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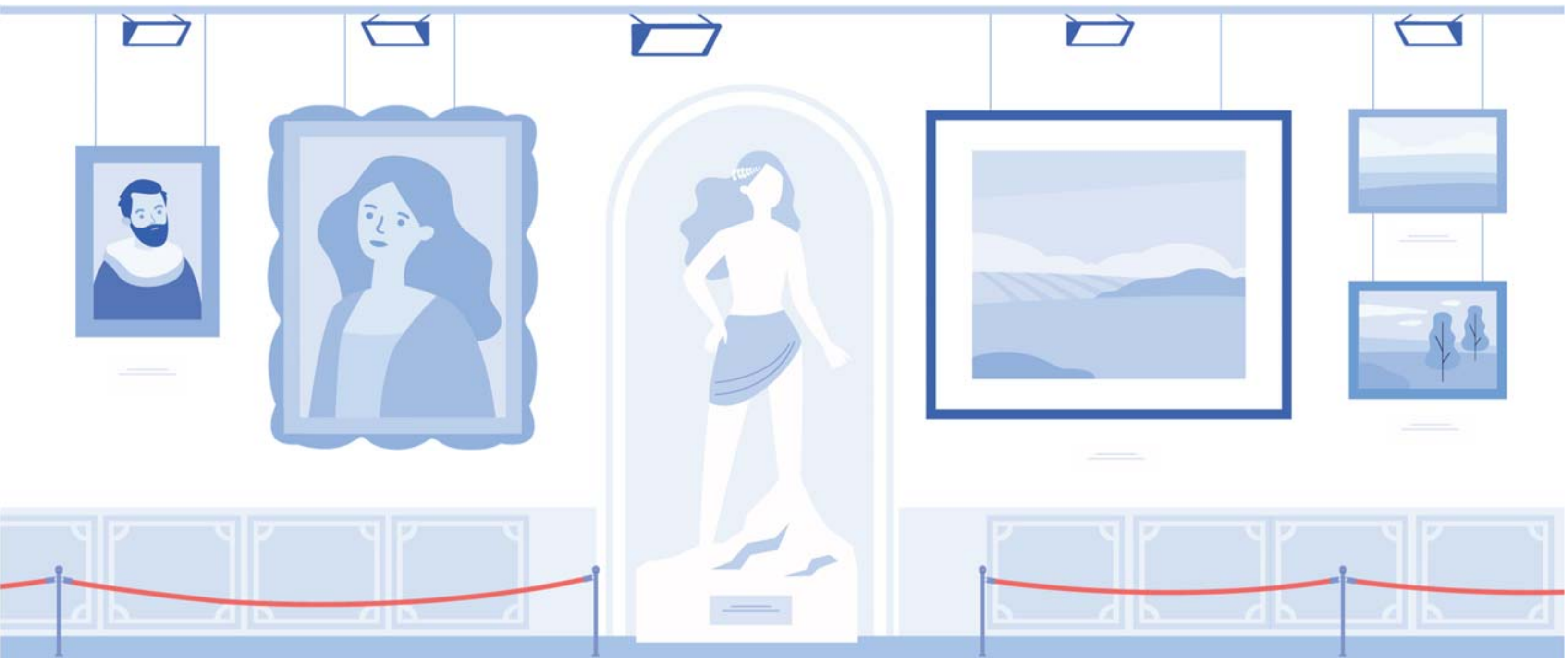
SIMIACCI

Deliverable D4.2

Specifications for the adsorbent materials to be developed



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

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Main authors	**T Aaboub (CNRS-IMAP), A-L Dupont (CNRS-CRC), A Al Mohtar (ISTD), G Mouchaham (CNRS-IMAP), M Pinto (ISTD), N Savodnik (SQT), N Wallaszkovits (ABK)**
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Document's objective and executive summary

