOCs.

- **Formation of Decomposition or Secondary Reaction Products:** Interactions between sorbents and pollutants can sometimes generate new, potentially harmful compounds, which may be released into the GLAM environment.

- **Lack of Visual Indicators**: There are often no easy visual clues to indicate when a passive sorbent is spent or losing effectiveness. This complicates maintenance and can lead to unnoticed periods of reduced protection.

- **Limited Effectiveness for all target Pollutants**: While activated carbon is generally effective for many organic acids and VOCs, other materials like zeolites or silica gel may have limited adsorption capacity for certain GLAM-relevant pollutants and can be difficult to handle or integrate into display cases.

- **Need for Regular Monitoring**: Because of the above issues, regular IAQ monitoring is essential to ensure that passive sorbents are functioning as intended and not contributing to secondary pollution or failing due to saturation.

In summary, passive sorbents are a practical and effective tool for controlling gaseous pollutants in GLAMs environments, especially where active ventilation is limited or inexistent. Their successful use depends on careful selection, placement, and ongoing monitoring to avoid breakthrough, secondary emissions, or unintended interactions with collection materials. Activated carbon remains the most broadly effective and preferred choice under typical GLAMs conditions, while zeolites and other specialized sorbents may be considered for specific needs or environments. However, activated carbon is not without limitations: its adsorption capacity can be significantly reduced by moisture uptake, it lacks selectivity, and saturation can be difficult to detect, leading to unnoticed breakthrough and diminished protection. These drawbacks underscore the need for novel adsorbent materials in GLAMs environments to achieve more sustainable and reliable pollutant control in the future. This is developed in the report D4.2.

2.9 Considerations for the integration of sorbents in active systems for GLAMs (HVAC)

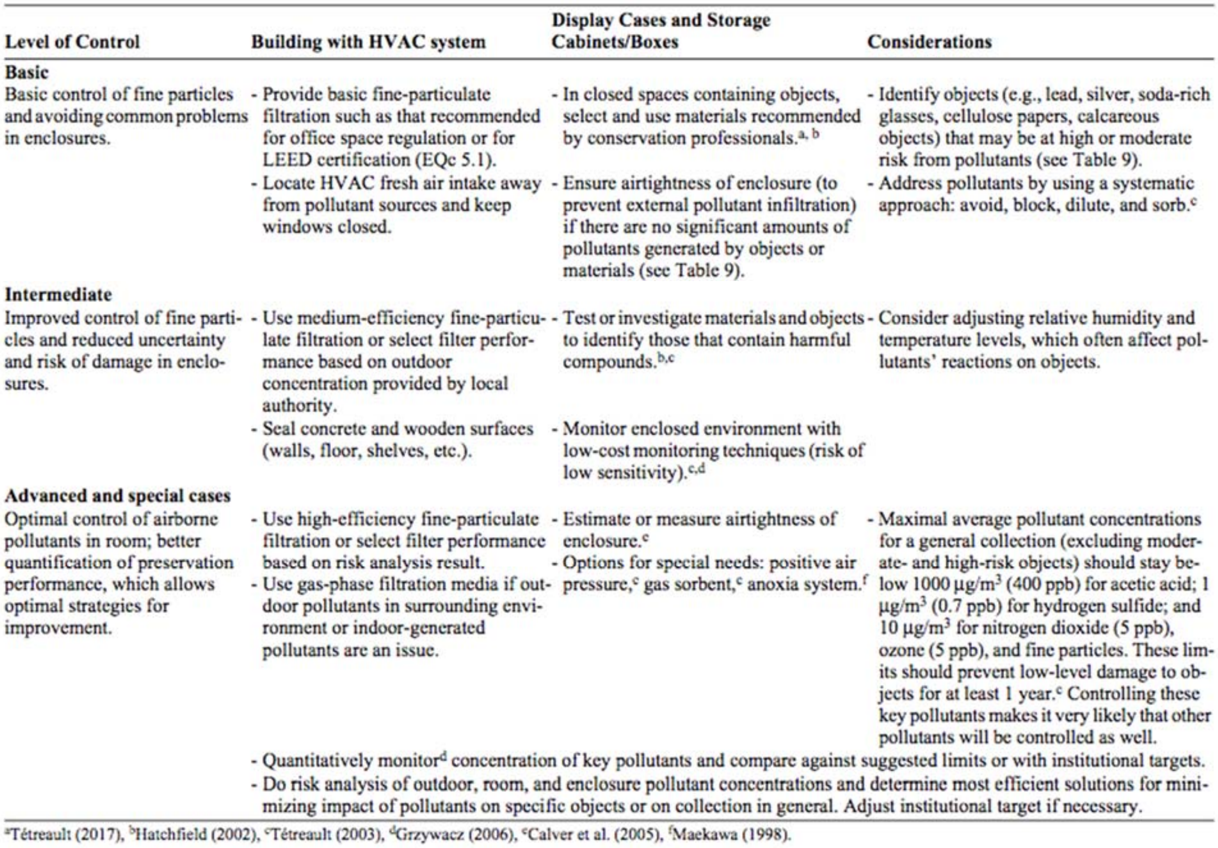
The use of Heating, Ventilation, and Air Conditioning (HVAC) systems plays a crucial role in regulating not only temperature and relative humidity but also air quality within museum environments. Advanced HVAC systems integrate gas-phase filtration using HEPA filters, activated carbon, and potassium permanganate media to remove particulates and gaseous contaminants. Maintaining stable relative humidity—typically between 40–55%—reduces the volatility of acidic compounds and slows down chemical reactions responsible for material degradation.

HVAC systems can be configured for entire buildings, individual rooms, or even specialized microclimates inside display cases. These systems offer simultaneous management of multiple environmental parameters and are compatible with centralized Building Management Systems (BMS) for automation and monitoring.

The previous sections gave a detailed account of the challenges of the selection of a sorbent system. In summary, it should be based on the specific gaseous contaminants present in the facility, as different sorbents exhibit varying removal and retention efficiencies. Activated carbon may effectively remove some gases, other gases may require specialized or treated sorbent beds. A variety of porous materials (zeolites and aluminosilicates, MOFs, composite materials, and functionalized materials) have been studied to enhance VOC adsorption in terms of capacity, hydrophobic properties, thermal stability, and regenerability. However, as emphasized above, they present several challenges: determining their effective lifespan, identifying clear indicators of performance decline, and assessing the risk of re-emission of absorbed pollutants.

It is thus important to thoroughly assess the service life of molecular filtration media integrated in HVAC systems. Although many service life evaluations focus on the sorbent's potential mass removal capacity when fully immersed in a test chemical, this data may not accurately reflect its performance in an airstream, where removal effectiveness can diminish well before the sorbent is technically spent. When implementing a molecular filtration system, it is worth noting that some gas filter designs may require downstream particulate filters. As these filters age, they can release dust that may compromise HVAC systems and sensitive CH collections. System design should also account for institutional staffing capabilities and preventive maintenance practices. The facility must be equipped—both in terms of labour and budget—for timely replacement of filtration media. Before committing to a full gas-phase filtration system, it is advised to monitor and analyse the facility's gaseous contaminants. As already mentioned, activated carbon, zeolite, and organic polymers are recognized as three of the most widely used adsorbents for VOC treatment, according to estimates by the U.S. Environmental Protection Agency (EPA). Table 9 summarises the strategies for the control of EIQ and Table 10 gathers the categories and properties of sorbents used for active (HVAC systems) as well as for passive sorption.

Table 9. Strategies for the control of Airborne Pollutants with HVAC (Table from ASHRAE 2019)[34]



Level of Control	Building with HVAC system	Display Cases and Storage Cabinets/Boxes	Considerations
Basic			
Basic control of fine particles and avoiding common problems in enclosures.	- Provide basic fine-particulate filtration such as that recommended for office space regulation or for LEED certification (EQc 5.1). - Locate HVAC fresh air intake away from pollutant sources and keep windows closed.	- In closed spaces containing objects, select and use materials recommended by conservation professionals.[a, b] - Ensure airtightness of enclosure (to prevent external pollutant infiltration) if there are no significant amounts of pollutants generated by objects or materials (see Table 9).	- Identify objects (e.g., lead, silver, soda-rich glasses, cellulose papers, calcareous objects) that may be at high or moderate risk from pollutants (see Table 9). - Address pollutants by using a systematic approach: avoid, block, dilute, and sorb.[c]
Intermediate			
Improved control of fine particles and reduced uncertainty and risk of damage in enclosures.	- Use medium-efficiency fine-particulate filtration or select filter performance based on outdoor concentration provided by local authority. - Seal concrete and wooden surfaces (walls, floor, shelves, etc.).	- Test or investigate materials and objects to identify those that contain harmful compounds.[b,c] - Monitor enclosed environment with low-cost monitoring techniques (risk of low sensitivity).[c,d]	- Consider adjusting relative humidity and temperature levels, which often affect pollutants' reactions on objects.
Advanced and special cases			
Optimal control of airborne pollutants in room; better quantification of preservation performance, which allows optimal strategies for improvement.	- Use high-efficiency fine-particulate filtration or select filter performance based on risk analysis result. - Use gas-phase filtration media if outdoor pollutants in surrounding environment or indoor-generated pollutants are an issue.	- Estimate or measure airtightness of enclosure.[c] - Options for special needs: positive air pressure,[c] gas sorbent,[c] anoxia system.[f]	- Maximal average pollutant concentrations for a general collection (excluding moderate- and high-risk objects) should stay below 1000 $\mu g/m^3$ (400 ppb) for acetic acid; 1 $\mu g/m^3$ (0.7 ppb) for hydrogen sulfide; and 10 $\mu g/m^3$ for nitrogen dioxide (5 ppb), ozone (5 ppb), and fine particles. These limits should prevent low-level damage to objects for at least 1 year.[c] Controlling these key pollutants makes it very likely that other pollutants will be controlled as well.
	- Quantitatively monitor[d] concentration of key pollutants and compare against suggested limits or with institutional targets. - Do risk analysis of outdoor, room, and enclosure pollutant concentrations and determine most efficient solutions for minimizing impact of pollutants on specific objects or on collection in general. Adjust institutional target if necessary.		

[a] Tétreault (2017), [b] Hatchfield (2002), [c] Tétreault (2003), [d] Grzywacz (2006), [e] Calver et al. (2005), [f] Maekawa (1998).

2.9.1 *Activated Carbon and Other Carbon Compounds*

Adsorption-based filtration systems are widely used in museum environments for the passive or active removal of gaseous pollutants and activated carbon (AC) is the material of choice. Indeed, AC filtration is one of the most common and cost-effective methods for controlling gaseous pollutants in indoor environments[60,61],. This method relies on the physical adsorption of gas-phase molecules onto the highly porous surface of activated carbon granules. With a surface area ranging from 500 to 1500 m² per gram, activated carbon is highly effective in capturing a broad spectrum of volatile organic compounds, especially non-polar substances such as toluene and benzene. Modified forms of activated carbon—impregnated with potassium permanganate or alkaline compounds—are capable of trapping acidic gases like acetic acid.

In museums, AC is widely implemented in various forms, including in HVAC system filters, stand-alone purifiers, and passive filtration panels within display cases. The primary advantages of activated carbon filtration include its scalability, ease of deployment, and high removal efficiency for a wide array of indoor pollutants. However, limitations include saturation over time, which can lead to breakthrough if not monitored, and reduced efficacy for small, polar molecules unless specifically designed for acid gas removal. Regular replacement is essential to maintain filtration performance.

Many companies such as CalgonCarbon, Haycarb, Kelincarbon, Carbotech, Trojan Technologies, Desotec, Mellifiq, or Qizhong Chemicals market it at industrial level for capturing gaseous pollutants in industrial air conditioning systems or air purification installations operating in CH organizations. AC is indeed the benchmark adsorbent most widely used in most CCIs[7] as it captures a broad range of VOCs and other compounds (such as ammonia). Its cost varies significantly depending on factors such as facility characteristics, regulatory requirements, system sizing, and other economic parameters. As a result, it is not feasible to establish reliable cost estimation rules of thumb. However, compared to other sorbents, the cost is relatively low (between $ 1000 to $ 1500 per ton). The conditioning is carried out on fixed beds (as opposed to fluidized beds). As reported by CPL Puragen, activated carbon is conditioned in the form of Granular Activated Carbon (GAC), Powdered Activated Carbon (PAC), Extruded (Pelletized) Activated Carbon, or Solid Carbon Monoliths after the processes of carbonization and activation. The AC is placed on the walls inside a cartridge such as in Camcarb and SAAF canister or in cassettes such as from AAF along the airflow for CH artefacts.

The flammability of AC can pose a fire risk, particularly during the exothermic adsorption process (e.g Air Quality Engineering). Additionally, the resistance to transfer, clogging of the pores, and the hygroscopic character of AC may limit its efficiency. Energy consumption depends on the pressure drop during air passage.

Activated Carbon Fiber (ACF), developed in the 1960s, comes in the form of microfilaments arranged in an orderly manner. It can be transformed into thread, fabric, felt/carpet, textile paper, and other forms to optimize process designs for engineering applications[62]. The raw materials used for ACF manufacturing are generally non-renewable, such as viscose, polyacrylonitrile fibers, and pitch fibers[63]. ACF is a pure carbon solid with a specific surface area ranging from 1200 to 1400 m^2g^{-1} [64]. The pore width is generally between 0.5 and 1 nm. Commercially available ACF is expensive due to the high cost of raw materials, fiber spinning and weaving, subsequent thermal processes, as well as significant weight loss during activation. Unlike classical activated carbon, ACF presents faster adsorption kinetics and higher mass transfer rate due to its fine, short, and straight fiber shape with direct micropores. Additionally, its fiber structure helps overcome the challenges associated with high-pressure drops and mass transfer limitations in adsorption beds. ACF is widely used in adsorption and chemical and biochemical separation fields, air and water purification, as a catalyst or catalyst support, in safety masks, medical care, and the protection of cultural heritage mostly for passive uses (*e.g.* Activated Charcoal Cloth Plain® from CXD).

Graphene[65,66] and Carbon Nanotubes[67,68] (CNTs) are next-generation carbon materials with exceptional adsorption properties. They are beginning to attract attention in the field of air purification, including experimental GLAMs applications. Graphene is a two-dimensional sheet of carbon atoms arranged in a hexagonal structure. Due to its large specific surface area (>2600 m^2/g), high conductivity, and modifiable surface properties, it is very effective for the adsorption of many pollutants. Although very efficient, these adsorbents are considerably more expensive than AC, which limits their use for large-scale air treatment applications. To this date, the only source of carbon adsorbent less expensive than AC is biochar from biomass anoxic pyrolysis[69]. However, its adsorption properties remain inferior to those of AC[70].

2.9.2 *Impregnated AC and sorbent blends*

While activated carbon proves effective for many VOCs, it is less effective for hydrogen sulfide, sulfur dioxide, and nitrogen oxides. To improve the adsorption of acidic gases and certain reactive compounds, notably formaldehyde, sulfur dioxide (SO_2), hydrogen sulfide (H_2S), nitrogen dioxide (NO_2), and ozone (O_3), AC is impregnated with potassium iodide (KI). In this form, it seems particularly suitable for CCI's environments. Activated carbon impregnated with potassium hydroxide such as SAAFCarb is also available for the capture of these compounds, but in this form, it is uncommon in CH environments.

In conclusion, many CCIs use activated carbon in their air purification systems; however, carbon-based materials often suffer from disadvantages such as flammability and poor regenerability. Alumina pellets impregnated with sodium or potassium (Air Quality Engineering) permanganate (Purafil, AAF, B.C. AIRFILTER etc.) are often used as chemisorbent mixed with activated carbon. First developed in 1960 by Borg-Warner Corporation, Purafil® is composed of activated alumina (45-55%) impregnated with potassium permanganate (4-8%), sodium bicarbonate (10-20%), and water (15-25%). It is used to improve IAQ by absorbing airborne pollutants, odours, and particulates. It is sold in filter units incorporated in HVAC systems for dry-scrubbing air filtration. It absorbs sulfur dioxide, nitrogen oxide, formaldehyde, ozone, and hydrogen sulfide. Since potassium permanganate is a strong oxidizing agent, it reacts with many atmospheric pollutants and permanently removes the contaminant. Consequently, the potassium permanganate infiltrated alumina product does not off-gas pollutants when the filter becomes saturated. However, it may release reaction products such as chlorine gas from absorbed hydrogen chloride, and media treated with potassium permanganate are generally discouraged due to the potential harm posed by their highly oxidative dust to both collections and surrounding surfaces[34]. The non-flammable and non-toxic pellets do not allow bacterial or fungal growth. Its advantage also lies in its colour change (from violet to brown when saturated), providing a visual indication of the saturation level. By using these media in combination, Purafil® ensures the elimination of all contaminants and has become a popular IAQ purification solution in GLAMs.

2.9.3 *Zeolites, polymers and MOFs*

Another type of adsorbent is the alumino-silicate crystal structure known as zeolite[71], which features uniformly sized pores throughout its crystalline framework. The specific structure of the 118 known zeolite types is defined by the ratio of Si to Al present during crystal formation. Naturally occurring zeolites are hydrophilic, meaning they attract polar molecules such as water, and they inherently contain aluminum.

To make zeolite hydrophobic, and suitable for capturing non-polar substances like many volatile organic compounds (VOCs), the Al content is chemically replaced with silicon—a process known as dealumination—without altering the crystal's structure. Hydrophobic zeolites can also be synthetically produced, with crystal sizes ranging from 1 μm to 1 mm. These crystals can be bonded into larger granules to reduce airflow resistance in HVAC filtration systems. Due to the high synthesis cost, this process is reserved for producing either hydrophobic zeolites or zeolite catalysts designed with specific large pore sizes.

Zeolites have been proposed for the adsorption of various gaseous pollutants in air conditioning systems[72]. However, it appears that they are mainly used in GLAMs as passive air quality control devices in enclosed environments such as boxes and display cases and not in HVAC systems. While zeolites offer specific advantages—particularly in the adsorption of certain polar volatile organic compounds (VOCs)—their overall efficiency is generally lower than that of activated carbon for a broader range of pollutants. Moreover, the zeolites typically implemented in GLAMs contexts are those that are hydrophilic.

Functionalized polymers or composite polymers can also be used for the adsorption of certain specific pollutants[73]. These synthetic materials contain built-in pores formed during their manufacture. These pores vary in size, from large (macroporous) to dimensions close to those of molecules. However, the smallest pores in polymeric adsorbents are usually larger than the micropores found in AC. These materials are typically shaped as granules or beads. Compared to AC, polymers tend to release more readily the substances they have adsorbed. Like AC, they are generally non-selective, meaning they can adsorb a wide range of VOCs. Nonetheless, depending on their chemical structure, some polymers may have a stronger affinity for certain VOCs than others[72].

There is still significant research activity focused on developing or improving adsorbents for capturing VOCs[63]. However, they come with advantages and disadvantages. For instance, silica gel (SG) is announced as a promising porous adsorbent[74,75] as it exhibits excellent thermal, mechanical, and chemical stability, low density, a large microporous surface area, and many functional groups (such as silanols and siloxanes). Although SG often exhibits poor performance in humid environments due to the hydrophilic nature of the silicon hydroxyl groups on its surface.

Hybrid or composite materials combining different types of adsorbents have also been developed to enhance pollutant adsorption performance in air conditioning systems such as HVACs[76]. Nowadays, it appears that the largest GLAMs in economically advanced countries have implemented chemical filtration in HVAC systems, based on AC shaped as granules or beads—sometimes modified with potassium iodide or mixed with activated alumina impregnated with potassium permanganate. As for display cases and enclosed environments such as boxes or cabinets, other types of sorbents such as ACF cloth or zeolites are often used.

In recent years, metal–organic frameworks (MOFs) have emerged as promising alternatives due to their tunable porosity and highly selective adsorption properties. MOFs such as MIL-101, ZIF-8, and HKUST-1 demonstrate superior adsorption capacities for formaldehyde and small organic acids, even under humid conditions, as explained in great detail in the deliverable D4.2 report (SEN). Compared to activated carbon, MOFs offer better compound selectivity, improved performance at low concentrations, and higher structural stability. However, limitations include higher production cost, limited commercial availability, and still unproven long-term performance in CH environments. While activated carbon remains the standard choice for most applications due to its low cost and versatility, MOFs may offer future potential as part of hybrid or targeted pollutant control strategies[1, 77] in next-generation adsorption-based systems, with improved selectivity and uptake capacity for key indoor pollutants[78]. The use of MOFs, pioneered for GLAMs in NEMOSINE and is being developed further in SIMIACCI, also in parallel making its debut in air conditioning systems for other applications[79,80]. It appears that, their ability to capture moisture with lower energy consumption than other desiccant —such as silica gel – or by cooling may hold the promise of a faster adoption in HVAC systems within CCIs, before the foreseen utilization for gaseous pollutants removal studied in SIMIACCI. One can hope that this application may pave the way for further uses in air purification.

Funded by
the European Union

2.10 Use of Low-Emission Materials

A critical strategy for pollutant control that cannot be overlooked in GLAMs involves the use of low-emission materials during exhibit construction and collections storage. Many building and exhibit materials—including medium-density fibreboard, adhesives, paints, sealants, and certain plastics. All of these off-gas harmful pollutants such as formaldehyde, acetic acid, and other VOCs. By carefully selecting materials with minimal emissions, the need for active pollutant mitigation can be substantially reduced.

Pre-screening of materials is a standard practice in most CCIs, involving methods such as Oddy tests (section 3.1), microchamber analysis, or SPME-GC/MS profiling. These tests help identify potentially harmful emissions prior to installation. Museums such as National Museum in Stockholm and the Kunsthistorisches Museum in Vienna have conducted comprehensive renovations of their storage and display infrastructure, replacing problematic components with inert or tested materials like aluminium honeycomb panels, powder-coated steel, and archival-quality boards.

The benefit of this approach lies in its preventive nature, a standard yet innovative approach in conservation. It aim at reducing the pollutants burden at the source in alignment with long-term preservation goals. However, it requires time-consuming testing, often specialized analytical facilities, and sometimes trade-offs in terms of aesthetics, weight, or cost. Despite these challenges, low-emission material selection is a foundational element in modern preventive conservation strategies.

2.11 Mitigation through microclimate/Passive Regulation

The use of Heating, Ventilation, and Air Conditioning (HVAC) systems plays a crucial role in regulating not only temperature and relative humidity but also air quality within museum environments. As explained in section 2.9, advanced HVAC systems integrate gas-phase filtration using HEPA filters, activated carbon, and potassium permanganate media to remove particulates and gaseous contaminants. Maintaining stable RH—typically between 40–55%—reduces the volatility of acidic compounds and slows down chemical reactions responsible for material degradation.

HVAC systems can be configured for entire buildings, individual rooms, or even specialized microclimates inside display cases. These systems offer simultaneous management of multiple environmental parameters and are compatible with centralized Building Management Systems (BMS) for automation and monitoring. The advantages of environmental control systems include their scalability, precision, and integrative capabilities. However, they require significant infrastructure investment, regular maintenance, and periodic recalibration. They may also be impractical for historic buildings without invasive retrofitting or where passive climate control is part of the building’s conservation plan.

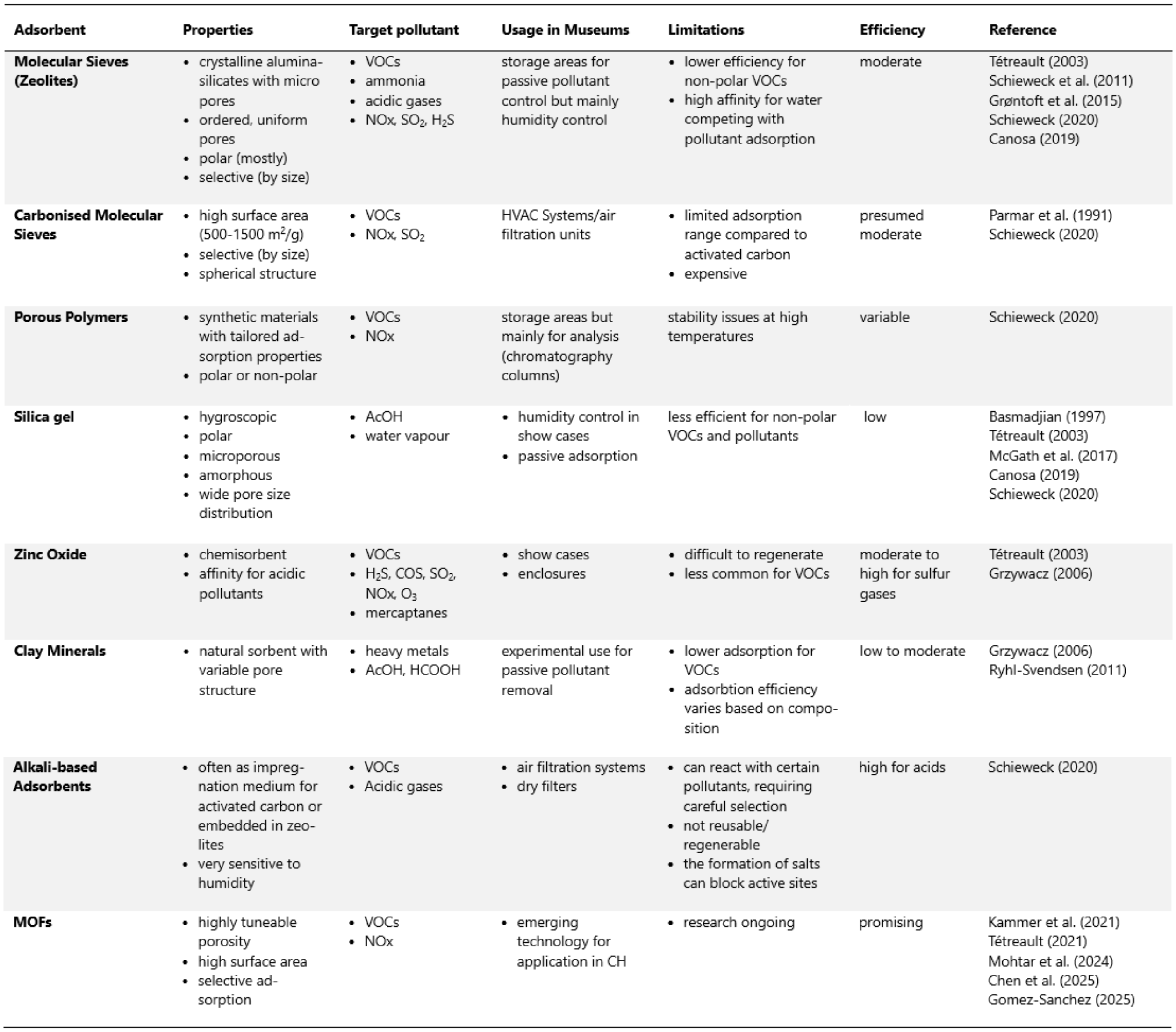
Where mechanical systems are impractical or restricted, passive ventilation offers a low-energy method for diluting indoor pollutants. This approach relies on diffusion or pressure-driven airflow, using architectural features like vent holes, louvers, or gaskets to facilitate air exchange. In sealed display cases, passive ventilation may be supplemented with diffusion valves or breathable barrier materials that allow gas exchange while maintaining dust protection. Passive ventilation is sometimes preferred and is most effective when paired with sorbent materials to capture gases. Although it lacks the responsiveness and precision of mechanical systems, this method is maintenance-free, and does not require a power supply.

The benefits of passive systems include simplicity, low cost, and ease of implementation in protected historic structures. However, they are inherently limited in their ability to reduce pollutant concentrations quickly and may allow outdoor pollutants to infiltrate indoor spaces. Additionally, they are not suitable for environments with high internal emission sources or sensitive objects requiring tight environmental control.

Funded by
the European Union

Table 10. Categorisation and properties of adsorbent media

Adsorbent	Properties	Target pollutant	Usage in Museums	Limitations	Efficiency	Reference
Activated carbon	• high surface area (100-3000 m^2/g) • easy to regenerate • wide pore-size (2-50 nm) • non-polar	• VOCs (AcOH, formaldehyde) • NOx, SO_2, O_3, H_2S • ammonia and amines	• show cases • storage cabinets • HVAC systems/air filters	• saturation over time • requires periodic regeneration • not selective • adsorbs humidity and replaces in turn adsorbed organic compounds • highly flammable	very high	Parmar et al. (1991) Tétreault (2003) Grzywacz (2006) Cruz et al. (2008) Schieweck et al. (2011) Grøntoft et al. (2015) Schieweck (2020) Canosa (2019) Verma et al. (2023)
Graphitised Carbon Blacks	• crystalline structures with layers of graphene • hydrophobic	• VOCs (best aromatic hydrocarbons) • NOx, SO_2, O_3, H_2S • ammonia and amines	• trace level applications • HVAC systems/ air filtration	lower surface area than activated carbon (ca. 100 m^2/g)	presumed high	Schieweck (2020)
Activated Carbon Fibers (ACFs)	• high surface area (1200 – 1400 m^2/g) • orderly arranged microfilaments	• VOCs (AcOH, formaldehyde, also odors, microbial pollutants) • NOx, SO_2, O_3, H_2S • ammonia and amines	• enclosures • show cases • storage cabinets • HVAC systems/ air filtration	• expensive raw materials • affected by humidity	moderate to good	Jonathan et al. (2017) Li et a. (2020) Joo et al. (2025)
Charcoal Cloths/ High performance ACF	• high surface area (2500 m^2/g) • flexible adsorption medium	• VOCs (AcOH, formaldehyde, also odors, microbial pollutants) • NOx, SO_2, O_3, H_2S • ammonia and amines	• enclosures • show cases • storage cabinets	• lower adsorption capacity compared to solid activated carbon • can degrade over time • cannot be regenerated	moderate to good	Tétreault (2003) Grzywacz (2006) Nieto-Delgado et al. (2019) Schieweck (2020)
Charcoal Foams	• high surface area • flexible adsorption medium	• VOCs (AcOH, formaldhehyde) • NOx, SO_2	• enclosures • show cases	• may require structural reinforcement for long-term use • can degrade over time • cannot be regenerated	moderate	Schieweck (2020)
Impregnated activated carbon	• high surface area slightly lower than activated carbon (500-1500 m^2/g) • $KMnO_4$, NaOH or metal oxides improve adsorption • polarity dependent on impregnation • enhanced selectivity	• VOCs (AcOH, formaldehyde) • NOx, SO_2, O_3, H_2S • ammonia and amines	• show cases • storage cabinets • HVAC systems / air filters	• limited regeneration due to chemical saturation • sensitive to humidity	high for specific pollutants	Grzywacz (2006) Schieweck (2020) Verma et al. (2023)
Carbon Nanotubes (CNT)	• single-/multi-walled • high surface area (>2600 m^2/g) • π-π-interactions • modifiable functional groups	• VOCs • NOx, SO_2, O_3, H_2S • microplastics • PM • viruses	• experimental use in air purifiying filters • potential for show cases/enclosures	• very high costs • safety/toxicity concerns • not yet/much used in museums	high	Yu et al. (2018) Nehra et al. (2021) Tao et al. (2022) Gulati et al. (2022)
Activated/Archival cardboard	• cellulose-based • chemically treated surfaces	• VOCs (AcOH, formaldhehyde) • limited: NOx, SO_2	archival boxes and shelving	lower adsorption capacity compared to solid activated carbon	moderate to low	Ryhl-Svendsen et al. (2009) Schieweck (2020)
Activated alumina	• polar • crystalline • wide pore size distribution • chemisorbent	• VOCs (aldehydes, organic acids) • NO, SO_2, H_2S • amines • mercaptanes	• HVAC systems / air Filters • desiccant • analysis (chromatography columns)	• cannot be regenerated • toxic when impregnated with $KMnO_4$	low to moderate	Tétreault (2003) Grzywacz (2006) Canosa (2019) Schieweck (2020)



Adsorbent	Properties	Target pollutant	Usage in Museums	Limitations	Efficiency	Reference
Molecular Sieves (Zeolites)	• crystalline alumina-silicates with micro pores • ordered, uniform pores • polar (mostly) • selective (by size)	• VOCs • ammonia • acidic gases • NOx, SO_2, H_2S	storage areas for passive pollutant control but mainly humidity control	• lower efficiency for non-polar VOCs • high affinity for water competing with pollutant adsorption	moderate	Tétreault (2003) Schieweck et al. (2011) Grøntoft et al. (2015) Schieweck (2020) Canosa (2019)
Carbonised Molecular Sieves	• high surface area (500-1500 m^2/g) • selective (by size) • spherical structure	• VOCs • NOx, SO_2	HVAC Systems/air filtration units	• limited adsorption range compared to activated carbon • expensive	presumed moderate	Parmar et al. (1991) Schieweck (2020)
Porous Polymers	• synthetic materials with tailored adsorption properties • polar or non-polar	• VOCs • NOx	storage areas but mainly for analysis (chromatography columns)	stability issues at high temperatures	variable	Schieweck (2020)
Silica gel	• hygroscopic • polar • microporous • amorphous • wide pore size distribution	• AcOH • water vapour	• humidity control in show cases • passive adsorption	less efficient for non-polar VOCs and pollutants	low	Basmadjian (1997) Tétreault (2003) McGath et al. (2017) Canosa (2019) Schieweck (2020)
Zinc Oxide	• chemisorbent • affinity for acidic pollutants	• VOCs • H_2S, COS, SO_2, NOx, O_3 • mercaptanes	• show cases • enclosures	• difficult to regenerate • less common for VOCs	moderate to high for sulfur gases	Tétreault (2003) Grzywacz (2006)
Clay Minerals	• natural sorbent with variable pore structure	• heavy metals • AcOH, HCOOH	experimental use for passive pollutant removal	• lower adsorption for VOCs • adsorbtion efficiency varies based on composition	low to moderate	Grzywacz (2006) Ryhl-Svendsen (2011)
Alkali-based Adsorbents	• often as impregnation medium for activated carbon or embedded in zeolites • very sensitive to humidity	• VOCs • Acidic gases	• air filtration systems • dry filters	• can react with certain pollutants, requiring careful selection • not reusable/ regenerable • the formation of salts can block active sites	high for acids	Schieweck (2020)
MOFs	• highly tuneable porosity • high surface area • selective adsorption	• VOCs • NOx	• emerging technology for application in CH	• research ongoing	promising	Kammer et al. (2021) Tétreault (2021) Mohtar et al. (2024) Chen et al. (2025) Gomez-Sanchez (2025)

3. IAQ monitoring in GLAMs

Monitoring VOCs is an important part of the control strategies that GLAMs can implement before and/or after a remediation approach using passive or active purification solutions[81]. Monitoring helps in the assessment of the level of pollution the GLAMs have to mitigate, and once purification solutions are used, it helps in assessing the remediation efficiency. As explained in section 1, these strategies can follow or derive from guidelines and specifications. According to Tétreault[16], avoid, block, dilute, and filter/sorb are all relevant strategies to reduce the levels of the pollutants in the ambient air. Avoiding the occurrence of VOCs being the best yet often a difficult option, blocking becomes more realistic, which is developed in section 2. In the following section, we explore the methods that are available to GLAMs to monitor the air quality in order to act upon the data collected to improve IAQ. These monitoring methods are not standardized, and, in practice are not often used for various reasons (see Annex A). For instance, the time at which the monitoring or sampling is conducted can greatly impact the results, but the weather, human activities, urban or rural areas specific types of pollutants also have an influence. Tables 23 & 24, in

Funded by the European Union

Tétreault[16], which are not reproduced here, give an overview of the sampling and detection techniques as well as their limit of detection as available at the time of the publication (2003). Most of them are still available to this day.

This section focuses on evaluating commercially available sensor technologies, or laboratory based ones, for detecting VOCs, NOx, and H_2S. It also delve into calibrating selected sensors in a laboratory setting, and deploying them in a CCI to assess their performance in real operational conditions. Depending on their functioning mode (semi-qualitative or quantitative), they are categorised as dosimeters, diffusive and passive samplers, sensors and loggers, and laboratory analytical techniques. Their commercial availability or unavailability is indicated, as well as their operation mode, the evaluation of the results, the gases detected[2] (with the detection limits), as well as the reported advantages and drawbacks. The list established is not exhaustive in terms of the different commercial devices, but gathers all the sensor and dosimeter technology types.

3.1 Indicators and Dosimeters

Dosimeters for CH applications are usually meant to measure the damaging potential or an overall combined effect of indoor atmospheres on cultural heritage objects, whether UV radiation, visible light, temperature and humidity and/or chemically aggressive atmospheres. Dosimeters provide a semi-qualitative response[16]. They are recommended for preliminary quick screenings to assess IAQ. Dosimeters are especially favoured in GLAMs for their advantages: they are simple to use, low-cost, they evaluate an overall environmental situation, most of them have a direct visual assessment, and a direct immediate reading, and they are implementable by non-technical staff. Their intent is often to function as an early-warning system of how and to what extent an object can degrade. Some are also fast responding, which is another key benefit for quick implementation of mitigation strategies. For all these reasons they are well-known and popular in the GLAMs community.

One prominently used indicator is the so-called A-D strip from the Image Permanence Institute (RIT, Rochester, NY), which is a paper strip impregnated with a pH sensitive colourant (bromocresol green), which provides an acid-base response on the scale 3.8 - 5.4. The response is ranked in terms of levels 0 (good) to 3 (critical), qualifiers that relate to cellulose acetate film preservation target for which they have been developed in the first place. They are influenced by other environmental factors (light and to RH above 60%) and that has been reported as a drawback by some authors as well as the observed interference from atmospheric carbon dioxide[82, 83, 84]. Additionally, the dye is water sensitive and the contact with artefacts has to be avoided. Despite this, because of its simplicity the AD strip is universally used in the GLAMs community, but foremost for acetate cellulose films collections.

An even simpler indicator, easy to fabricate in-house in any conservation workshop or any GLAM, is proposed by Tétreault by using a pH-sensitive paper impregnated with glycerin/H_2O. The recommendation for best calibrated response is to use a pH strip sensitive on the scale 4-7[85, 86]. The response is of course indiscriminate for all acid vapours, but it is calibrated using AcOH in ambient set conditions, and the sensitivity of the response is reliable over the AcOH concentration range 0.5 -150 ppm.

Another such simple device, within everyone's reach and worth mentioning is the elastomer dosimeter proposed by Ryhl-Svendsen[87], which reacts to ozone and has been semi quantitatively calibrated measuring

---

[2] the list is limited to the gases of interest within the SIMIACCI project

Funded by the European Union

the size of the cracks in the rubber through ozone exposure above 500 ppb and and using FTIR for exposure below 500 ppb (carbonyl bands).

The so-called Oddy test also falls among the dosimeters type of device as it is based on accelerated corrosion of metal coupons (silver, copper, and lead) in a closed vial at 100% RH and 60°C. A first level of assessment is the visual examination of corrosion levels after an exposure of 28 days[88, 89, 90, 91, 92]. The detection is unspecific since all corrosive gases will give a response. The methodology being subject to great variability, the corrosion can also be more precisely appraised and measured through photographic or microscopic observation[93], colourimetry[94], mass gain[95], X-ray diffraction[96], micro-Raman spectroscopy, FTIR, gravimetry[97] or quartz crystal microbalance (QCM). Three levels of response are usually described to characterise the material tested: *i.e.* permanent, temporary or unsuitable. This popular test is trusted by the GLAMs and conservation community for testing the quality of materials since it is implemented in a closed vial where any small amount of a given emissive corrosive material can be placed, and has been used for decades[98]. However, it is also criticised and the reported drawbacks include the work-intensiveness, the lack of objectivity for evaluating the corrosion levels of the coupons (since there are no set criteria) and the fact that there is no coupon assessment tool. Depending on the operator a wide variations of assessments for the same materials tested have been reported[99]. Hence guidelines have been produced thanks to multiple laboratory efforts from the conservation research community, which thrive to make the test more reproducible and quantitative[97, 100, 101, 102]. However, no standardized protocol is available, and recommendations for the purity of the metals used, the surface preparation of the coupons, the volume of H_2O in the testing vessel, the vessel volume, etc, would help the GLAMs in establishing the test in the routines of IAQ assessment.