Using pioneering Metal-Organic Framework (MOF) materials - a porous structure crafted from metal ions and organic linkers- SIMIACCI intends to achieve a breakthrough in capturing volatile organic compounds (VOCs) and hydrogen sulfide (H_2S) and eliminating nitrogen oxides (NOx) from indoor air in Galleries, Libraries, Archives, and Museums (GLAMs) under real environment conditions (*in-loco)*. To this end, based on literature and backed up by the results of a comprehensive survey conducted by WP4 within a large group of indoor air quality (IAQ) specialists in GLAMs, D4.2 aims at providing specifications for the new MOF materials to be developed. Based on materials featuring MOFs, available on the market or published in the literature, the first part of the report defines a blueprint for new sustainable easy-to-use and-easy-to implement array of preferred solutions using the identified benchmark MOFs MIL-100(Fe), MIL-127(Fe), Al-3,5-PDA (or MOF-303(Al)). Requirements on shaping, performance and selectivity as well as other specifications such as reusability, stability and innocuousness, sustainability, cost- and energy-efficiency are reviewed. The second part of the report is a literature review, which identifies other MOFs that could eventually fulfil the criteria of green synthesis, affordable cost, scalability as well as performance, particularly for at least one class of target pollutants (acids, formaldehyde, H_2S, or NOx) in the intended applications.

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Introduction

The Horizon Europe project SIMIACCI aims to transform indoor air quality management in Galleries, Libraries, Archives, and Museums (GLAMs) by implementing advanced technologies that significantly reduce energy consumption while protecting sensitive cultural heritage (CH) collections. At the core of this strategy is the use of Metal-Organic Frameworks (MOFs) — a class of crystalline porous materials with exceptionally high surface area, tuneable chemistry, and remarkable adsorption capacities — to remove key indoor air pollutants that are the most detrimental to CH, including volatile organic compounds (VOCs), nitrogen oxides (NOx), hydrogen sulfide (H_2S), and acetic acid.

1. Objectives and Requirements

To meet the stringent demands of air purification in GLAMs environments, MOF-based materials must satisfy several critical performance requirements:

(i) **Target pollutants**: Formaldehyde, acetic acid, NOx, H_2S
(ii) **Performance needs**: High adsorption efficiency, no reemission of captured pollutants, good mechanical stability, scalability, and compatibility with HVAC systems and portable air purification devices
(iii) **Operating conditions**: Room temperature (RT), variable humidity, and minimal pressure drop across the filter medium

Compared to conventional adsorbents such as activated carbon, MOFs offer clear advantages including higher adsorption capacity, selective removal of specific pollutants, and the possibility of low-energy regeneration. Moreover, their ability to retain structural integrity under variable humidity and temperature conditions makes them highly promising for air purification[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

2. MOFs already identified for the scope of the project

The SIMIACCI project has identified a selection of Metal-Organic Frameworks (MOFs) as promising candidates for the removal of priority indoor air pollutants, including **NOx, H_2S, acetic acid, and formaldehyde**, within GLAMs environments.

For **nitrogen oxides (NOx)** removal, the iron-based MOFs MIL-100 and MIL-127 stand out for their ability to catalytically degrade NOx into harmless N_2 and O_2 under ambient conditions, leveraging their unique Fe(II)/Fe(III) redox pairs[13]. This represents a major advance, as it enables effective NOx removal without the need for additional reducing agents or elevated temperatures.

In terms of **hydrogen sulfide (H_2S)** capture, MIL-100(Fe) and MIL-127(Fe) have demonstrated superior adsorption capacity and stability compared to other MOFs, activated carbon, and zeolites, particularly under humid conditions[17]. These materials maintained structural integrity and showed no re-emission of H_2S, positioning them as strong candidates for use in CH conservation and industrial applications. Future work will focus on understanding their selective sorption mechanisms and evaluating regeneration strategies.

For **acetic acid mitigation**, MIL-100(Fe) synthesized through a green process has proven highly stable and compatible with sensitive cultural heritage materials. Field trials using a smart box prototype validated predictive models for optimizing adsorbent quantities and demonstrated that this MOF-based approach can significantly extend the preservation lifetime of materials, while also reducing the carbon footprint relative to conventional cold storage methods[18].

Regarding **formaldehyde** capture, Al-3,5-PDA (MOF-303) has emerged as a highly promising material. It combines environmental stability, selective adsorption, and reusability under real-world indoor conditions, including varying VOC levels, humidity, and temperature. Importantly, it operates without risk of unintended pollutant release, making it well-suited for demanding indoor environments[16,19].

Together, these MOFs represent a new generation of air purification materials with the potential to outperform conventional adsorbents in terms of efficiency, selectivity, sustainability, and ease of integration into HVAC and portable systems. The document's next steps will involve a shortlist of other possible MOFs that could be used for the purification of the identified key pollutants from indoor air in GLAMs, advancing scalable shaping methods and composite designs discussion to transition these materials from laboratory-scale research to practical deployment in GLAM settings.

3. Specifications for the MOFs to be developed

3.1 Literature review

Metal–organic frameworks (MOFs) have demonstrated considerable potential in adsorption processes, particularly for the capture of airborne molecules such as volatile organic compounds (VOCs), formaldehyde (FA), acetic acid (AA), hydrogen sulfide (H_2S), and nitrogen oxides (NO_x). In addition to their high surface areas and tunable pore structures, MOFs, when rationally selected, can be considered as environmentally friendly and economically viable in terms of production costs. Nevertheless, not all MOFs exhibit optimal performance under practical conditions, where high selectivity, competitiveness, and operational stability are essential for real-world applications. Under such conditions, humidity in the GLAMs environment is considered a significant limitation due to the competition between water and the targeted volatile molecules, especially when the latter are in low concentrations (ppm–ppb). Tailoring MOFs to overcome this issue and achieve VOC selectivity over water has been addressed through various strategies. One such approach involves creating hydrophobic sites by introducing fluorinated functions into the MOF structure, which can be achieved by using non-polar metallic nodes or employing linkers with fluorinated terminals. Zr-based MOFs such as UiO-66-2FC$_3$ and MIL-140-B have demonstrated the ability to capture acetic acid selectively [20], thanks to their appropriate pore sizes and organic spacers (*i.e.,* linkers with perfluorinated groups), which facilitate physical bonding with acetic acid rather than water. Subsequently, MIL-53(Al)-CF$_3$ was introduced as a promising material to surpass the previously mentioned MOFs[21], showing a high level of hydrophobicity and strong affinity for acetic acid and other VOCs in the presence of humidity, making it a suitable material for indoor applications.

More recently, it has been demonstrated that Fe-based MOFs with open metal sites (OMS) (Fe^{3+}), such as MIL-100 and MIL-127, outperform fluorinated MOFs in capturing not only acetic acid but also other volatile molecules such as formic acid, acetone, and methanol in the presence of humidity. This is due to specific interactions between the VOC and the Fe-trimers of this class of MOFs suppressing the effect of water to some extent. For the capture of tiny molecules such as aldehydes, the Al-3,5-PDA MOF has proven to be a highly selective material, exhibiting excellent efficiency for formaldehyde capture at very low concentrations (< 0.2 ppm), even in the presence of water and at relatively high temperatures (70 °C), without any leakage. This performance was later attributed to a chemisorption mechanism involving the interaction between the Pyrazole group and formaldehyde.

The selection of these MOFs for the SIMIACCI project is based not only on their outstanding performance under realistic conditions, but also on the feasibility of scaling up their production to the ton scale using greener, more eco-friendly processes at competitive and affordable costs. Additionally, these materials offer high versatility in processability, as they can be shaped using various shaping methods and technologies. Below are listed the most promising MOF candidates identified as per the aforementioned selection criteria.

3.1.1 MIL-100(Fe)

Among the most promising materials for volatile organic compound (VOC) capture under humid conditions, MIL-100(Fe), or $[Fe_3O(OH)(C_6H_3(CO_2)_3)_2 \cdot (H_2O)_2] \cdot nH_2O$, stands out due to its exceptional porosity, chemical robustness, and thermal stability. This metal-organic framework is built from Iron(III) oxo trimers coordinated with 1,3,5-benzene tricarboxylate (BTC) linkers, forming a three-dimensional network. The structure contains two large mesoporous cages (25 and 29 Å in diameter), accessible through microporous windows of 5.5 and 8.6 Å (Figure 1). This zeotype-like (MTN) framework features a high density of open metal sites and a large internal surface area, typically ranging from 1500 to 2200 m²/g, depending on the synthesis conditions, the choice of metal precursor, the particle size, etc.