An indicator that functions also based on accelerated corrosion of copper and silver coupons is the CCC (Corrosion Classification Coupon) from Purafil (Figure 6, Figure 16). Unlike the indicators above, the reading of CCC cannot be made *in-loco* by the GLAMs staff. Once exposed to the indoor air, the device is sent to Purafil for laboratory analysis that will measure the corrosion layers thicknesses using analytical instruments. The results are classified as mild/moderate/harsh/severe to define an environment's aggressiveness. This dosimeter is specific only for sulfur gases H_2S and to SO_2. Besides the limited range of gases tested, one advantage that this method has over the others is that it is standardised (ISA Standard 71.04-2013, ISO 11844-2:2020).

Figure 6. Corrosion Classification Coupon (Purafil)

Reflecting on the need and enthusiasm of the GLAMs and conservation community for simple IAQ assessment tools, several European projects funded over the years within different Framework Programs emerged from this community (Figure 2) and focussed on developing IAQ monitoring dosimeters mostly based on decay mechanisms to overall environment aggressiveness to objects. Some have even produced devices that overcame the commercialisation ‘’barrier’’ commonly encountered in the applied research community, with more or less success, and were therefore commercially available for a short period after the project completion. One prominent such project is MEMORI (FP 7). The MEMORI early–warning system is an aggregation of two dosimeters developed in previous EC projects: the Fraunhofer-ISC Glass Slide Dosimeter (GSD) from AMECP EU project, and the Early Warning dosimeter for Organic materials (EWO) from NILU-led MASTER EU project. Both devices are made of sensitive glass that react to the most common and prominent damaging pollutant gases indoor in GLAMs[103] (Figure 7 & Figure 8). GSD reacts with the urban traffic and industrial pollutants (NO_2, SO_2, TVOC) that infiltrate indoor from outdoor by corroding and forming gel-layer containing alkali-leached water. The corrosion related to the amount of water which is quantified using FTIR. EWO reacts with indoor acidic gases. The exposure time recommended was 3 months. The dosimeters responses are calibrated and dose-response functions for materials degradation were produced during the project to help decision-making. However, it was noted that temperature, humidity and UV light increased the response of the dosimeter.

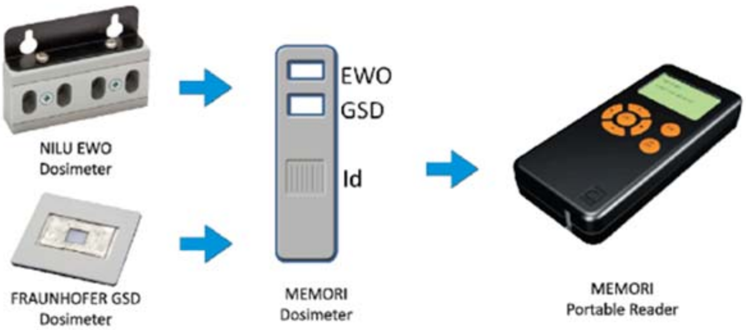


Figure 7. The MEMORI Dosimeter, which will be analysed with the portable MEMORI Reader (Fig 1 [103])

Figure 8. (left) The MEMORI dosimeter in a stand; (right) the MEMORI dosimeter reader (https://memori.nilu.no/Product)

The project also developed a decision support model to give some information on the magnitude of deterioration effects. Initially a wider marketing of the dosimeter technology was integrated in the project plan of MEMORI, but it allowed the commercial availability only for one year after the project completion, in 2014. Several research projects on IAQ in GLAMs have used the MEMORI system to interpret gas pollution data in relation with CH artefacts[8, 59, 95, 104].

Quartz Crystal Microbalance (QCM) are yet another type of dosimeter. Serving primarily as sensors, they are described in section 3.2.

Attaining Technology Readiness Levels (TRL) high enough to reach the commercialisation of a dosimeter and overcoming the barriers of a stable product marketing with a thought-through business strategy has been a huge challenge for most VOCs dosimeters developed in EC projects. None of the dosimeters developed in EC projects on IAQ for cultural heritage have made it beyond the prototype level. Reflecting upon this difficulty, the Annex B in D4.2 (SEN report) gathers the result of person-to-person interviews from SIMIACCI partners with past EC projects coordinators (MEMORI, SENSMAT, NEMOSINE, APACHE) to better understand the pitfalls and challenges met for effective IAQ management in GLAMs. These include business strategy, communication, implementation costs, etc. The outcome should guide SIMIACCI to evaluate the minimal requirements to meet for a successful large-scale distribution of a product destined to the GLAMs community.

3.2 Sensors, samplers and loggers

Unlike most dosimeters, sensors are calibrated under controlled laboratory conditions to ensure accurate, repeatable measurements that reflect real indoor air pollutant concentrations. These calibrated sensors can also be integrated in loggers and are deployed in a GLAM setting, enabling long-term monitoring of air quality conditions and environment fluctuations. The deteriotation of CH materials as well as the deterioration of their perceived and objective value being the result of cumulative damage, the meaningful factors involved are to monitor on the long-term so to be able to draw meaningful averages and implement the proper preservation and mitigation strategies. The data collected by the sensors has to be analysed and interpreted in that sense.

The data are analyzed to assess sensor performance in situ, determine the effects of environmental factors such as temperature and relative humidity, and compare sensor outputs to established thresholds and reference methods. SIMIACCI will ultimately recommend strategies for indoor air quality control, drawing from both sensor results and published best practices, particularly those developed by the Swedish National Heritage Board[55].

3.2.1 *Comparative Analysis of VOC Sensor Technologies*

This section provides a detailed evaluation of VOC sensor technologies applicable to CH organizations. The analysis draws on established research and museum field studies, including those conducted by Grzywacz[7], Tétreault[105] and Clements et al.[106] and to compare the performance, applicability, and limitations of various sensor types.

Electrochemical Sensors

Electrochemical sensors are analytical devices that detect specific gases through electrochemical reactions at electrode surfaces, generating an electrical signal proportional to the concentration of the target analyte[107] (Figure 9). These sensors operate based on redox reactions: when a gas such as formaldehyde, NO_2, or H_2S contacts the working electrode, it either donates or accepts electrons, producing a measurable current. The internal design includes an anode and cathode, separated by an electrolyte, which facilitates ion exchange. A reference electrode maintains a stable potential to ensure accurate readings. In some configurations, a gas diffusion barrier is added to enhance selectivity and response linearity[7].

The key components of an electrochemical sensor include the working, reference, and counter electrodes, the electrolyte, and a membrane or diffusion barrier to regulate gas flow. Several types exist, including amperometric sensors (used for O_2 and H_2S), potentiometric sensors (for pH or ion-specific detection), and conductometric sensors (which measure conductivity changes in the electrolyte)[108].

In CH contexts, electrochemical sensors are widely employed to detect formaldehyde, nitrogen dioxide, and hydrogen sulphide. One of the reasons is that they are direct-reading devices which allow for real-time monitoring without the need for sampling and subsequent laboratory analysis[109]. Common applications include real-time monitoring with formaldehyde badges or wall-mounted NO_2 sensors used to evaluate HVAC performance[43]. These sensors offer high sensitivity, often down to ppb levels (detection range of 100 ppb–50 ppm[109]), and are compact and cost-effective. Their advantages include low power consumption and good selectivity through tailored electrode chemistry. However, they are prone to cross-sensitivity to interfering gases, are sensitive to environment humidity and temperature conditions, and have a limited lifespan (typically between 6 and 24 months). Frequent and regular calibration is essential to maintain data quality.

Figure 9. ME3 series Electrochemical Gas SensorME3 series Electrochemical Gas Sensor

Photoionization Detectors (PIDs)

Photoionization detectors (PIDs) are designed to detect low concentrations of VOCs by ionizing gas molecules using ultraviolet (UV) light (Figure 10). The ionized particles create an electrical current that is proportional to the concentration of the ionized gas[107]. A UV lamp, typically rated at 10.6 eV, emits photons that ionize molecules with lower ionization potentials. The resulting current is collected by electrodes, providing real-time output on VOC levels.

The primary components of a PID include a UV lamp, an ionization chamber, collection electrodes, and either a diffusion or an active pump system to introduce the air sample. PIDs are sensitive to a wide range of VOCs, including solvents such as toluene, benzene, ethanol, formaldehyde, and isopropanol. However, they are ineffective at detecting inorganic gases like NOx, CO_2, and H_2S due to their high ionization energies[7].

PIDs are well suited for museum environments where rapid or local changes in air quality may occur, such as during installation activities or the use of new materials. Their fast response time and portability make them ideal for short-term assessments and dynamic monitoring.

The strengths of PID sensors include fast response, real-time data output, high sensitivity range (1 ppb–1000 ppm), and simple operation. However, they are non-selective, measuring total VOCs (TVOCs) without distinguishing specific compounds. Their sensitivity is affected by humidity, and the UV lamp requires regular cleaning and periodic replacement. Reference gases such as isobutylene, with compound-specific correction factors applied as needed for calibration. The Metropolitan Museum of Art, for example, has used PID sensors to track VOC levels during renovation phases[108].

Figure 10. Portable PID MiniRAE 3000

Metal Oxide Semiconductor (MOS) Sensors

MOS sensors are solid-state devices that detect gas-phase pollutants by measuring changes in electrical resistance caused by gas interactions on a heated metal oxide surface (Figure 11). Like the PIDs and electrochemical sensors, they are also direct-reading devices. Common materials include tin dioxide (SnO_2), zinc oxide (ZnO), and tungsten trioxide (WO_3). When a gas is adsorbed, the resistance of the sensing material changes, depending on whether the gas is reducing or oxidizing[107]. These sensors typically operate between 200–400°C.

The core components include a metal oxide sensing layer, an integrated heater to maintain operational temperature, a resistive circuit, and sometimes environmental filters. MOS sensors can detect a broad spectrum of gases including ethanol, toluene, acetone, formaldehyde, and inorganic compounds like NOx, ozone, and H_2S[7].

In museum settings, MOS sensors are commonly used for distributed air quality monitoring due to their low cost and ability to detect a wide range of pollutants. They are often embedded in commercial IAQ monitors or custom-built wireless nodes.

Advantages include affordability, suitability for continuous 24/7 operation, and long operational lifespan. In contrast to other sensors, MOS sensors have a lower sensitivity and can only measure volatiles in the ppm range. Other drawbacks are the sensitivity to humidity and temperature, and baseline drift over time. Therefore, they require regular calibration and, in some cases, compensation algorithms or machine learning models to interpret data accurately.

Figure 11. MQ-9B MOS Sensor for Carbon Monoxide

Funded by
the European Union

Quartz Crystal Microbalance (QCM) Sensors

Quartz Crystal Microbalance (QCM) sensors are mass-sensitive analytical devices that detect gases by measuring changes in the resonance frequency of a vibrating quartz crystal (Figure 12). When gas molecules are adsorbed onto the surface of the crystal—usually coated with a chemically active or sorptive film—the added mass results in a measurable decrease in oscillation frequency. This relationship is described by the Sauerbrey equation, which correlates mass change with frequency shift[107].

QCM sensors typically consist of an AT-cut quartz crystal oscillating at a fundamental frequency of 5–10 MHz, metal electrodes (usually gold), a functional coating layer, and an oscillator circuit. The sensor's extreme sensitivity allows for detection of mass changes in the nanogram range, making it ideal for measuring adsorbed pollutants such as acetic acid, formic acid, and aldehydes.

These sensors are particularly valuable in CH environments for real-time monitoring of corrosion for instance. When coated with reactive metals like lead or silver, QCM sensors can serve as dosimeters, indicating the corrosive potential of the microenvironment inside display cases or storage units. Examples include their use in EC projects MIMIC[110], MEMORI[8,103] and PROPAINT[104] focused in their integration for cultural heritage protection[43, 108].

The primary advantages of QCM sensors are their ultra-high sensitivity, capability for real-time monitoring, compact design, and suitability for integration into enclosed heritage environments. However, their limitations include the need for specific coatings to achieve selectivity, sensitivity to ambient temperature and humidity, and the risk of signal saturation during long-term exposure. Interpretation of results often requires additional environmental compensation.

Figure 12 .OPENQCM WI2, Quartz Crystal Microbalance (QCM) Sensor

Solid Phase Microextraction – Gas Chromatography/Mass Spectrometry (SPME-GC/MS)

It could be considered out of the scope to include organic analysis separation techniques such as chromatography separation with mass spectrometry detection (GC/MS) in the list of sensors. However, hyphenated with GC/MS, SPME (Solid Phase MicroExtraction) is a sorbent methodology privileged by several conservation research laboratories for selectively capturing VOCs. SPME-GC/MS combines passive sampling of the analytes with a highly resolutive separation and a highly sensitive detection technique to provide compound-specific analysis of organic airborne pollutants. The SPME polymer fibre traps VOCs from the surrounding environment, after which it is inserted into the injection port of a GC for thermal desorption.

The separated compounds can then be identified through their molecular structure based on their mass-to-charge ratios and quantified [107].

The setup typically used includes a polymer-coated SPME fibre placed in a sealed sampling container or small vial (Headspace sampling mode) (Figure 13) or in a display case or cabinet [111], [112], [113], [114], [115] or directly inserted in a CH object such as a book, to sample the VOCs emitted by the artefact (Figure 14). SPME fibres are available with different types of polymer coatings to improve the selectivity, notably due to different polarity[81]. PA and PDMS/DVB coatings are most often used for the analysis of a wide range of volatile analytes[116], especially those of interest for GLAMs, such as aldehydes, carboxylic acids, alcohols, ketones, aromatic hydrocarbons, as well as plasticizers used in CH materials. In museum applications, SPME-GC/MS is therefore useful to identify and quantify off-gassed compounds from construction materials, adhesives, textiles, or enclosed artifacts and supports decisions on material compatibility and effectiveness of mitigation systems.

The technique is praised for its sensitivity (detection down to parts per trillion), compound specificity, and suitability for passive sampling in constrained areas as the sorbing fibre is thin and typically 10 cm long (Figure 14) and can be easily placed in small containers, or in display cases without disturbing the aesthetics. However, the analysis is not done in real-time since the fibre has to be brought to the laboratory for desorption in the GC/MS instrument, and thus requires laboratory instrumentation and trained personnel. It can also be influenced by ambient humidity and exposure conditions.

Figure 13. SPME fibre in headspace sampling mode in a small vial (Agilent)

Figure 14. (Left) SPME fibre ; (Right) the SPME fibre inserted in a book to sample the VOCs emitted. (Photo credit: A-L Dupont. CRC-MNHN)

Adsorption-Based Sensors (passive and diffusive)

Adsorption-based sensors work by capturing gaseous pollutants on the surface of a solid adsorbent material through physical or chemical interactions (Figure 15). These sensors are typically used in passive sampling systems or in dosimeters, with subsequent analysis conducted in a laboratory but can also work in active mode using pumps to force the air through. Materials used for adsorption include activated carbon or graphitized charcoal (such as in radial symmetry diffusive sampler from Radiello - Figure 16 Left), Tenax TA, silica gel, and Chromosorb resins[107].

A typical setup consists of an adsorbent tube or badge housed in a protective shell with filter screens to exclude particulates. After the exposure period, the adsorbent is thermally desorbed or extracted chemically and analysed using gas or liquid chromatographic techniques (GC-MS or HPLC). In GLAMs environments, adsorption-based sensors are used for long-term monitoring of VOCs inside showcases or storage units, screening materials for off-gassing, and validating air cleaning systems. Their simplicity and relatively low cost make them ideal for baseline surveys and extended exposure periods. For instance, IVL diffusive samplers were used at National museum in Sweden to monitor acetic acid and formaldehyde[107].

Other types of diffusion tubes include Palmes[117], which were originally developed for nitrogen dioxide sampling in a standardised protocol[118] and that are commercialized by Gradko for formic and acetic acids measurement when followed by ion chromatography analysis. SAfeAir and ChromeAir badges are also available for formaldehyde and sulfur gases. Dräger and Gastec short-term or long-term tubes are also favoured for IAQ monitoring in GLAMs as they available for a large range of VOCs and allow for a direct visual semi-quantitative reading (Figure 16). These brands also offer active detector types based on the same calibrated reactive principle, where a diffusion of gas is forced through the reagent with a small pumping device.

These sensors are easy to deploy and require no power supply, which makes them ideal for short-term and long-term passive assessments. However, they do not provide real-time data, and their performance may be affected by environmental variables like temperature and humidity. Accurate quantification depends on careful calibration by the manufacturers, exposure logging, and proper handling.

Figure 15. Passam Ag diffusion samplers

Figure 16. (Left) Exposure of Purafil coupons and Radiello® tubes in an archival box from Puy-de-Dôme French Provincial Archives (Figure 4 in Dubus et al. 2015 [119]). (Right). Used Dräger and Gastec used detection tubes (Photograph credit: J. Tétreault, CCI)

Corrosion-Based Sensors

Corrosion-based sensors assess the cumulative presence of pollutants by monitoring the corrosion or tarnishing of reactive metal surfaces (Figure 17 Left). These sensors are not designed to quantify specific gases but instead provide an overall indication of pollutant aggressiveness in the environment as explained in the section 3.1 dedicated to dosimeters. Metals such as silver, lead, and copper are used to detect pollutants like hydrogen sulfide, acetic acid, formic acid, ozone, and nitrogen dioxide[107].

Such sensors may take the form of passive metal coupons (described in section 3.1) or active sensor systems that measure mass changes or resistance variations due to corrosion. Quartz Crystal Microbalance (QCM)-based and Electrical Resistance (ER)-based corrosion sensors represent more advanced versions.

Applications in CH settings include monitoring pollutant exposure in display cases and storage enclosures, testing the suitability of exhibition materials, and validating the effectiveness of filtration or HVAC systems. For example, Purafil OnGuard use silver and copper sensors to assess corrosion risk in museums and archives[107].

These sensors are valued for their low cost and ability to capture long-term environmental trends. They are particularly useful for assessing micro-environmental risks to metal-based artefacts. However, they are not compound-specific, and analysis typically requires laboratory support. Environmental factors like humidity and dust also influence the rate of corrosion.

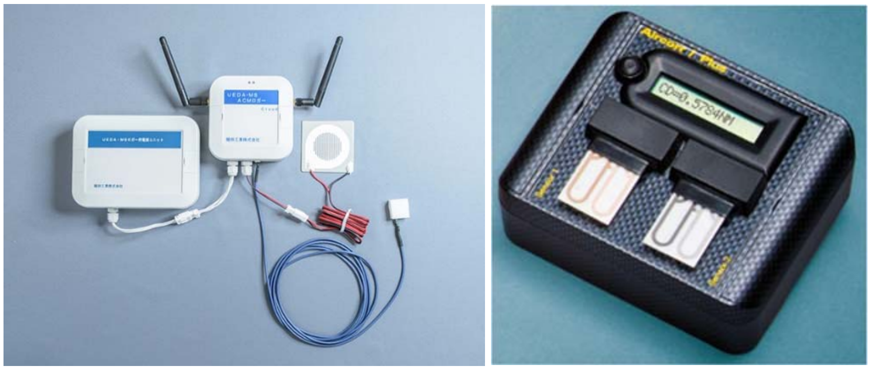


Figure 17. (Left) Radio Wave Type Monitoring Unit for a corrosion-based sensor; (Right) AirCorr corrosion monitoring system equipped with Ag-50 nm and Cu-50 nm sensors (Fig 1 in Kouril et al 2014 [120])

Other corrosion-based sensors include AirCorr[121, 120] (Figure 17 Right) which was developed in European project MUSECORR and was available for purchase by GLAMs from the French Corrosion Institute (Brest) until recently. The device reached a high level of popularity among the GLAMs conservation community for being sensitive, reliable and easy to use and deploy. As a replacement, some GLAMs have started using Camfil ISA Check II, calibrated and based on ANSI/ISA-71.04-2013 standard. However, the results based on corrosion thickness measurements are reported as not so trivial to interpret.

Optical Sensors

Optical sensors detect gases based on their interaction with light—usually absorption, scattering, or fluorescence—in the UV, visible, or IR spectrum (Figure 18). These systems are capable of real-time, non-invasive monitoring with high selectivity. The Beer–Lambert Law governs the relation-ship between light attenuation and gas concentration, allowing quantitative analysis[77].

Common techniques include Non-Dispersive Infrared (NDIR) for detecting CO_2 and hydrocarbons, UV absorption for ozone and NO_2, and Tunable Diode Laser Absorption Spectroscopy (TDLAS) for high-resolution gas measurements. Core components are a light source, sample cell, optical filters, and a photodetector.

In CH applications, optical sensors are used for continuous monitoring of ozone and NO_2, pre-installation air quality assessments, and integration into HVAC control systems. For example, the Uffizi Gallery in Florence utilized optical sensors in combination with corrosion dosimeters to guide conservation decisions[107].

Advantages include high precision, non-contact operation, and specificity for individual gases. Limitations involve high cost, sensitivity to dust and humidity, and the need for optical alignment and maintenance.

Figure 18. Through-Beam Optical Sensor

3.2.2 *Choices of sensors in GLAMs*

The literature review highlights the strengths and limitations of each sensor type. Electrochemical sensors are ideal for pollutant-specific applications requiring precision. PIDs are best suited for real-time alerting and monitoring in areas with fluctuating VOC concentrations. MOS sensors are most appropriate for distributed deployment in HVAC-zoned environments, where general VOC trends were more relevant than specific compound identification.

A tiered monitoring approach—combining different sensor types based on location, pollutant profile, and required response time—offers the most effective solution. This approach balances sensitivity, specificity, cost, and maintenance, enabling institutions to achieve comprehensive air quality oversight without compromising on practical constraints.

Table 11 provides a summary of the possible choices of sensors depending on their capacities.

Table 11. Sensor selection and citing literature

SENSOR TYPE	TARGET POLLUTANTS	ADVANTAGES	LIMITATIONS	RECOMMENDED USE	FINAL SELECTION
ELECTROCHEMICAL	NOx, H_2S	High specificity, low detection limits	Needs frequent calibration, limited lifespan[122, 123]	Critical pollutant-specific monitoring (archives, labs)	Yes
PHOTOIONIZATION DETECTOR (PID)	VOCs	Real-time, broad detection range, fast response	Sensitive to RH, UV lamp aging and replacement	Real-time alerting in dynamic gallery environments	Yes
METAL OXIDE SEMICONDUCTOR (MOS)	VOCs, NOx	Low cost, compact, long-term use	Sensitive to RH and temperature, low selectivity[124, 122]	Distributed VOC trend tracking in HVAC zones	Yes
QUARTZ CRYSTAL MICROBALANCE (QCM)	Organic acids, aldehydes	Ultra-sensitive, real-time corrosion/vapor mass detection	Humidity/temperature sensitive, complex interpretation[125]	Corrosion risk detection in display cases[106, 123]	No
SPME-GC/MS	VOCs (individual species)	Highly specific and sensitive lab analysis	Not real-time, requires lab, high cost	Baseline pollutant ID and emission source profiling	No
ADSORPTION-BASED	VOCs, acids	Low cost, passive long-duration monitoring	Not real-time, sensitive to RH/temp, lab analysis required	Long-term background VOC tracking	No
CORROSION-BASED	H_2S, acetic/formic acid, O_3	Cumulative pollutant effect indicator	Non-specific, environmental variables affect accuracy	Micro-environment aggressiveness mapping	No
OPTICAL SENSORS	NO_2, O_3, CO_2	Non-contact, specific, high precision	Expensive, affected by RH/dust, alignment needed	Remote ozone/NO_2 monitoring, BMS integration	No

3.2.3 *Wireless Network Integration*

To enhance the effectiveness and responsiveness of indoor air quality (IAQ) monitoring in museum environments, integrating sensor technologies into a wireless network architecture is strongly recommended. A proposed framework involves deploying sensor nodes using Zigbee or Wi-Fi-based mesh communication protocols, which can support real-time data acquisition across diverse spatial zones within a museum. This network would consist of modular components, including gateway devices linked to cloud-based storage and analytics platforms, strategically placed sensors near HVAC vents, display cases, and archival storage, and repeater modules to extend coverage in signal-limited areas. Such an approach would enable flexible sensor positioning, facilitate centralized data management, and improve long-term pollutant tracking. Although this architecture has not yet been widely adopted in museums, it draws on proven applications of wireless sensor networks in smart building and cultural heritage monitoring projects[126, 127, 128].

In these projects, signal reliability emerges as a critical performance indicator. In open gallery environments with minimal physical obstructions, the wireless network maintains over 95% uptime. However, in locations with architectural constraints—such as stone-lined vaults or reinforced display enclosures—signal attenuation is observed. In these areas, the deployment of repeater modules or alternate communication pathways is necessary to ensure data continuity and prevent trans-mission loss.

Power management presented another consideration. Electrochemical and MOS sensors can be powered using battery packs capable of sustaining operation for two to three months, depending on data transmission frequency and environmental conditions. PID sensors, due to their higher energy demands, either require connection to a wall outlet or use of extended-capacity battery modules. To optimize energy efficiency, transmission intervals and sensor duty cycles have to be adjusted based on location criticality and expected pollutant variability.

Data integrity was maintained through time-stamped transmissions, which enabled precise synchronization and retrospective validation during trend analysis and anomaly detection. The network's ability to provide continuous, real-time data streams significantly reduced the need for manual logging and periodic spot checks, thereby enhancing the responsiveness of conservation staff to adverse environmental changes.

Wireless network integration also supported the scalability of the monitoring system. New sensors could be added without the need for structural modifications, making the system adaptable to evolving exhibition layouts, storage configurations, or temporary installations. This plug-and-play flexibility is especially advantageous in heritage institutions where architectural preservation restricts intrusive interventions such as hard-wired connections.

Overall, the deployment of a wireless mesh network created a robust foundation for intelligent IAQ management. It enabled spatially distributed monitoring, facilitated remote diagnostics, and improved situational awareness for preventive conservation. The system's cloud connectivity and compatibility with building automation infrastructure further position it as a scalable and sustainable solution for heritage environments.

3.2.4 *Laboratory Calibration*

To ensure reliable data collection, sensors undergo calibration under controlled laboratory conditions. This process involves exposing the sensors to known concentrations of target gases—VOCs, NOx, and H_2S—and recording their responses. The methods used for calibration vary depending on the gas of interest.

Calibration is benchmarked using high-precision reference instruments such as GC-MS for VOCs and chemiluminescence analysers for NOx. For H_2S, electrochemical analysis was performed using cylinders of known concentrations. Standard calibration gases and certified reference mixtures are employed to generate calibration curves, which allows for the correlation of sensor output signals with actual pollutant concentrations[111].

Objectives of Calibration

The objective of calibration is to ensure that sensors accurately reflect the concentrations of target pollutants, demonstrate repeatability over time, and provide results that are traceable to international standards. Accurate calibration is particularly critical in CH settings, where pollutant concentrations often fall within the parts-per-billion or even parts-per-trillion range. High precision is necessary to draw meaningful conclusions about pollutant-related degradation.

Standard calibration setups include gas cylinders or permeation tubes with certified mixtures, a dynamic dilution system to produce known concentrations by mixing pollutant gases with zero air, and a sealed test chamber to expose sensors to controlled gas environments. The chamber often includes temperature and humidity control to simulate museum conditions. Reference instruments such as GC-MS, FTIR, or UV-DOAS serve as the benchmark for verifying sensor responses. Calibration protocols are tailored to each sensor type. Electrochemical sensors are calibrated using certified gases in both dry and humidified air. A two-step process is followed: zero calibration using clean air and span calibration using known concentrations (e.g., 100 ppb NO_2). Multi-point calibration curves are created to correct for non-linear response patterns[129]. Photoionization detectors (PIDs) are calibrated using certified reference gas mixtures, typically based on isobutylene. Calibration involves exposing the PID sensor to known concentrations of isobutylene under controlled temperature and humidity conditions to generate baseline ionization response curves. Since PIDs measure total VOCs and are sensitive to ionization potential rather than compound identity, correction factors are applied for other VOCs based on their relative ionization energies. To ensure accuracy, calibration is repeated at multiple concentrations and under varying humidity levels, as water vapor is known to interfere with UV ionization. Maintenance of the UV lamp, including regular cleaning and periodic replacement, is also essential to prevent signal degradation and ensure calibration reliability as reported by Ion Science and Industrial Scientific.

MOS sensors require extended stabilization times and are calibrated under realistic environmental conditions to account for signal drift. Known VOC mixtures, such as ethanol and formaldehyde, are used for calibration, and in some cases, regression models or machine learning algorithms are applied to differentiate between overlapping gas responses[124].

QCM sensors are calibrated by exposing them to gravimetrically deposited masses or to vapours of known acid concentrations. The change in resonant frequency is plotted against the mass of the adsorbed pollutant. Temperature and humidity compensation is applied to isolate true frequency shifts due to pollutant interaction[125].

For SPME-GC/MS calibration, standard addition or external calibration with reference compounds is used. Calibration curves relate the peak area obtained from GC analysis to the concentration of each compound in $\mu g/m^3$. Proper control of fibre exposure time, temperature, and desorption conditions is necessary to ensure reproducibility[111].

Optical sensors using techniques like NDIR or UV absorption require calibration with gas cells containing certified concentrations of target pollutants. Dual-channel or reference-beam designs are used to correct for signal drift. Where necessary, desiccants or compensation algorithms are used to address humidity interference[77]. Environmental factors such as temperature and relative humidity have a measurable impact on all sensor types. Relative humidity influence adsorption processes and the conductivity of materials, particularly in MOS and electrochemical sensors. Temperature variations affect gas phase reactivity and material properties, leading to baseline drift in QCM or corrosion-based sensors. Cross-sensitivities—such as the reaction of electrochemical H_2S sensors to SO_2—also introduce complications that required adjustment during calibration.

To address these challenges, calibration is performed across the expected environmental operating range, and compensation algorithms are applied where available. Sensor accuracy and consistency are enhanced by referencing international standards such as ISO 16000-29 for VOC sensor calibration and EN 14662-3 (cancelled) for aldehyde monitoring. In the United States, guidelines like ASHRAE 62.1[34] helps define indoor air quality benchmarks for CH environments.

Funded by the European Union

Post-calibration validation include cross comparisons with reference instruments, duplicate and blank sample testing, and the use of control charts to monitor drift over time. Electrochemical sensors typically require recalibration every 6 to 12 months, while QCM and optical systems can extend up to 24 months with proper maintenance and validation. This ensures sustained data integrity and confidence in long-term pollutant monitoring.

In summary, standardization of calibration protocols under CH-specific conditions remains critical. In particular, controlled exposure to acetic acid should be included in protocols, given its prominence in microenvironments like display cases[16, 111]. Further research should also explore correlations between pollutant concentrations and material degradation rates, strengthening the predictive value of sensor outputs in conservation planning[1, 108, 130].

Environmental Factors and Cross-Sensitivities

Environmental variables significantly influence the accuracy and reliability of gas sensor performance. Among the most critical factors are relative humidity (RH), temperature, and the presence of interfering gases.

Relative humidity affects the adsorption properties of sensing surfaces and alters electrochemical reaction kinetics. This is particularly true for Metal Oxide Semiconductor (MOS) and electrochemical sensors, where variations in RH can lead to false readings or signal suppression. Elevated RH levels may alter the sensor's baseline or cause drift, requiring the use of humidity correction algorithms or colocated RH sensors for compensation.

Temperature also plays a substantial role in modifying gas-phase reactivity and sensor material behavior. For example, fluctuations in ambient temperature can cause baseline drift in MOS sensors or affect the resonance frequency of Quartz Crystal Microbalance (QCM) sensors. Corrosion-based sensors using metal coupons are similarly affected, as temperature influences the rate of oxidation and corrosion reactions.

Cross-sensitivities present another challenge, particularly for electrochemical and MOS technologies. These sensors may exhibit responses to gases other than their primary targets. For example, an H_2S sensor may also show sensitivity to SO_2 or other sulfur-containing compounds. Such responses can lead to overestimation or misidentification of pollutants unless appropriate compensation methods are applied.

To mitigate these influences, sensor calibration must be conducted across the expected range of temperature and humidity conditions typical of the deployment environment. Advanced systems incorporate environmental compensation models, while others require empirical adjustment based on laboratory calibration data.

Use of Reference Standards

To ensure the accuracy and comparability of sensor data, all calibration procedures must be traceable to recognized national or international standards. This traceability establishes a verifiable link between the measurement results and certified reference materials or procedures, such as those from the Standard Organisations ISO and NIST.

Calibration of VOC sensors, for example, is typically conducted in accordance with ISO 16000-29:2014, which defines the procedure for evaluating performance characteristics and ensuring consistency across instruments. For aldehydes monitoring—commonly required in conservation environments—EN 14662-3 provides a standardized method using active sampling with 2,4-dinitrophenylhydrazine (DNPH) cartridges.

In addition to ISO and European standards, U.S.-based guidelines such as ASHRAE 62.1[34] offer benchmarks for acceptable indoor air quality, including permissible concentrations for common pollutants. These standards provide valuable targets for conservation environments and help define the conditions under which sensors must operate.

Utilizing reference-grade calibration gases (e.g., ISO 6145-certified or NIST-traceable gas cylinders) is essential during the setup and validation phases. These gases provide known concentrations of analytes in air or nitrogen, allowing precise and reproducible calibration curves to be established.

Validation and Quality Assurance

After calibration, sensors must undergo a validation process to ensure that their performance aligns with the expected standards under field conditions. One of the primary methods of validation is intercomparison with reference-grade instruments, such as co-location studies where sensors are deployed alongside GC-MS, UV-DOAS, or chemiluminescence analysers. These intercomparisons help identify systematic biases and quantify deviations from accepted reference values. In addition to reference comparisons, blank and duplicate sampling protocols are used to assess system stability and data quality. Blanks help detect contamination or background interference, while duplicate measurements assess repeatability. These practices are especially important when passive samplers or long-term deployments are involved.

Control charts are another essential tool in quality assurance. By plotting sensor readings over time against control limits, users can identify drift, step changes, or trends indicating sensor degradation. These charts are particularly useful for tracking long-term stability in sensors deployed in CH environments, where subtle changes may signal pollutant accumulation or environmental shifts. Routine recalibration is critical to maintaining data reliability. Electrochemical sensors typically require recalibration every 6 to 12 months due to changes in electrolyte concentration and electrode degradation. QCM and optical sensors may remain stable for longer periods—up to 1 to 2 years—provided they are operated within recommended environmental conditions and subjected to regular validation checks. Establishing a preventive maintenance schedule and maintaining detailed calibration records is vital to ensure traceability and long-term sensor performance.

3.2.5 *Remote monitoring with commercially available systems and wireless sensors*

Remote monitoring systems have become an indispensable component of environmental management in CH organisations, offering continuous, automated, and unobtrusive control of air quality parameters. A variety of commercial IAQ monitoring systems are now available that are specifically adapted for use in GLAMs environments. These systems integrate sensing technology, data communication protocols, and cloud-based analytics to deliver real-time insight into microclimatic conditions, supporting both preventive conservation and facility operations.

A hallmark of these systems is their ability to provide around-the-clock surveillance of environmental parameters such as temperature, RH, dew point, carbon dioxide levels, and TVOC concentrations. They employ calibrated, high-resolution sensors and are equipped with internal memory, remote data access capabilities, and alarm functions that trigger alerts when conditions deviate from predefined thresholds.

One of the central features of these platforms is their real-time notification system, which sends alerts through multiple communication channels, including SMS and email. This enables conservation staff to respond promptly to environmental deviations—whether caused by HVAC failure, visitor-induced load, or unplanned activities such as cleaning or installation. These systems help bridge the gap between environmental monitoring and operational response, allowing timely intervention before damage occurs.

Cloud-based dashboards associated with remote IAQ systems offer substantial benefits. They provide an intuitive interface for visualizing environmental trends, setting alarm conditions, and generating reports.

Data is stored in secure servers, allowing for remote access and historical comparisons. This level of accessibility facilitates collaborative conservation efforts, enabling curators, conservators, and facility managers to work from different locations while maintaining oversight of the environmental conditions impacting collections.

Integration with building automation systems, including HVAC and lighting control, allows these monitoring platforms to trigger automatic adjustments based on real-time readings. Such integration supports conservation best practices by ensuring that environmental conditions remain within tight tolerances even in the absence of staff intervention.

Case studies from museums across Europe and North America have demonstrated the utility of these systems in reducing environmental fluctuations. For instance, fluctuations in RH and temperature during seasonal transitions have been minimized through automated HVAC corrections initiated by monitoring system alerts. Moreover, in GLAMs where pollutant-generating activities occur—such as exhibit renovations or material testing—elevated VOC concentrations can be identified and mitigated in real time.

One of the leading solutions in this domain is the ExactAire® system developed by Polygon Group, which has been specifically tailored for CH environments such as GLAMs. The system enables continuous measurement, analysis, and reporting of key environmental parameters, contributing significantly to preventive conservation strategies.

The ExactAire system is designed to function as a fully networked, cloud-connected platform capable of capturing real-time data on temperature, relative humidity, dew point, and TVOCs. Sensors are calibrated to high standards and operate continuously, offering a level of granularity that allows conservation professionals and facility managers to track short-term fluctuations as well as long-term trends.

The ExactAire system also supports integration with building automation infrastructure. Using industry-standard protocols such as BACnet/IP, the system can interface directly with HVAC systems and lighting controls. This enables automated environmental responses—such as adjusting airflow, activating filtration, or modifying lighting conditions based on real-time sensor output.

Overall, the system's data-driven framework supports sustainable preservation by shifting conservation efforts from reactive to proactive. Predictive analytics, historical trend visualization, and cross-site performance comparisons empower institutions to implement long-term strategies that extend the life of their collections and reduce the risk of damage caused by environ-mental instability.

In conclusion, modern remote monitoring platforms have become integral to the infrastructure of environmental control in heritage institutions. Their ability to detect, communicate, and respond to air quality threats in real time enhances the institution's capacity for preventive conservation, reduces reliance on manual intervention, and provides data-driven evidence to guide environmental management decisions.

Several wireless sensor platforms also demonstrate high utility for CH applications. Airthings' Monitair system offers sensors for RH, CO_2, VOCs, and radon, operating over LTE and LoRaWAN for wide coverage, ideal for retrofitted historical buildings. Vaisala's RFL100 provides highly accurate temperature and humidity readings via its proprietary VaiNet protocol, with long battery life and cloud connectivity. Onset's HOBO MX1101 uses Bluetooth Low Energy for localized RH and temperature logging, often employed in microclimates like display cases. Systems by SenseWay and Libelium utilize LoRaWAN to monitor pollutants over large museum complexes, while Conserv Cloud by Conserv.io integrates Zigbee sensors with conservation-focused risk analytics.

Wireless sensor systems offer major benefits to CH organisations. Their non-invasive installation makes them especially suitable for historic buildings where structural alterations are restricted. Scalability is another advantage, allowing sensors to be relocated or expanded based on conservation needs. These systems are

Funded by the European Union

typically energy-efficient, with many operating for years on battery power. Real-time monitoring and alerting capabilities enable rapid response to environmental threats, reducing reliance on manual checks and improving long-term conservation outcomes through continuous, data-informed oversight.

While the benefits of wireless systems are clear, CCIs must also plan for challenges such as signal interference in historic buildings, data security, and alignment with institutional governance policies. Ensuring full integration with HVAC or BMS systems is also crucial to leverage the potential for automated environmental control and minimize manual intervention.

3.2.6 *Challenges in Monitoring and implementing new technologies*

Implementing effective indoor air quality (IAQ) monitoring systems in CH environments presents several practical and technical challenges. While sensor technology has advanced significantly in recent years, the reliability and interpretability of sensor output remain heavily influenced by environmental variables and operational constraints. Key challenges identified during this study include environmental interferences, sensor drift, and the need for robust validation protocols.

One of the most significant challenges in pollutant monitoring is the influence of environmental conditions—particularly RH and temperature—on sensor accuracy. High RH levels, especially those exceeding 60%, are found to suppress or distort sensor responses. For instance, PID and MOS sensors show measurable signal deviation under elevated humidity, requiring the use of humidity compensation algorithms or parallel RH measurements to normalize data. Similarly, temperature fluctuations affect the conductivity of MOS sensors and the electrochemical activity in electrochemical sensors, leading to baseline drift and decreased sensitivity. These findings underscore the importance of climate stabilization in CH settings, not only for preservation but also for reliable data collection.