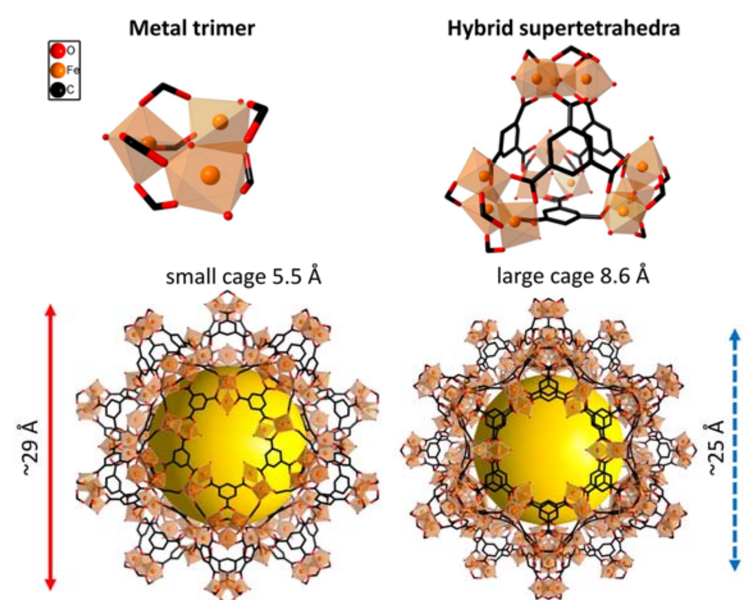

Figure 1. Crystal structure of MIL-100(Fe) depicting the Fe-trimer building unit, the supertetrahedra and the 2 cages forming the MTN-type framework. Fe, orange polyhedra; O, red; C, black; H-atoms are omitted for clarity.

In the context of scale-up for industrial production, the choice of iron precursor is critical. Using Fe(III) salts (*e.g., $Fe(NO_3)_3$ or $FeCl_3$*) directly provides the required oxidation state for the formation of $[Fe_3O]$ clusters, resulting in faster nucleation and the formation of smaller particles. However, these precursors are relatively expensive, which can limit their use at a large scale. Alternatively, employing Fe(II) salts (*e.g., $FeSO_4 \cdot 7H_2O$*) requires in-situ oxidation of Fe^{2+} to Fe^{3+} to form the trimeric [Fe_3O] clusters, allowing greater control over particle size and morphology. More importantly, Fe(II) salts are less costly and widely available, making them well-suited for industrial-scale synthesis, with production costs for MIL-100(Fe) falling below $30 per kilogram, and demonstrating a space-time yield (STY) of 120 $kg \cdot m^{-3} \cdot day^{-1}$, enabling by that the manufacturing at the ton scale[22].

Beyond its performance and scalability, MIL-100(Fe) can be synthesized under mild, green conditions, typically in aqueous media using non-toxic and inexpensive reagents. The synthesis avoids harmful solvents and is compatible with eco-friendly processing methods. Moreover, MIL-100(Fe) is amenable to various shaping and post-processing techniques, including extrusion, pelletization, spray drying, and incorporation into composite materials — all without compromising its structural integrity or porosity. These features make MIL-100(Fe) particularly attractive for large-scale deployment in air purification systems, especially for indoor environments (*e.g., GLAMs*) where both selectivity and durability in humid air are critical.

3.1.2 MIL-127(Fe)

MIL-127(Fe), or [$Fe_3O(TazBz)_{1.5}(H_2O)_3$]$\cdot nH_2O$, is an iron(III)-based metal-organic framework that has emerged as a highly attractive material for the capture of volatile organic compounds (VOCs) and H_2S under humid conditions . As for the MIL-100(Fe), this MOF is built from Fe_3O clusters bridged by 3,3′,5,5′-azobenzenetetracarboxylate (TazBz) linkers. This MOF adopts a **soc**-type topology with one-dimensional microporous channels (5–7 Å), offering structural rigidity and excellent accessibility to its active sites as shown in Figure 2. MIL-127(Fe) is appealing because of its dual-channel architecture composed of hydrophilic and hydrophobic regions, which enables the selective adsorption of polar and corrosive small molecules such as H_2S, even in the presence of water. At H_2S saturation, MIL-127 exhibited an adsorption capacity of 1.3 $mmol_{H2S}/g$ with no release while keeping its structural integrity[17]. The material also demonstrates a high surface area of up to 1400 m^2/g, and outstanding stability in water across a wide pH range.