An additional challenge identified during sensor selection and deployment is the difficulty of accurately detecting acidic gases, particularly acetic acid. Many commonly used sensor technologies, such as MOS and PID sensors, lack the specificity or sensitivity needed to detect acetic acid at low concentrations typical in GLAMs. Acetic acid has low vapor pressure and high polarity and is therefore less detectable with broad-spectrum VOC sensors. Electrochemical sensors for acid gases are rare, and PIDs can only detect acetic acid weakly due to its high ionization potential. This limitation underscores the need for specialized detection methods such as adsorptive dosimeters, QCM sensors with functional coatings, or passive samplers analyzed via chromatography. Sensor selection for environments where acetic acid is likely—such as sealed cases containing wood or acetate-based materials—must account for this gap in sensor capability[108, 122, 130].

Sensor drift is another critical issue, particularly for low-cost sensors intended for long-term deployment. Electrochemical sensors experience baseline shifts over time due to changes in electrolyte concentration and electrode degradation. Without periodic recalibration, these changes compromise the accuracy and consistency of measurements. MOS sensors also display drift, particularly under cyclical temperature conditions, further emphasizing the need for scheduled recalibration and drift-correction algorithms.

Validation of sensor data is essential to ensure credibility in conservation decision-making. Cross-comparisons between deployed sensors and laboratory reference instruments such as GC-MS and UV-DOAS are essential for identifying and correcting systematic biases in sensor output. Without such cross-referencing, low-cost sensors risk producing misleading data, particularly in environments with complex pollutant profiles or overlapping chemical interferences. However, these cross-comparisons are only possible in the framework of large, multi-consortium and well-supported projects.

Another challenge lies in the complexity of pollutant mixtures and their interactions with sensor materials. For example, H_2S sensors were found to respond to SO_2, leading to false positives unless pre-filters or software-based signal correction was implemented. In environments where multiple reactive gases are present, sensor specificity becomes a limitation, complicating the attribution of measured values to specific compounds.

Operational constraints such as power supply, data logging, and network reliability also impact monitoring success. Wireless systems require careful consideration of battery life and signal strength—particularly in historic buildings with thick walls or metallic shielding that inhibited data transmission. These issues necessitate the use of signal repeaters or alternative communication protocols to maintain data continuity.

Despite the benefits of the systems described, several implementation challenges persist. Environmental sensitivity remains a limitation, particularly for MOS and PID sensors, which perform poorly under high humidity or temperature fluctuations[131]. Power management is another concern, especially for wireless networks operating on battery power in locations without easy access to electricity. Signal reliability can be compromised by the dense materials and thick walls common in historic buildings, sometimes requiring repeaters or network redesign. Regular sensor calibration remains essential for ensuring data accuracy, which can be resource-intensive[7, 106, 124].

In summary, successful IAQ monitoring in CCIs demands a multi-faceted approach that addresses both the technological limitations of sensors and the contextual challenges posed by historic environments. Strategies such as environmental compensation, hybrid sensor deployment, regular calibration, and validation against reference methods are essential to ensure the reliability and interpretability of monitoring data. As Canosa & Norrehed[1] and Grzywacz[7] emphasize, layered mitigation and robust data verification are fundamental to effective preventive conservation.

As a conclusion, sensor drift and long-term stability continue to challenge the use of low-cost systems. Adaptive compensation algorithms and sensor redundancy networks are recommended to mitigate these issues and extend operational life[106,123]. Greater interoperability with museum IT systems and building automation infrastructure, facilitated by modular APIs and universal communication standards, would enhance real-time integration and responsiveness.

3.2.7 *Emerging Trends and Future Directions*

Recent innovations are focused on increasing the robustness and efficiency of IAQ systems. Integration with Internet of Things (IoT) frameworks is becoming more widespread, enabling automated data collection and cloud-based control[132]. Simultaneously, efforts are being made to develop low-power, multi-gas sensors that extend battery life while maintaining high performance. Enhanced data analytics and predictive modeling are also on the rise, allowing institutions to shift from reactive maintenance to proactive, condition-based conservation strategies.

Several priorities emerge for future research and system development. There is a growing need for integrated sensor platforms capable of detecting multiple pollutants simultaneously, while maintaining selectivity in complex VOC mixtures. Machine learning algorithms hold promise for improving signal interpretation, particularly in sensors like PIDs and MOS that lack inherent compound specificity[77, 123, 124].

In conclusion, the evolving landscape of sensor technology, analytics, and environmental control systems presents an unprecedented opportunity for CH organisations to build smart, scalable, and proactive IAQ monitoring programs. Future development should continue to align with the dual goals of preserving collections and optimizing operational sustainability.

4. Conclusion and perspectives

Throughout this report, the intent was to provide a thorough and complete account of the state-of-the-art of indoor air quality management in GLAMs. The most problematic gaseous pollutants, their impact on the artefacts and collections, as well as guidelines and recommendations for mitigation strategies are reviewed. The panel of sorbent materials available and their use in passive as well as in active (HVAC) systems for GLAMs are provided in the first part of the report. Based on the main criteria for sorbent selection, it appears that none of them meets all the IAQ requirements, and that a combination of materials is often necessary for the different applications, whether humidity control or pollutants control. Among all the products available on the market, the capabilities of metal–organic frameworks (MOFs) standout. These hybrid porous crystallised materials have emerged in recent years as promising alternatives for targeted pollutant sorption in a variety of industrial and commercial applications. While activated carbon remains the standard choice for most applications, including in CH preservation, due to its low cost and versatility, MOFs offer outstanding future potential for targeted pollutant control strategies. Better compound selectivity, improved performance at very ow concentrations, and higher structural stability are some of their advantages. Noteworthy, not the least benefit will be that these new solutions shall enable substantial 30-50% reduction in the energy consumption usually dedicated to IAQ in GLAMs. However, their long-term performance in CH environments being still unproven, SIMACCI is dedicated to explore such strategies with the partners GLAMs.

The second part of the report, dedicated to monitoring solutions for IAQ control outlines the variety of devices, from simple dosimeters to technically advanced sensors and remote technologies, their advantages and drawbacks, as well as the challenges associated with their implementation in GLAMs. This thorough account will help SIMIACCI make appropriate and well thought-out choices among the wide range of sensors available, to be integrated in smart wireless monitoring systems for IAQ management in GLAMs in a budget-conscious and sustainable fashion.

6. References

(1) Canosa, E.; Norrehed, S. Strategies for Pollutant Monitoring in Museum Environments. **2019**.

(2) Krichmar, S. I.; Bezpalchenko, V. M. A Sensor for Detecting Hydrogen Sulphide in the Atmosphere of Industrial and Laboratory Premises. *Industrial Laboratory* **1995**, *61* (9), 521–522.

(3) Sease, C.; Selwyn, L. S.; Zubiate, S.; Bowers, D. F.; Atkins, D. R. Problems with Coated Silver: Whisker Formation and Possible Filiform Corrosion. *Studies in Conservation* **1997**, *42* (1), 1–10. https://doi.org/10.1179/sic.1997.42.1.1.

(4) Chiantore, O.; Poli, T. Indoor Air Quality in Museum Display Cases: Volatile Emissions, Materials Contributions, Impacts. *Atmosphere* **2021**, *12* (3), 364. https://doi.org/10.3390/atmos12030364.

(5) Vergelli, L.; Frasca, F.; Bertolin, C.; Favero, G.; Siani, A. M. Review of Organic Gaseous Pollutant Concentrations in Indoor Conservation Spaces. *Environmental Pollution* **2025**, *368*, 125829. https://doi.org/10.1016/j.envpol.2025.125829.

(6) Weschler, C. J.; Shields, H. C.; Naik, D. V. Indoor Ozone Exposures. *JAPCA* **1989**, *39* (12), 1562–1568. https://doi.org/10.1080/08940630.1989.10466650.

(7) Grzywacz, C. M. *Monitoring for Gaseous Pollutants in Museum Environments*. https://www.getty.edu/conservation/publications_resources/pdf_publications/monitoring_gaseous.html (accessed 2023-02-02).

(8) Grøntoft, T.; Odlyha, M.; Mottner, P.; Dahlin, E.; Lopez-Aparicio, S.; Jakiela, S.; Scharff, M.; Andrade, G.; Obarzanowski, M.; Ryhl-Svendsen, M.; Thickett, D.; Hackney, S.; Wadum, J. Pollution Monitoring by Dosimetry and Passive Diffusion Sampling for Evaluation of Environmental Conditions for Paintings in Microclimate Frames. *Journal of Cultural Heritage* **2010**, *11* (4), 411–419. https://doi.org/10.1016/j.culher.2010.02.004.

(9) Ryhl-Svendsen, M. The Role of Air Exchange Rate and Surface Reaction Rates on the Air Quality in Museum Storage Buildings. In *Museum Microclimates: Contributions to the Copenhagen Conference 19 – 23 November*; Padfield, T., Borchersen, K., Eds.; National Museum of Denmark: Copenhagen, 2007; pp 221–226.

(10) Blades, N.; Kruppa, D.; Henriksen, J.; Grøntoft, T.; Brimblecombe, P.; Raychaudhuri, M.; Smith, S.; Czop, J.; Obarzanowski, M. *Innovative Modelling of Museum Pollution and Conservation Thresholds (IMPACT)*; European Commission; Final project report EVK4-CT-2000–00031; 2004.

(11) Shashoua, Y. *Conservation of Plastics*, 1st ed.; Routledge: London, 2008. https://doi.org/10.4324/9780080878782.

(12) Quye, A.; Littlejohn, D.; Pethrick, R. A.; Stewart, R. A. Investigation of Inherent Degradation in Cellulose Nitrate Museum Artefacts. *Polymer Degradation and Stability* **2011**, *96* (7), 1369–1376. https://doi.org/10.1016/j.polymdegradstab.2011.03.009.

(13) Grosjean, D.; Grosjean, E.; Williams, E. L. Fading of Artists' Colorants by a Mixture of Photochemical Oxidants. *Atmospheric Environment. Part A. General Topics* **1993**, *27* (5), 765–772. https://doi.org/10.1016/0960-1686(93)90194-4.

(14) Whitmore, P. M.; Cass, G. R.; Druzik, J. R. The Ozone Fading of Traditional Natural Organic Colorants on Paper. *Journal of the American Institute for Conservation* **1987**, *26* (1), 45–57. https://doi.org/10.1179/019713687806027906.

(15) Bégin, P.; Deschâtelets, S.; Grattan, D.; Gurnagul, N.; Iraci, J.; Kaminska, E.; Woods, D.; Zou, X. The Effect of Air Pollutants on Paper Stability. *Restaurator* **1999**, *20* (1), 1–21. https://doi.org/10.1515/rest.1999.20.1.1.

(16) Tétreault, J. *Airborne Pollutants in Museums, Galleries, and Archives: Risk Assessment, Control Strategies, and Preservation Management*; Canadian Heritage; Canadian Conservation Institute: Ottawa, 2003.

(17) Lavédrine, B. *A Guide to the Preventive Conservation of Photograph Collections*, B Lavédrine, J-P Gandolfo&S Monod (Eds).; J. Paul Getty Trust: Los Angeles, 2003.

(18) Smith, G. D.; Derbyshire, A.; Clark, R. J. H. In Situ Spectroscopic Detection of Lead Sulphide on a Blackened Manuscript Illumination by Raman Microscopy. *Studies in Conservation* **2002**, *47* (4), 250–256. https://doi.org/10.1179/sic.2002.47.4.250.

(19) Carlyle, L.; Townsend, J. H. An Investigation of Lead Sulphide Darkening of Nineteenth Century Painting Materials. In *Dirt and pictures separated: Papers given at a conference held jointly by UKIC and the Tate Gallery, January 1990*; UKIC: London, UK, 1990; pp 40–43.

(20) Watts, S. F. The Mass Budgets of Carbonyl Sulfide, Dimethyl Sulfide, Carbon Disulfide and Hydrogen Sulfide. *Atmospheric Environment* **2000**, *34* (5), 761–779. https://doi.org/10.1016/S1352-2310(99)00342-8.

(21) Tétreault, J.; Dupont, A.-L.; Bégin, P.; Paris, S. The Impact of Volatile Compounds Released by Paper on Cellulose Degradation in Ambient Hygrothermal Conditions. *Polymer Degradation and Stability* **2013**, *98* (9), 1827–1837. https://doi.org/10.1016/j.polymdegradstab.2013.05.017.

(22) Gibson, L. T.; Watt, C. M. Acetic and Formic Acids Emitted from Wood Samples and Their Effect on Selected Materials in Museum Environments. *Corrosion Science* **2010**, *52* (1), 172–178. https://doi.org/10.1016/j.corsci.2009.08.054.

(23) Niklasson, A.; Langer, S.; Arrhenius, K.; Rosell, L.; Bergsten, C. J.; Johansson, L. G.; Svensson, J. E. Air Pollutant Concentrations and Atmospheric Corrosion of Organ Pipes in European Church Environments. *Studies in Conservation* **2008**, *53* (1), 24–40.

(24) Oikawa, T.; Matsui, T.; Matsuda, Y.; Takayama, T.; Niinuma, H.; Nishida, Y.; Hoshi, K.; Yatagai, M. Volatile Organic Compounds from Wood and Their Influences on Museum Artifact Materials I. Differences in Wood Species and Analyses of Causal Substances of Deterioration. *J Wood Sci* **2005**, *51* (4), 363–369. https://doi.org/10.1007/s10086-004-0654-y.

(25) Dupont, A.-L.; Tetreault, J. Cellulose Degradation in an Acetic Acid Environment. *Studies in Conservation* **2000**, *45* (3), 201–210. https://doi.org/10.1179/sic.2000.45.3.201.

(26) Tennent, N. H.; Baird, T. the identification of acetate efflorescence on bronze antiquities stored in wooden cabinets. *The Conservator* **1992**, *16* (1), 39–47. https://doi.org/10.1080/01400096.1992.9635625.

(27) Gibson, L. T.; Cooksey, B. G.; Littlejohn, D.; Linnow, K.; Steiger, M.; Tennent, N. H. The Mode of Formation of Thecotrichite, a Widespread Calcium Acetate Chloride Nitrate Efflorescence. *Studies in Conservation* **2005**, *50* (4), 284–294. https://doi.org/10.1179/sic.2005.50.4.284.

(28) Thomson, G. *The Museum Environment*, 2nd ed.; Butterworths series in conservation and museology; Butterworths, in association with the International Institute for Conservation of Historic and Artistic Works: London Boston, 1986.

(29) Lee, K.; Vallarino, J.; Dumyahn, T.; Ozkaynak, H.; Spengler, J. D. Ozone Decay Rates in Residences. *Journal of the Air & Waste Management Association* **1999**, *49* (10), 1238–1244. https://doi.org/10.1080/10473289.1999.10463913.

(30) Graedel, T. E. Corrosion Mechanisms for Silver Exposed to the Atmosphere. *J. Electrochem. Soc.* **1992**, *139* (7), 1963–1970. https://doi.org/10.1149/1.2221162.

(31) *Urban Pollution and Changes to Materials and Building Surfaces*; Brimblecombe, P., Ed.; Air pollution reviews; Imperial College Press: Hackensack, NJ, 2016.

(32) Newman, R.; Derrick, M.; Byrne, E.; Tan, M.; Chiantore, O.; Poli, T.; Riedo, C. Strange Events Inside Display Cases at the Museum of Fine Arts, Boston, and Lessons To Be Learned From Them – Part 1. In *Conservation and Exhibition Planning: Material Testing for Design, Display, and Packaging*; Smithsonian American Art Museums and National Portrait Gallery: Washington, D.C., 2015; p 11.

(33) Van Iperen, J.; Van Keulen, H.; Keune, K.; Abdulah, K.; Van Langh, R. Crystalline Deposits in New Display Cases at the Rijksmuseum: Characterisation and Origin. *Studies in Conservation* **2021**, *66* (5), 253–271. https://doi.org/10.1080/00393630.2020.1811475.

(34) ASHRAE. *Heating, Ventilating, and Air-Conditioning Applications-2019 Ashrae handbook*; 2019.

(35) Simon, S.; Bratasz, L. How Little Is Enough – Key Performance Indicators for Energy Consumption and Climate in Memory Institutions. *Michael Imhof Verlag GmbH & Co. KG* **2023**.
(36) Ryhl-Svendsen, M.; Smedemark, S. Environmental Conditions for Danish Storage Buildings: A Summary of 20Years of Air Quality Surveys. *Studies in Conservation* **2024**, *70* (2), 148–169. https://doi.org/10.1080/00393630.2024.2351761.
(37) Bizot GROUP. *The Bizot Green Protocol*; Declaration and guidelines; 2023; p 6.
(38) Bickersteth, J. IIC and ICOM-CC 2014 Declaration on Environmental Guidelines. *Studies in Conservation* **2016**, *61* (sup1), 12–17. https://doi.org/10.1080/00393630.2016.1166018.
(39) Sulaiman, R.; Kamaruzzaman, S. N.; Yau, Y. H. Indoor Air Quality Performance in Air-Conditioned Museum Gallery. *IOP Conf. Ser.: Mater. Sci. Eng.* **2019**, *609* (4), 042098. https://doi.org/10.1088/1757-899X/609/4/042098.
(40) Hisham, M. W. M.; Grosjean, D. Sulfur Dioxide, Hydrogen Sulfide, Total Reduced Sulfur, Chlorinated Hydrocarbons and Photochemical Oxidants in Southern California Museums. *Atmospheric Environment. Part A. General Topics* **1991**, *25* (8), 1497–1505. https://doi.org/10.1016/0960-1686(91)90009-V.
(41) Dabanlis, G.; Loupa, G.; Tsalidis, G. A.; Kostenidou, E.; Rapsomanikis, S. The Interplay between Air Quality and Energy Efficiency in Museums, a Review. *Applied Sciences* **2023**, *13* (9), 5535. https://doi.org/10.3390/app13095535.
(42) Grau-Bové, J.; Strlič, M. Fine Particulate Matter in Indoor Cultural Heritage: A Literature Review. *Herit Sci* **2013**, *1* (1), 8. https://doi.org/10.1186/2050-7445-1-8.
(43) Breitung,. E. *Indoor Air Quality in the Museum Environment*; Report on a workshop sponsored by The Alfred P. Sloan Foundation; NY, 2020; p 26.
(44) Loupa, G.; Dabanlis, G.; Kostenidou, E.; Rapsomanikis, S. Air Quality and Energy Use in a Museum. *Air* **2025**, *3* (1), 5. https://doi.org/10.3390/air3010005.
(45) Nunez-Delgado, A. *Sorbents Materials for Controlling Environmental Pollution: Current State and Trends*; Elsevier: San Diego, 2021.
(46) Cruz, A. J.; Pires, J.; Carvalho, A. P.; Brotas De Carvalho, M. Comparison of Adsorbent Materials for Acetic Acid Removal in Showcases. *Journal of Cultural Heritage* **2008**, *9* (3), 244–252. https://doi.org/10.1016/j.culher.2008.03.001.
(47) Schieweck, A.; Salthammer, T. Indoor Air Quality in Passive-Type Museum Showcases. *Journal of Cultural Heritage* **2011**, *12* (2), 205–213. https://doi.org/10.1016/j.culher.2010.09.005.
(48) Schieweck, A. Adsorbent Media for the Sustainable Removal of Organic Air Pollutants from Museum Display Cases. *Herit Sci* **2020**, *8* (1), 12. https://doi.org/10.1186/s40494-020-0357-8.
(49) Smedemark, S. H.; Ryhl-Svendsen, M.; Toftum, J. Removal of Organic Acids from Indoor Air in Museum Storage Rooms by Active and Passive Sorption Techniques. *Studies in Conservation* **2020**, *65* (5), 251–261. https://doi.org/10.1080/00393630.2020.1754057.
(50) Smedemark, S. H.; Ryhl-Svendsen, M. Indoor Air Pollution in Archives: Temperature Dependent Emission of Formic Acid and Acetic Acid from Paper. *Journal of Paper Conservation* **2020**.
(51) Atkins, P. W.; de Paula, J.; Keeler, J. J. *Atkins' Physical Chemistry*, Eleventh edition.; Oxford University Press: Oxford New York, 2018.
(52) *Air Filtration in HVAC Systems*, 2nd rev. ed.; Gustavsson, J., Ginestet, A., Tronville, P., Hyttinen, M., Federation of European Heating and Airconditioning Associations, Eds.; REHVA guidebook; REHVA, Federation of European Heating, Ventilation and Air-conditioning Associations: Brussels, Belgium, 2011.
(53) Rouquerol, F.; Rouquerol, J.; Sing, K. S. W.; Llewellyn, P. L.; Maurin, G. *Adsorption by Powders and Porous Solids: Principles, Methodology and Applications*, Second edition.; Elsevier/AP: Amsterdam, 2014.
(54) Rettner, C. T.; Auerbach, D. J.; Tully, J. C.; Kleyn, A. W. Chemical Dynamics at the Gas−Surface Interface. *J. Phys. Chem.* **1996**, *100* (31), 13021–13033. https://doi.org/10.1021/jp9536007.

(55) Canosa, E.; Norrehed, S. *Strategies for Pollutant Monitoring in Museum Environments*; Riksantikvarieämbetet, 2019; p 66.

(56) Shashoua, Y.; Shilling, M.; Mazurek, J. The Effectiveness of Conservation Adsorbents at Inhibiting Degradation of Cellulose Acetate. In *Preprints ICOM-CC 17th triennial conference: "Building strong culture through conservation", 15-19 September 2014, Melbourne, Australia*; Bridgland, J., Ed.; International Council of Museums (ICOM): Paris, 2014.

(57) Tétreault, J. *Control of Pollutants in Museums and Archives*; Technical Bulletin 37; Technical Bulletin; Canadian Conservation Institute. https://www.canada.ca/en/conservation-institute/services/conservation-preservation-publications/technical-bulletins/pollutants-museums-archives.html.

(58) Thickett, D. Better Use of Showcases for Preservation and Sustainability. *Studies in Conservation* **2022**, *67* (sup1), 267–276. https://doi.org/10.1080/00393630.2022.2066309.

(59) Grøntoft, T.; Lankester, P.; Thickett, D. Reduction of Acidic Pollutant Gases Inside Showcases by the Use of Activated Carbon Adsorbers. *e-Preservation Science* **2015**, *12*, 28–37.

(60) Mondal, S.; De, S.; Saha, P. Removal of VOCs and Improvement of Indoor Air Quality Using Activated Carbon Air Filter. In *Advances in Structural Technologies*; Adhikari, S., Dutta, A., Choudhury, S., Eds.; Lecture Notes in Civil Engineering; Springer Singapore: Singapore, 2021; Vol. 81, pp 123–132. https://doi.org/10.1007/978-981-15-5235-9_10.

(61) Kumar, P.; Kim, K.-H.; Mehta, P. K.; Ge, L.; Lisak, G. Progress and Challenges in Electrochemical Sensing of Volatile Organic Compounds Using Metal-Organic Frameworks. *Critical Reviews in Environmental Science and Technology* **2019**, *49* (21), 2016–2048. https://doi.org/10.1080/10643389.2019.1601489.

(62) Joo, J.-H.; Kim, S.-H.; Kim, J. H.; Kang, H.-J.; Lee, J. H.; Jeon, H.-J.; Jang, Y. H.; Lee, J.-H.; Lee, S.-Y.; Park, S.-J.; Seo, M.-K. Recent Advances in Activated Carbon Fibers for Pollutant Removal. *Carbon Lett.* **2025**, *35* (1), 21–44. https://doi.org/10.1007/s42823-024-00803-4.

(63) Li, X.; Zhang, L.; Yang, Z.; Wang, P.; Yan, Y.; Ran, J. Adsorption Materials for Volatile Organic Compounds (VOCs) and the Key Factors for VOCs Adsorption Process: A Review. *Separation and Purification Technology* **2020**, *235*, 116213. https://doi.org/10.1016/j.seppur.2019.116213.

(64) Jonathan Y Chen, Ed. *Activated Carbon Fiber and Textiles*; Woodhead publishing series in textiles; Woodhead Publishing: Duxford, UK, 2017.

(65) Tao, H.; Mei, T.; Cheng, H. Graphene-Based Materials for the Removal of Volatile OrganicCompounds. *RICE* **2022**, *15* (3), 159–168. https://doi.org/10.2174/2405520415666220817122440.

(66) Nehra, S.; Sharma, R.; Kumar, D. Removal of Air Pollutants Using Graphene Nanocomposite. In *Environmental Remediation Through Carbon Based Nano Composites*; Jawaid, M., Ahmad, A., Ismail, N., Rafatullah, M., Eds.; Green Energy and Technology; Springer Nature Singapore: Singapore, 2021; pp 275–291. https://doi.org/10.1007/978-981-15-6699-8_13.

(67) Yu, L.; Wang, L.; Xu, W.; Chen, L.; Fu, M.; Wu, J.; Ye, D. Adsorption of VOCs on Reduced Graphene Oxide. *Journal of Environmental Sciences* **2018**, *67*, 171–178. https://doi.org/10.1016/j.jes.2017.08.022.

(68) Gulati, S.; Lingam B, H. N.; Kumar, S.; Goyal, K.; Arora, A.; Varma, R. S. Improving the Air Quality with Functionalized Carbon Nanotubes: Sensing and Remediation Applications in the Real World. *Chemosphere* **2022**, *299*, 134468. https://doi.org/10.1016/j.chemosphere.2022.134468.

(69) Tan, X.; Liu, S.; Liu, Y.; Gu, Y.; Zeng, G.; Hu, X.; Wang, X.; Liu, S.; Jiang, L. Biochar as Potential Sustainable Precursors for Activated Carbon Production: Multiple Applications in Environmental Protection and Energy Storage. *Bioresource Technology* **2017**, *227*, 359–372. https://doi.org/10.1016/j.biortech.2016.12.083.

(70) Sadegh, F.; Sadegh, N.; Wongniramaikul, W.; Apiratikul, R.; Choodum, A. Adsorption of Volatile Organic Compounds on Biochar: A Review. *Process Safety and Environmental Protection* **2024**, *182*, 559–578. https://doi.org/10.1016/j.psep.2023.11.071.

(71) Wu, L.; Zhu, Y.; Yuan, J.; Guo, X.; Zhang, Q. Advances in Adsorption, Absorption, and Catalytic Materials for VOCs Generated in Typical Industries. *Energies* **2024**, *17* (8), 1861. https://doi.org/10.3390/en17081861.

(72) U. S. Environmental Protection Agency (EPA). *Choosing an Adsorption System for VOC: Carbon, Zeolite, or Pol*; Office of Air Quality, P. and S., Series Ed.; 456/F-99–004; Clean Air Technology Center, U. S. Environmental Protection Agency (EPA): Research Triangle Park, North Carolina, U. S, 1999; p 32.

(73) Lu, S.; Liu, Q.; Han, R.; Guo, M.; Shi, J.; Song, C.; Ji, N.; Lu, X.; Ma, D. Potential Applications of Porous Organic Polymers as Adsorbent for the Adsorption of Volatile Organic Compounds. *Journal of Environmental Sciences* **2021**, *105*, 184–203. https://doi.org/10.1016/j.jes.2021.01.007.

(74) Cosseron, A.-F.; Daou, T. J.; Tzanis, L.; Nouali, H.; Deroche, I.; Coasne, B.; Tchamber, V. Adsorption of Volatile Organic Compounds in Pure Silica CHA, ∗BEA, MFI and STT-Type Zeolites. *Microporous and Mesoporous Materials* **2013**, *173*, 147–154. https://doi.org/10.1016/j.micromeso.2013.02.009.

(75) Yu, Q.; Li, J.; Liu, W.; Wang, Y.; Chu, W.; Zhang, X.; Xu, L.; Zhu, X.; Li, X. Rational Design of a Novel Silica-Based Material with Abundant Open Micropores for Efficient VOC Removal. *Chemical Engineering Journal* **2023**, *454*, 140077. https://doi.org/10.1016/j.cej.2022.140077.

(76) Andre, R. S.; Sanfelice, R. C.; Pavinatto, A.; Mattoso, L. H. C.; Correa, D. S. Hybrid Nanomaterials Designed for Volatile Organic Compounds Sensors: A Review. *Materials & Design* **2018**, *156*, 154–166. https://doi.org/10.1016/j.matdes.2018.06.041.

(77) Kraševec, I.; Markelj, J.; Elnaggar, A.; Cigić, I. K. Indoor Air Pollutants and Their Seasonal Monitoring in European Museums. *Herit Sci* **2024**, *12* (1), 50. https://doi.org/10.1186/s40494-024-01164-x.

(78) Kraševec, I.; Menart, E.; Strlič, M.; Kralj Cigić, I. Validation of Passive Samplers for Monitoring of Acetic and Formic Acid in Museum Environments. *Herit Sci* **2021**, *9* (1), 19. https://doi.org/10.1186/s40494-021-00495-3.

(79) Rocchetti, A.; Lippi, M.; Socci, L.; Gullo, P.; Khorshidi, V.; Talluri, L. Metal-Organic Framework Adsorbent Materials in HVAC Systems: General Survey and Theoretical Assessment. *Energies* **2022**, *15* (23), 8908. https://doi.org/10.3390/en15238908.

(80) Ding, D.; Qin, M. Comparative Study of Metal-Organic Frameworks (MOFs) for Indoor Moisture Control. *Applied Thermal Engineering* **2024**, *257*, 124329. https://doi.org/10.1016/j.applthermaleng.2024.124329.

(81) Paolin, E.; Strlič, M. Volatile Organic Compounds (VOCs) in Heritage Environments and Their Analysis: A Review. *Applied Sciences* **2024**, *14* (11), 4620. https://doi.org/10.3390/app14114620.

(82) Nicholson, C; O'Loughlin, E. The Use of A-D Strips for Screening Conservation and Exhibit Materials. *The Book and Paper Group Annual* **1996**, *15*, 83–85.

(83) Hackney, S. Colour Measurement of Acid-Detector Strips for the Quantification of Volatile Organic Acids in Storage Conditions. *Studies in Conservation* **2016**, *61* (sup1), 55–69. https://doi.org/10.1080/00393630.2016.1140935.

(84) Townsend, J. H.; Hackney, S.; Kearney, M. A Critical Assessment of A-D Strips® Used in Degradation Studies of Artworks Made from Cellulose Acetate. *Studies in Conservation* **2023**, *68* (1), 9–17. https://doi.org/10.1080/00393630.2021.1996091.

(85) Tétreault, J. Control of Pollutants in Museums and Archives – Technical Bulletin 37.

(86) Tétreault, J. La Mesure de l'acidité Des Produits Volatils - Measuring the Acidity of Volatile Products. *Journal of IIC-CG* **1992**, *17*, 17–25.

(87) Ryhl-Svendsen, M. An Elastomer Dosimeter for Monitoring Ozone Exposures in Museum Storage Rooms; Braunschweig, Germany, 2006.

(88) Green, L. R.; Thickett, D. Testing Materials for Use in the Storage and Display of Antiquities: A Revised Methodology. *Studies in Conservation* **1995**, *40* (3), 145. https://doi.org/10.2307/1506472.

(89) Bamberger, J. A.; Howe, E. G.; Wheeler, G. A Variant Oddy Test Procedure for Evaluating Materials Used in Storage and Display Cases. *Studies in Conservation* **1999**, *44* (2), 86–90. https://doi.org/10.1179/sic.1999.44.2.86.

(90) Robinet, L.; Thickett, D. A New Methodology for Accelerated Corrosion Testing. *Studies in Conservation* **2003**, *48* (4), 263–268.

(91) Korenberg, C.; Keable, M.; Phippard, J.; Doyle, A. Refinements Introduced in the Oddy Test Methodology. *Studies in Conservation* **2018**, *63* (1), 2–12. https://doi.org/10.1080/00393630.2017.1362177.

(92) Wang, S.; Kong, L.; An, Z.; Chen, J.; Wu, L.; Zhou, X. An Improved Oddy Test Using Metal Films. *Studies in Conservation* **2011**, *56* (2), 138–153. https://doi.org/10.1179/sic.2011.56.2.138.

(93) Long, E. R.; Bone, A.; Breitung, E. M.; Thickett, D.; Grau-Bové, J. Automated Corrosion Detection in Oddy Test Coupons Using Convolutional Neural Networks. *Herit Sci* **2022**, *10* (1), 150. https://doi.org/10.1186/s40494-022-00778-3.

(94) Tétreault, J.; Sirois, J.; Stamatopoulou, E. Studies of Lead Corrosion in Acetic Acid Environments. *Studies in Conservation* **1998**, *43* (1), 17–32. https://doi.org/10.1179/sic.1998.43.1.17.

(95) Thickett, D.; Grøntoft, T. Review of Interpreting Gaseous Pollution Data Regarding Heritage Objects. *Heritage* **2023**, *6* (10), 6917–6930. https://doi.org/10.3390/heritage6100361.

(96) Thickett, D.; Chisholm, R.; Lankester, P. REACTIVITY MONITORING OF ATMOSPHERES.

(97) Díaz, I.; Cano, E. Quantitative Oddy Test by the Incorporation of the Methodology of the ISO 11844 Standard: A Proof of Concept. *Journal of Cultural Heritage* **2022**, *57*, 97–106. https://doi.org/10.1016/j.culher.2022.08.001.

(98) Oddy, A. Ed. Butterworth—Heinemann Series in Conservation and Museology. In *The Museum Environment*; Elsevier, 1986; p ii. https://doi.org/10.1016/B978-0-7506-1266-1.50001-9.

(99) Díaz, I.; Alvarez-Martin, A.; Grau-Bové, J.; Norrehed, S.; Salvadori, B.; Kraševec, I.; Duran-Romero, D.; Cano, E. Review and Interlaboratory Comparison of the Oddy Test Methodology. *Herit Sci* **2024**, *12* (1), 95. https://doi.org/10.1186/s40494-024-01174-9.

(100) Buscarino, I. C.; Stephens, C. H.; Breitung, E. M. *Oddy Test Protocol at the Metropolitan Museum of Art (The Met)*; 20190226_OT _1; 2021; p 21. https://www.conservation-wiki.com/wiki/Oddy_Test_Protocols.

(101) Stephens, C. H.; Buscarino, I.; Breitung, E. Updating the Oddy Test: Comparison with Volatiles Identified Using Chromatographic Techniques. *Studies in Conservation* **2018**, *63* (sup1), 425–427. https://doi.org/10.1080/00393630.2018.1471887.

(102) Heine, H.; Jeberien, A. Oddy Test Reloaded: Standardized Test Equipment and Evaluation Methods for Accelerated Corrosion Testing. *Studies in Conservation* **2018**, *63* (sup1), 362–365. https://doi.org/10.1080/00393630.2018.1486093.

(103) Grøntoft, T.; Dahlin, E. The MEMORI Technology - An Innovative Tool for the Protection of Movable Cultural Assets. In *Progress in cultural heritage preservation: 4th International Conference, EuroMed 2012: Limassol, Cyprus, October 29-November 3, 2012: proceedings*; Ioannides, M., Ed.; Lecture notes in computer science; Springer: Berlin ; New York, 2012; pp 756–764.

(104) Grøntoft, T. Performance Evaluation For Museum Enclosures. Measurement, Modelling and Mitigation of Pollutant Impact on Objects in Museum Enclosures. **2012**.

(105) Tétreault, J. *Lutte contre les polluants dans les musées et les archives – Bulletin technique 37*. https://www.canada.ca/fr/institut-conservation/services/publications-conservation-preservation/bulletins-techniques/polluants-musees-archives.html (accessed 2023-02-08).

(106) Clements, A. L.; Griswold, W. G.; Rs, A.; Johnston, J. E.; Herting, M. M.; Thorson, J.; Collier-Oxandale, A.; Hannigan, M. Low-Cost Air Quality Monitoring Tools: From Research to Practice (A Workshop Summary). *Sensors* **2017**, *17* (11), 2478. https://doi.org/10.3390/s17112478.

(107) Schieweck Alexandra. AIRBORNE POLLUTANTS IN MUSEUM SHOWCASES – Material Emissions, Influences, Impact on Artworks. Dr. rer. nat., Hochschule für Bildende Künste Dresden, Dresden, 2009.

(108) Hatchfield, P. *Pollutants in the Museum Environment: Practical Strategies for Problem Solving in Design, Exhibition and Storage*, Reprinted ; Archetype Publications: London, 2005.

(109) Szulczyński, B.; Gębicki, J. Currently Commercially Available Chemical Sensors Employed for Detection of Volatile Organic Compounds in Outdoor and Indoor Air. *Environments* **2017**, *4* (1), 21. https://doi.org/10.3390/environments4010021.

(110) Odlyha, M.; Slater, J. M.; Grøntoft, T.; Jakiela, S.; Obarzanowski, M.; Thickett, D.; Hackney, S.; Andrade, G.; Wadum, J.; Christensen, A. H.; Scharff, M. A Portable Tool for the Evaluation of Microclimate Conditions within Museum Enclosures, Transit Frames, and Transport Cases. *Studies in Conservation* **2018**, *63* (sup1), 407–410. https://doi.org/10.1080/00393630.2018.1499841.

(111) Alvarez-Martin, A.; Kavich, G. SPME-GC–MS for the off-Gassing Analysis of a Complex Museum Object. *Microchemical Journal* **2021**, *167*, 106276. https://doi.org/10.1016/j.microc.2021.106276.

(112) Gibson, L. T.; Ewlad-Ahmed, A.; Knight, B.; Horie, V.; Mitchell, G.; Robertson, C. J. Measurement of Volatile Organic Compounds Emitted in Libraries and Archives: An Inferential Indicator of Paper Decay? *Chemistry Central Journal* **2012**, *6* (1), 42. https://doi.org/10.1186/1752-153X-6-42.

(113) Godoi, A. F. L.; Van Vaeck, L.; Van Grieken, R. Use of Solid-Phase Microextraction for the Detection of Acetic Acid by Ion-Trap Gas Chromatography–Mass Spectrometry and Application to Indoor Levels in Museums. *Journal of Chromatography A* **2005**, *1067* (1–2), 331–336. https://doi.org/10.1016/j.chroma.2004.12.054.

(114) Lattuati-Derieux, A.; Thao-Heu, S.; Lavédrine, B. Assessment of the Degradation of Polyurethane Foams after Artificial and Natural Ageing by Using Pyrolysis-Gas Chromatography/Mass Spectrometry and Headspace-Solid Phase Microextraction-Gas Chromatography/Mass Spectrometry. *Journal of Chromatography A* **2011**, *1218* (28), 4498–4508. https://doi.org/10.1016/j.chroma.2011.05.013.

(115) Lattuati-Derieux, A.; Egasse, C.; Thao-Heu, S.; Balcar, N.; Barabant, G.; Lavédrine, B. What Do Plastics Emit? HS-SPME-GC/MS Analyses of New Standard Plastics and Plastic Objects in Museum Collections. *Journal of Cultural Heritage* **2013**, *14* (3), 238–247. https://doi.org/10.1016/j.culher.2012.06.005.

(116) Lattuati-Derieux, A.; Bonnassies-Termes, S.; Lavédrine, B. Identification of Volatile Organic Compounds Emitted by a Naturally Aged Book Using Solid-Phase Microextraction/Gas Chromatography/Mass Spectrometry. *Journal of Chromatography A* **2004**, *1026* (1–2), 9–18. https://doi.org/10.1016/j.chroma.2003.11.069.

(117) Gibson, L. T.; Watt, C. M. Acetic and Formic Acids Emitted from Wood Samples and Their Effect on Selected Materials in Museum Environments. *Corrosion Science* **2010**, *52* (1), 172–178. https://doi.org/10.1016/j.corsci.2009.08.054.

(118) ADEME. *Passive Samplers For Nitrogen Dioxide*; ADEME Éditions, Paris, 2002; Réf. : 4414; Agence de l'Environnement et de la Maîtrise de l'Énergie Direction de l'Air et des Transports, Département Air; p 144.

(119) Dubus, M.; Asensi Amoros, V.; Bouvet, S.; Brarda-Wieber, J-M.; Colson, I.; Dupont, A-L.; Lattuati-Derieux, A.; Lavier, C.; Le Bourg, E.; Nguyen, T-P.; Rogaume, C.; Rottier, V. Composés Organiques Volatils Émis Par Les Boîtes d'archives Anciennes En Bois. *Support Tracé* **2015**, *14*, 68–76.