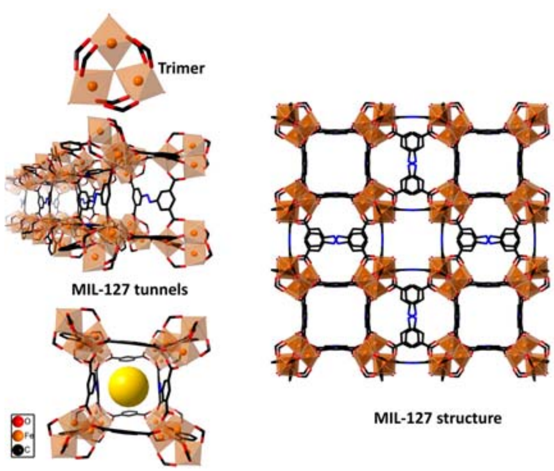

Figure 2. Crystal structure of MIL-127(Fe) showing the Fe-trimer, the channels and the 3D framework. Fe, orange polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity.

Originally synthesized under harsh solvothermal conditions using hydrofluoric acid (HF), the development of MIL-127(Fe) was historically limited by safety concerns and lack of scalability. However, we have successfully redesigned the synthesis to operate under milder conditions[23]. This greener method not only eliminates HF but also reduces reaction time (from 3 days to 16 hours) and gives higher yields. This MOF has been successfully scaled up without compromising structural integrity, porosity, or adsorption performance, with higher STY (from 0.5 to 61 $kg \cdot m^{-3} \cdot day^{-1}$), and an estimated production cost comparable to or lower than that of MIL-100(Fe), given the greener synthesis route and higher STY[23].

3.1.3 l-3,5-PDA (or MOF-303(Al))

Widely known for its application in harvesting water from arid air and desert (Zheng et al., 2023), MOF-303 or $[Al(OH)(PDA)] \cdot nH_2O$ — has emerged as a pioneering material for next-generation environmental applications. Built from aluminium hydroxide octahedral chains and 3,5-pyrazole dicarboxylic acid (PDA) linkers (Figure 3), its architecture features straight, one-dimensional channels (~6.5 Å) promoting a BET surface area of up to 1300 m^2/g. These channels are lined up with hydrophilic groups and forming pocket-like cavities that enable water adsorption at relatively low relative humidity.

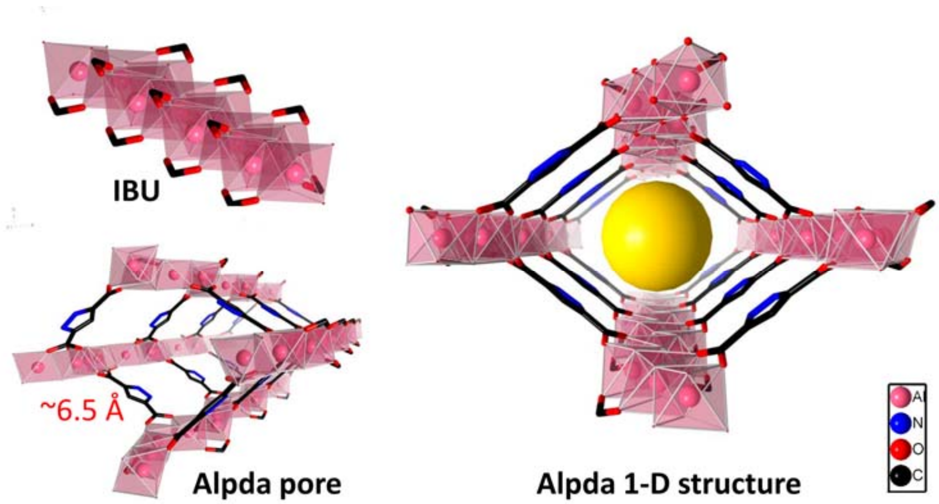

Figure 3. Crystal structure of MOF-303(Al) or Al 3,5-PDA showing the Al-chain and the 1-D channels as part of the 3D framework. Al, pink polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity structure

Beyond water harvesting, MOF-303(Al) shows strong potential for indoor air purification, particularly for removing formaldehyde (FA). Thanks to the Nitrogen-rich Pyrazole moieties, MOF-303(Al) exhibits an exceptional performance for the selective capture of formaldehyde. They interact chemically with formaldehyde molecules, enabling chemisorption capture that remains highly efficient even under humid conditions and beyond room temperature (70°C) without releasing the captured FA[24]. MOF-303(Al) combines high performance with industrial viability; it is synthesized entirely in water under mild, eco-friendly conditions, without any toxic solvents or modulators. The process has been successfully scaled, achieving a space-time yield above 180 $kg \cdot m^{-3} \cdot day^{-1}$ [25]. The material is compatible with standard shaping methods like extrusion and granulation. From a cost perspective, the fully aqueous synthesis allows production costs to remain below $40 per kilogram, making MOF-303 a high-performance solution for toxic formaldehyde and a realistic candidate for real environments in GLAMs.