(120) Kouril, M.; Prosek, T.; Scheffel, B.; Degres, Y. Corrosion Monitoring in Archives by the Electrical Resistance Technique. *Journal of Cultural Heritage* **2014**, *15* (2), 99–103. https://doi.org/10.1016/j.culher.2013.04.002.

(121) Prosek, T.; Kouril, M.; Dubus, M.; Taube, M.; Hubert, V.; Scheffel, B.; Degres, Y.; Jouannic, M.; Thierry, D. Real-Time Monitoring of Indoor Air Corrosivity in Cultural Heritage Institutions with Metallic Electrical Resistance Sensors. *Studies in Conservation* **2013**, *58* (2), 117–128. https://doi.org/10.1179/2047058412Y.0000000080.

(122) Karagulian, F.; Barbiere, M.; Kotsev, A.; Spinelle, L.; Gerboles, M.; Lagler, F.; Redon, N.; Crunaire, S.; Borowiak, A. Review of the Performance of Low-Cost Sensors for Air Quality Monitoring. *Atmosphere* **2019**, *10* (9), 506. https://doi.org/10.3390/atmos10090506.

(123) Barsan, N.; Koziej, D.; Weimar, U. Metal Oxide-Based Gas Sensor Research: How To? *Sensors and Actuators B: Chemical* **2007**, *121* (1), 18–35. https://doi.org/10.1016/j.snb.2006.09.047.

(124) Korotcenkov, G. *Handbook of Gas Sensor Materials: Properties, Advantages and Shortcomings for Applications Volume 1: Conventional Approaches*; Integrated Analytical Systems; Springer New York: New York, NY, 2013. https://doi.org/10.1007/978-1-4614-7165-3.

(125) Carro, G.; Schalm, O.; Storme, P.; Blanckaert, G.; Demeyer, S. Indoor Air Quality for Heritage Objects and Human Health: Just a Different Interpretation of the Same Measurements? *Air Qual Atmos Health* **2024**, *17* (1), 19–34. https://doi.org/10.1007/s11869-023-01427-9.

(126) L. M. Rodríguez Peralta; L. M. P. Leão Brito; B. A. Teixeira Gouveia. The WISE-MUSE Project: Environmental Monitoring and Controlling of Museums Based on Wireless Sensors Networks. *EJSE* **2009**, No. 01, 46–57. https://doi.org/10.56748/ejse.10901.

(127) Alhmiedat, T.; Samara, G. A Low Cost ZigBee Sensor Network Architecture for Indoor Air Quality Monitoring. **2017**. https://doi.org/10.48550/ARXIV.1712.04190.

(128) Khan, A. U.; Khan, M. E.; Hasan, M.; Zakri, W.; Alhazmi, W.; Islam, T. An Efficient Wireless Sensor Network Based on the ESP-MESH Protocol for Indoor and Outdoor Air Quality Monitoring. *Sustainability* **2022**, *14* (24), 16630. https://doi.org/10.3390/su142416630.

(129) Grzywacz, C. M. *Monitoring for Gaseous Pollutants in Museum Environments*. https://www.getty.edu/conservation/publications_resources/pdf_publications/monitoring_gaseous.html (accessed 2023-02-02).

(130) Alvarez-Martin, A.; McHugh, K.; Martin, C.; Kavich, G.; Kaczkowski, R. Understanding Air-Tight Case Environments at the National Museum of the American Indian (Smithsonian Institution) by SPME-GC-MS Analysis. *Journal of Cultural Heritage* **2020**, *44*, 38–46. https://doi.org/10.1016/j.culher.2020.01.004.

(131) NEDCC, Northeast Document Conservation Center. Monitoring Temperature and Relative Humidity. In *Preservation Leaflet*; 2007.

(132) Laohaviraphap, N.; Waroonkun, T. Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies. *Buildings* **2024**, *14* (12), 3979. https://doi.org/10.3390/buildings14123979.

7. List of figures

8. List of tables

Funded by the European Union

9. ANNEX A

SIMIACCI Survey – ''How is your Indoor Air Quality management?''

9.1 Rationale for the survey

A short online survey with 12 questions focused on Indoor Air Quality management in GLAMs was designed using Umfrageonline tool. The aim was to gather and exchange information with GLAMs professionals involved in IAQ managing, focusing on gaseous pollutants. It was tested first among WP4 partners, thereby improved and approved upon their comments, before disseminating via the partners' institutional contacts and professional groups. Additionally, the questionnaire was sent to key stakeholders (*e.g.* ICOM-CC, IIC), associations and e-mail lists with a wide distribution among professionals (*e.g.* Conservation Distribution List) reaching known dedicated - past and ongoing - activities on IAQ in GLAMs.

The survey was available for one month. A total number of 500 persons took the survey, whereof 104 fully responded to the 12 questions. From the answers gathered, 107 persons expressed their interest in participating to the Online Focus Meeting in the form of a videoconference with lectures from professionals in the fields of IAQ management and preventive conservation, organized within WP4 and which took pace June 3rd 2025 (Milestone 4). Below is a synthesis of the analysis of the results of the survey. The full answers to the survey are in D4.2 (SEN).

Overall, the survey reached all types of GLAMs with a majority of responses from museums, holding a wide span of artefacts typologies, yet a majority of paper-based materials and other organic-based artefacts, as well as metal objects. Where 77% of respondents indicated no involvement in projects related to IAQ or preventive conservation, it is noteworthy that 23% (90 respondents) indicated being or having been involved in such projects, and provided some insight as to the content and their role in those projects.

It resulted that more than half of the respondents did not know what type of VOC were a concern for the preservation of their collections, albeit those who knew indicated that organic acids were a prime concern, followed by aldehydes, hydrogen sulfide and nitrogen oxides. Consistent to the previous answers, about 70% of respondents answered negatively or did not know about any use of adsorbents for their collections. However, those who answered positively to using adsorbents, indicated it was predominantly in showcases, but also in repositories and individual boxes and public rooms.

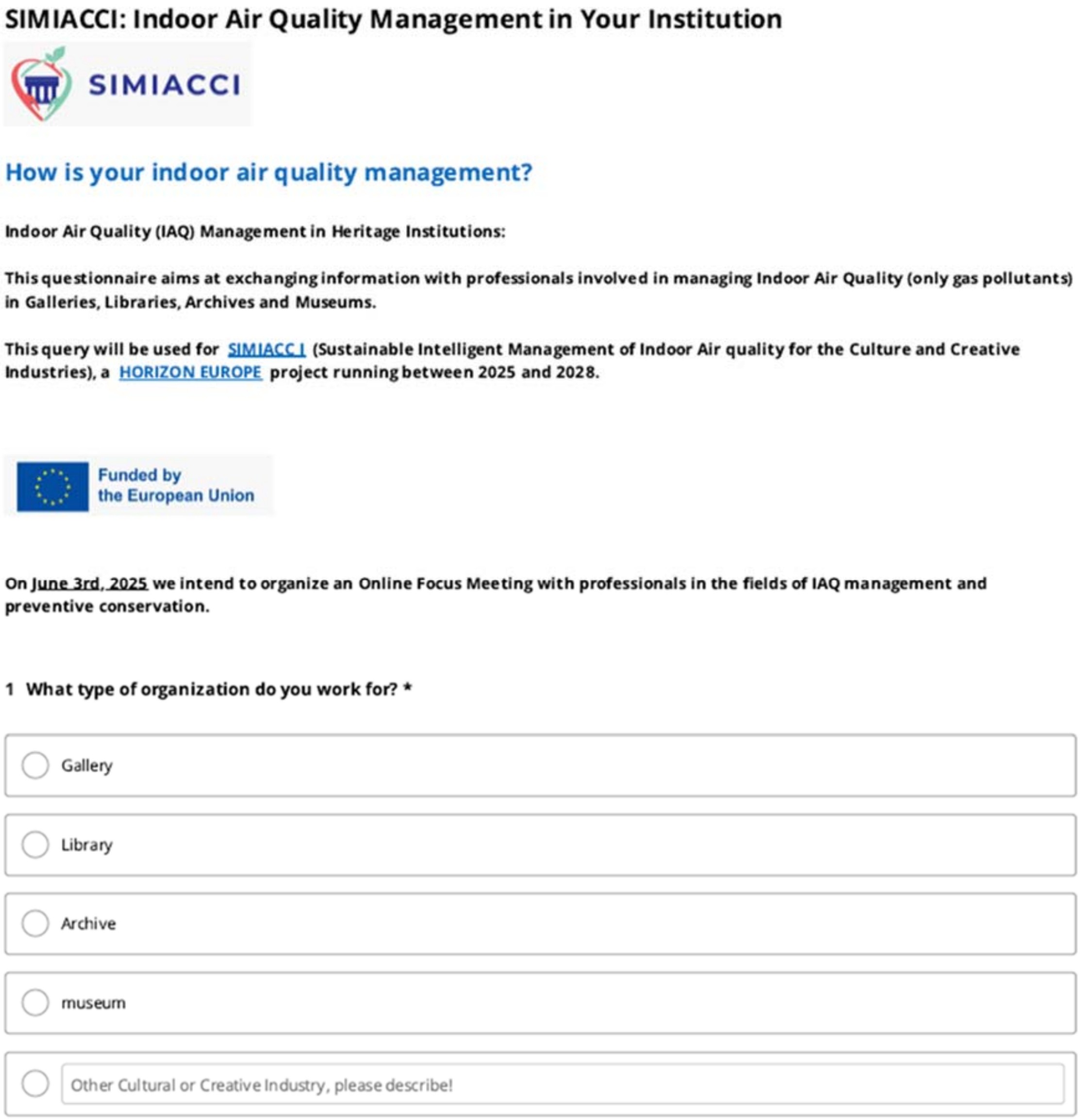
This pool of positive respondents indicated using porous silica or silica gel for humidity control, and activated carbon for air purification, while zeolites and alkaline adsorbents were seldom used. Interestingly, while porous silica and silica gel were reported to be used abundantly (by almost all the respondents), activated carbon appeared to be used only by half of the pool. The adsorbents were said to be used mostly in the form of beads and pellets, but also shaped as textile.

The survey also allowed to determine that those adsorbents were often used without a real knowledge about the nature of the pollutants nor their concentration since the majority of the respondents indicated not performing pollutants measurements, nor actively aiming at limiting the level of gaseous indoor pollutants.

That the implementation of adsorbents is not correlated with the occurrence of pollutants tends to indicate that it is rather to be correlated with RH control, even though an overwhelming proportion of respondents indicated that their organisation did not have an Indoor Air Quality or Climate Management Group or Department. This is not a surprise since temperature and Relative Humidity (RH) are two parameters of highest concern in GLAMs for the preservation of the collections. The 22% of respondents who indicated performing pollutants measurements, pointed towards a higher use of occasional rather than regular monitoring and the devices used spanned across the range of devices presented in this report (section 3).

The majority of GLAMs answered negatively to the question about adapting new trends towards relaxation of Temperature and RH recommendations. However, the number of positive answers reached 30%, which indicated a growing concern among the GLAMs community about energy-consumption, budget constraints and/or sustainability issues.

9.2 A copy of the questionnaire as posted in April 2025



SIMIACCI: Indoor Air Quality Management in Your Institution

SIMIACCI

How is your indoor air quality management?

Indoor Air Quality (IAQ) Management in Heritage Institutions:

This questionnaire aims at exchanging information with professionals involved in managing Indoor Air Quality (only gas pollutants) in Galleries, Libraries, Archives and Museums.

This query will be used for SIMIACC I (Sustainable Intelligent Management of Indoor Air quality for the Culture and Creative Industries), a HORIZON EUROPE project running between 2025 and 2028.

Funded by the European Union

On June 3rd, 2025 we intend to organize an Online Focus Meeting with professionals in the fields of IAQ management and preventive conservation.

1 What type of organization do you work for? *

○ Gallery

○ Library

○ Archive

○ museum

○ Other Cultural or Creative Industry, please describe!

2 Are/were you/your organization involved in projects related to IAQ/preventive conservation? *

You can select multiple options:

○ No

○ Yes, project funded by the European Commission

○ Yes, nationally funded project

○ Yes, other sources of funding

3 If yes, please briefly describe the project(s) and your role: *

4 What type of artefacts/materials are held in the collections of your organisation? *

You can select multiple options:

☐ Wood/Furniture/Lacquer/Polychromy

☐ Paper

☐ Leather/Parchment/Proteinaceous

☐ Textile

☐ Painting

☐ Natural History specimens/objects

☐ Photographic/Cinematographic/Audio-visual

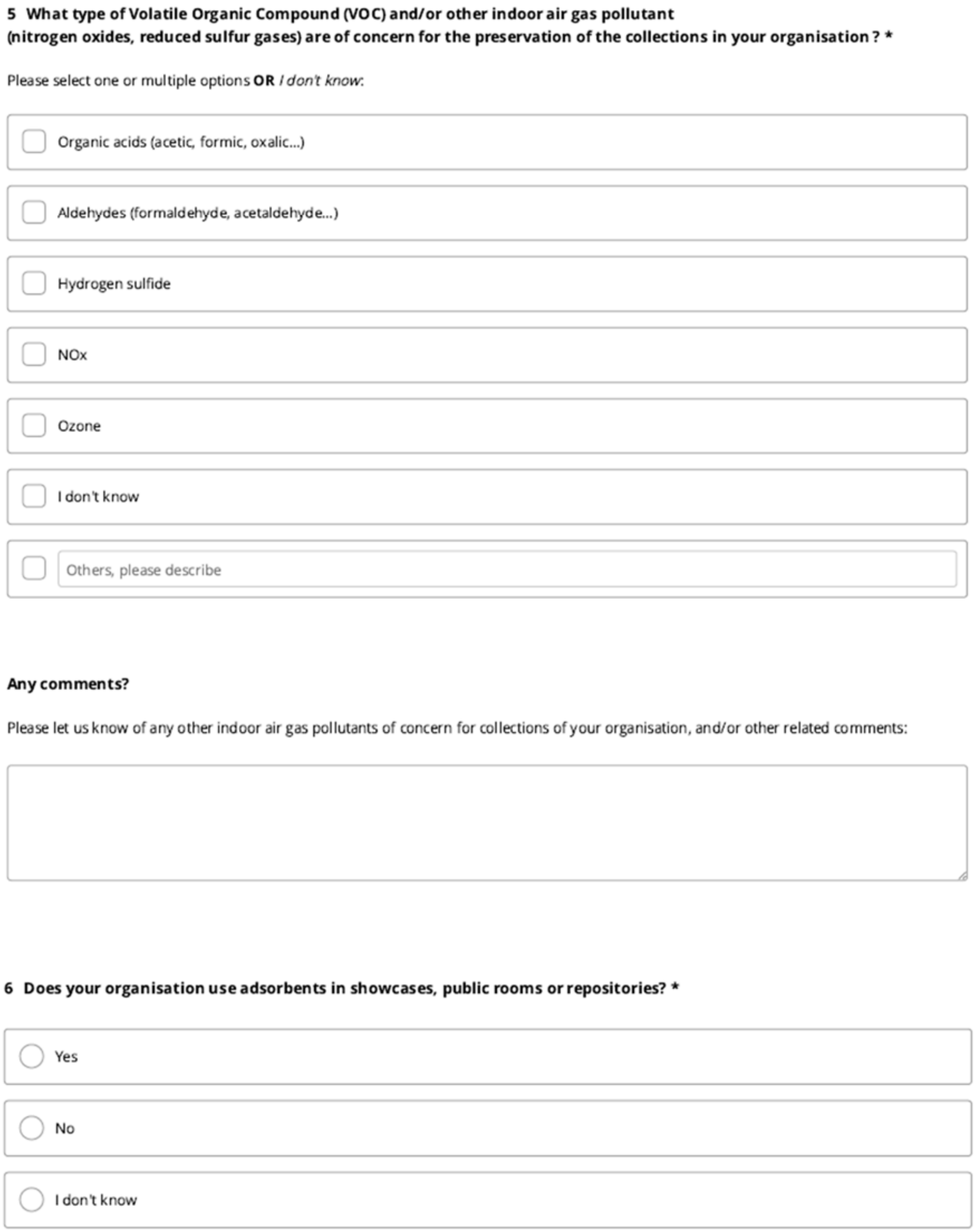
☐ Stone/Mural

☐ Glass/Ceramics

☐ Metal

☐ Modern materials (semi-synthetic & synthetic polymers)

☐ Others, please describe



5 What type of Volatile Organic Compound (VOC) and/or other indoor air gas pollutant (nitrogen oxides, reduced sulfur gases) are of concern for the preservation of the collections in your organisation ? *

Please select one or multiple options **OR** *I don't know*:

- ☐ Organic acids (acetic, formic, oxalic...)
- ☐ Aldehydes (formaldehyde, acetaldehyde...)
- ☐ Hydrogen sulfide
- ☐ NOx
- ☐ Ozone
- ☐ I don't know
- ☐ Others, please describe

Any comments?

Please let us know of any other indoor air gas pollutants of concern for collections of your organisation, and/or other related comments:

6 Does your organisation use adsorbents in showcases, public rooms or repositories? *

- ○ Yes
- ○ No
- ○ I don't know

6a Where are the adsorbents implemented? *

Please select one or multiple options **OR** *I don't know*:

☐ In public rooms

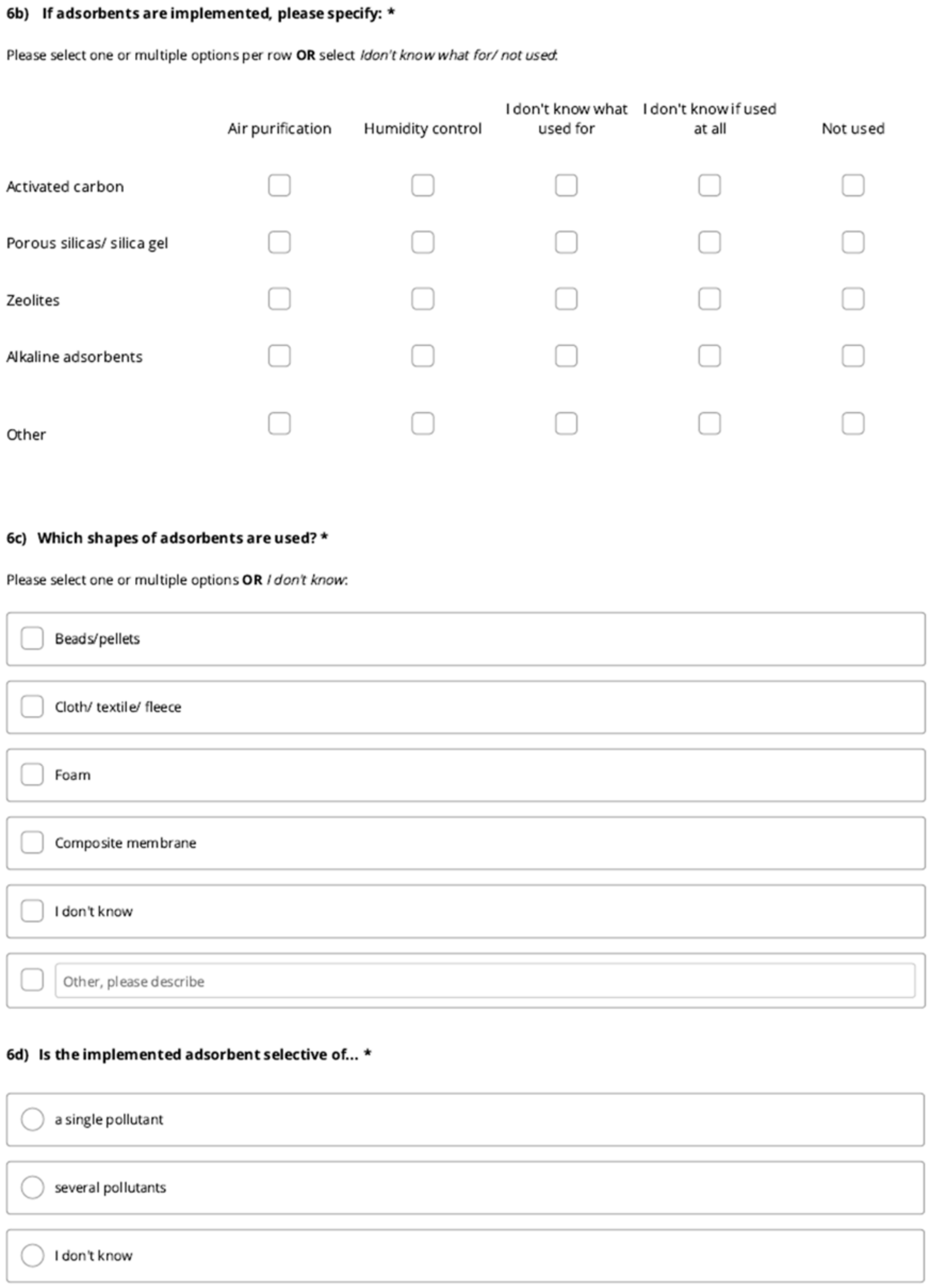
☐ In repositories

☐ In showcases

☐ In individual box(es)

☐ I don't know

☐ Other, please describe



6b) If adsorbents are implemented, please specify: *

Please select one or multiple options per row **OR** select *Idon't know what for/ not used*.

	Air purification	Humidity control	I don't know what used for	I don't know if used at all	Not used
Activated carbon	☐	☐	☐	☐	☐
Porous silicas/ silica gel	☐	☐	☐	☐	☐
Zeolites	☐	☐	☐	☐	☐
Alkaline adsorbents	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

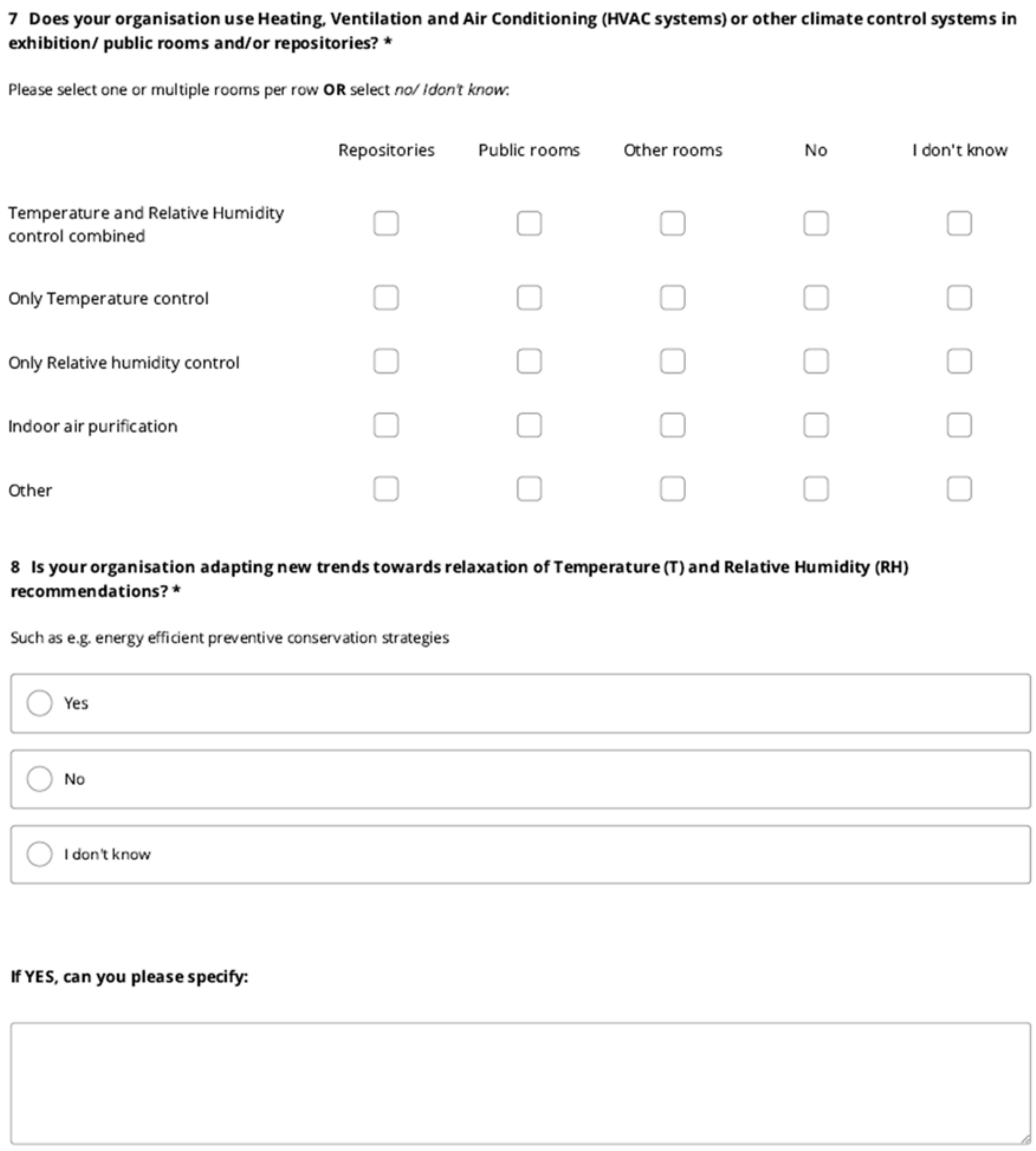
6c) Which shapes of adsorbents are used? *

Please select one or multiple options **OR** *I don't know*:

- ☐ Beads/pellets
- ☐ Cloth/ textile/ fleece
- ☐ Foam
- ☐ Composite membrane
- ☐ I don't know
- ☐ Other, please describe

6d) Is the implemented adsorbent selective of... *

- ○ a single pollutant
- ○ several pollutants
- ○ I don't know



7 Does your organisation use Heating, Ventilation and Air Conditioning (HVAC systems) or other climate control systems in exhibition/ public rooms and/or repositories? *

Please select one or multiple rooms per row **OR** select *no/ Idon't know*:

	Repositories	Public rooms	Other rooms	No	I don't know
Temperature and Relative Humidity control combined	☐	☐	☐	☐	☐
Only Temperature control	☐	☐	☐	☐	☐
Only Relative humidity control	☐	☐	☐	☐	☐
Indoor air purification	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

8 Is your organisation adapting new trends towards relaxation of Temperature (T) and Relative Humidity (RH) recommendations? *

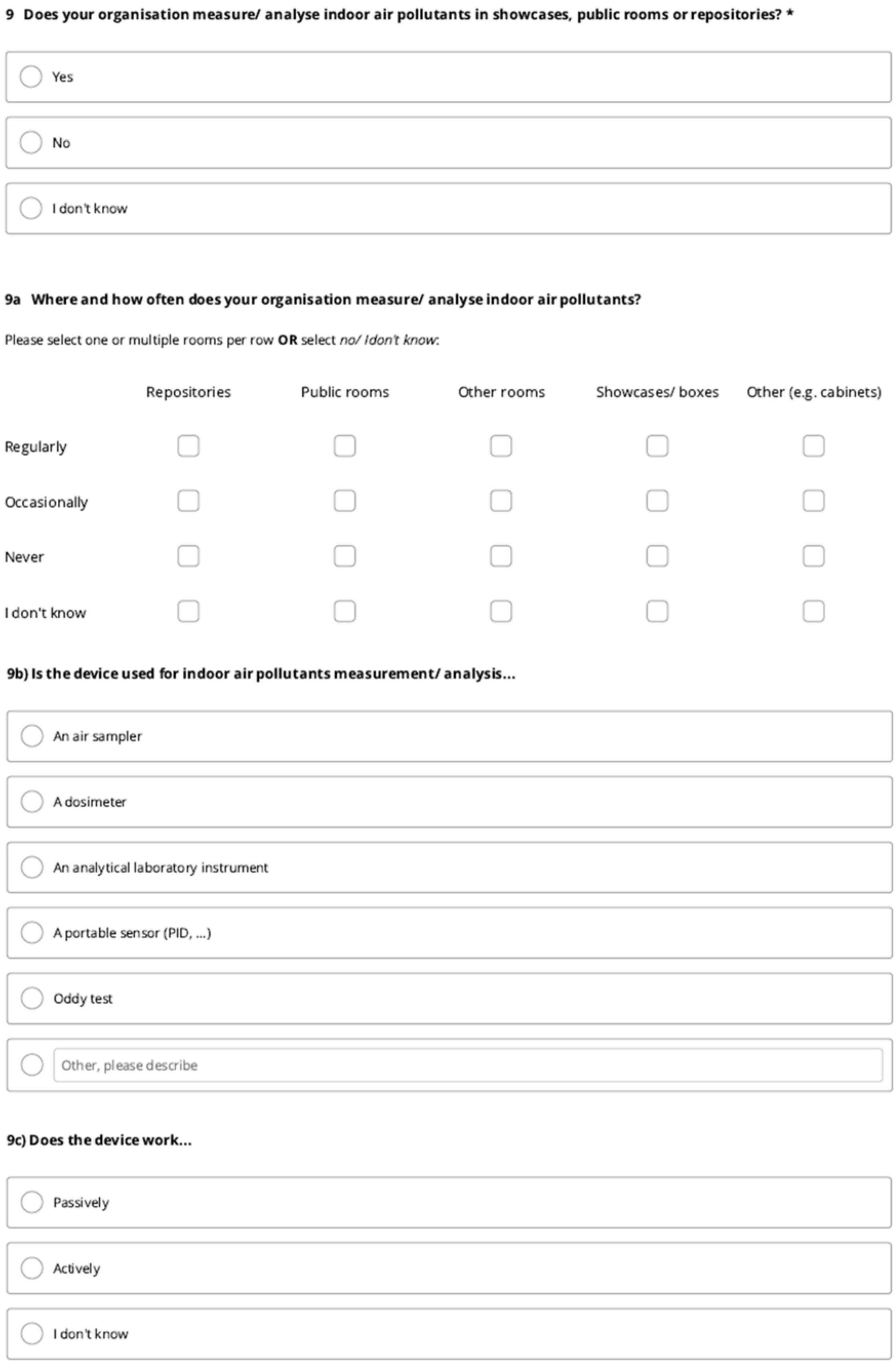
Such as e.g. energy efficient preventive conservation strategies

○ Yes

○ No

○ I don't know

If YES, can you please specify:



9 Does your organisation measure/ analyse indoor air pollutants in showcases, public rooms or repositories? *

○ Yes

○ No

○ I don't know

9a Where and how often does your organisation measure/ analyse indoor air pollutants?

Please select one or multiple rooms per row **OR** select *no/ Idon't know*:

	Repositories	Public rooms	Other rooms	Showcases/ boxes	Other (e.g. cabinets)
Regularly	☐	☐	☐	☐	☐
Occasionally	☐	☐	☐	☐	☐
Never	☐	☐	☐	☐	☐
I don't know	☐	☐	☐	☐	☐

9b) Is the device used for indoor air pollutants measurement/ analysis...

○ An air sampler

○ A dosimeter

○ An analytical laboratory instrument

○ A portable sensor (PID, ...)

○ Oddy test

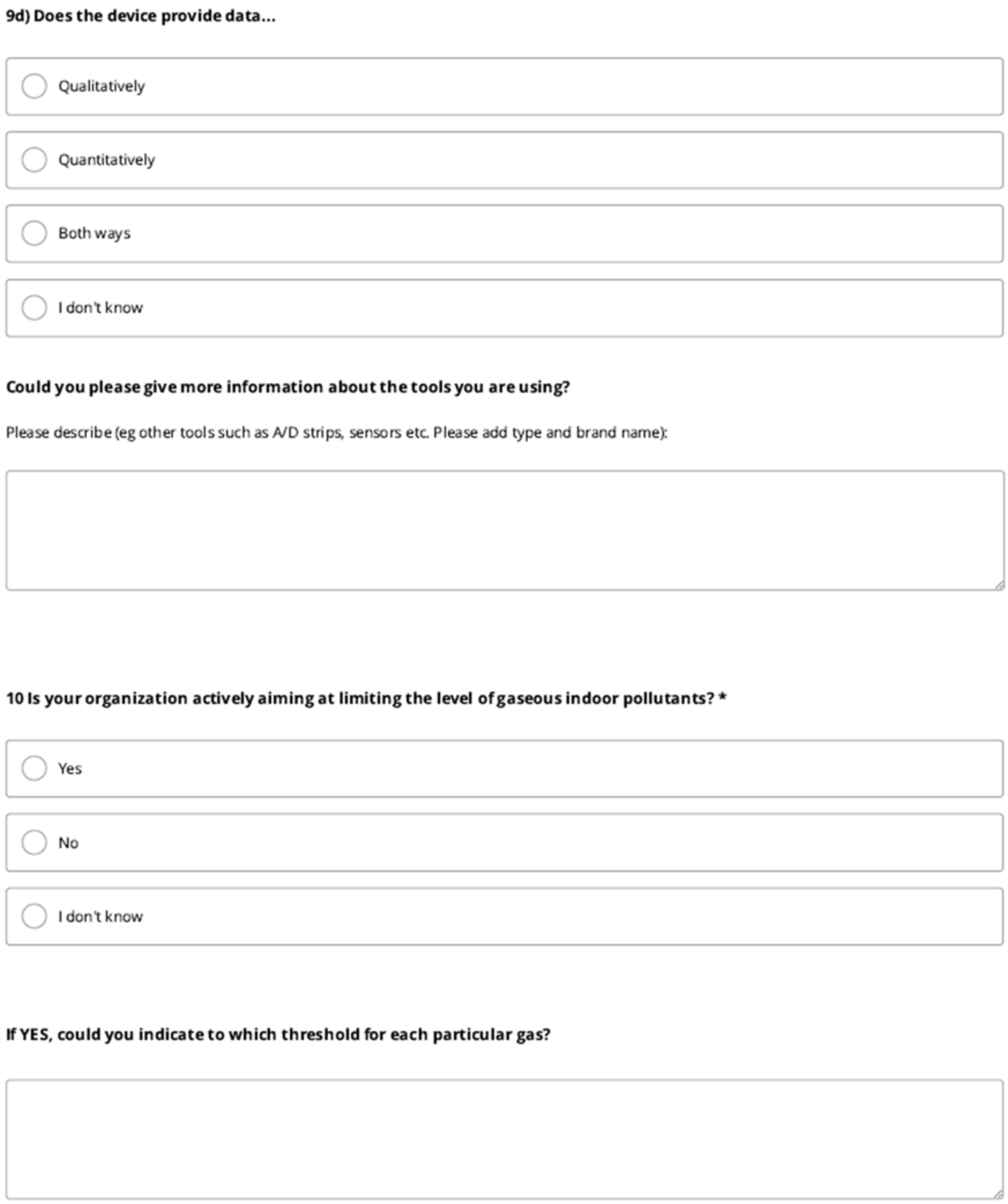
○ Other, please describe

9c) Does the device work...

○ Passively

○ Actively

○ I don't know



9d) Does the device provide data...

○ Qualitatively

○ Quantitatively

○ Both ways

○ I don't know

Could you please give more information about the tools you are using?

Please describe (eg other tools such as A/D strips, sensors etc. Please add type and brand name):

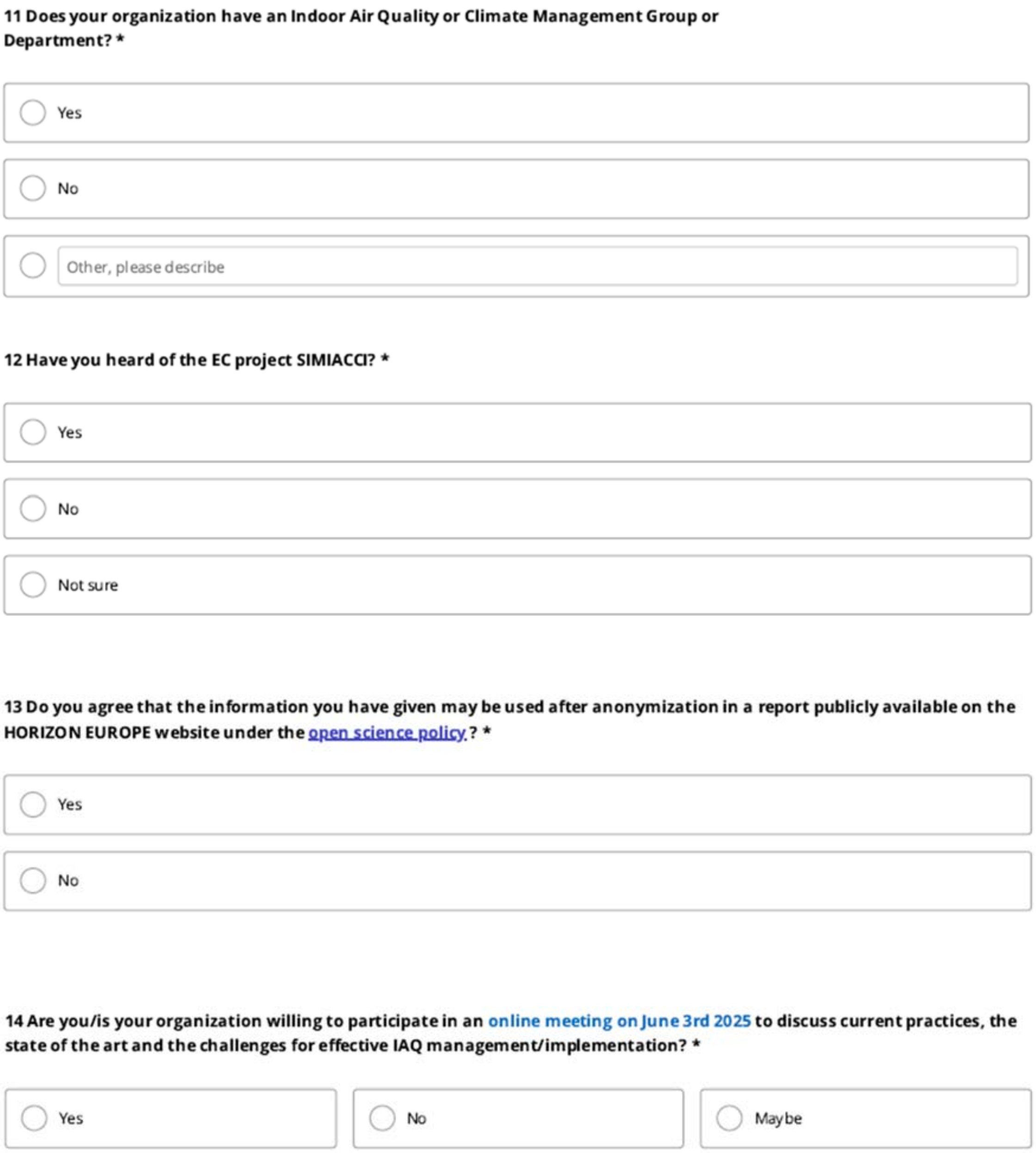
10 Is your organization actively aiming at limiting the level of gaseous indoor pollutants? *

○ Yes

○ No

○ I don't know

If YES, could you indicate to which threshold for each particular gas?



11 Does your organization have an Indoor Air Quality or Climate Management Group or Department? *

○ Yes

○ No

○ Other, please describe

12 Have you heard of the EC project SIMIACCI? *

○ Yes

○ No

○ Not sure

13 Do you agree that the information you have given may be used after anonymization in a report publicly available on the HORIZON EUROPE website under the open science policy? *

○ Yes

○ No

14 Are you/is your organization willing to participate in an online meeting on June 3rd 2025 to discuss current practices, the state of the art and the challenges for effective IAQ management/implementation? *

○ Yes ○ No ○ Maybe

Please add your contact details below - Thank you! *

I am hereby consenting that SIMIACCI consortium can process my personal data for the sole purpose of the survey of IAQ management in GLAMs, without sharing it with other projects or companies. I am aware and I was informed that I may withdraw my consent at any time and request the erasure of all personal data by sending an email request to the DPO moises.pinto@tecnico.ulisboa.pt

First name / Surname	
Job description/ Position	
organization	
City/Country	
Email address	

On behalf of the SIMIACCI team, thank you very much for having taken the time to answer this questionnaire!