4. Other possible MOFs with possible applications for IAQ control in GLAMs

Form the previous reports and learnings gained over the past decade, it turns that Fe-trimers based MOFs represent promising candidates for VOCs capture, including carboxylic acid, NOx and H2S. Therefore, in the following we have identified 3 potential MOFs, MIL-59(Fe), CAU-52(Fe) and MIP-21X(Fe) (Fe-FDCA), all built-up from the aforementioned Fe-trimers and inexpensive chemicals. Besides, the selections of these MOFs is also motivated by their synthesis know to be adjustable to meet eco-compatible conditions, if it is not already the case (*i.e.*, MIL-59(Fe), Fe-FDCA and Fe-MDIP).

4.1 MIL-59(Fe)

MIL-59(Fe) [26] is a lesser-known yet structurally intriguing iron-based metal-organic framework (MOF). The structure was initially reported in 2002 for its vanadium-based analogue, which is constructed from octahedral vanadium trimers interconnected by isophthalate (IPA) linkers[27], a structure that is initially obtained under hydrothermal harsh conditions. Later, the iron-based MIL-59(Fe) was synthesized as an isostructural counterpart, featuring a fully hydrated framework with the formula $[Fe_3(\mu_3\text{-}O)(C_8H_4O_4)_3(OH)(H_2O)_2]\cdot 10H_2O$. Its inorganic building unit (IBU) consists of a trinuclear $[Fe_3(\mu_3\text{-}O)]$ cluster formed by edge-sharing FeO_6 octahedra, similar to the ones of MIL-100(Fe) and MIL-127(Fe). Each IBU is connected to six others through six IPA linkers, generating a three-dimensional porous network. The spatial orientation of the linkers above and below the Fe_3 plane creates two types of pores. Although these pores have similar dimensions — approximately 7.2 Å (large pore, lp) and 6.8 Å (small pore, sp) — they differ in hydrophilicity. The framework is further interconnected by microporous windows of about 2.8 Å, allowing molecular diffusion throughout the structure (Figure 4).

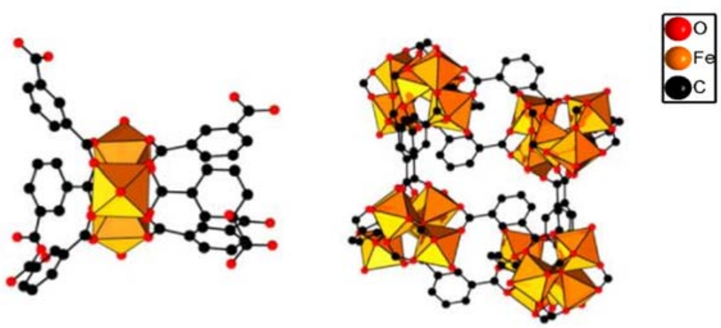

Figure 4. Crystal structure of MIL-59 (Fe) showing the Fe-trimer connected to 6 IPA and a cage, the channels and the 3D framework. Fe, orange polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity[28]

Our internal ongoing research and experimental developments confirm that MIL-59(Fe) can be synthesized via a green, water-based route under optimized conditions (12 hours reaction; 90% yield), avoiding harsh solvents or additives and ensuring high STY. Importantly, due to its dual-pore environment and accessible iron sites, MIL-59(Fe) shows strong potential for the selective capture of volatile organic compounds (VOCs), especially small acidic molecules (as it was shown for Fe-trimer -based MOFs), which make it a good candidate for GLAMs applications. Besides, the relatively inexpensive chemicals (Fe(III) and IPA) together with it easy, green and scalable synthesis reinforce its potentials for this project. Moreover, one can consider this MOF as a versatile platform where functional IPA can be used to tune the chemical and geometrical features of the pores.

4.2 CAU-59(Fe)

The linker used in this MOF, 2,5-furandicarboxylic acid (H_2FDC) [29], is well-known as potential precursor for bio-sourced plastics (to replace terephthalates) and for its role in the aluminium-based MIL-160(Al)[30], where it imparts strong hydrophilic character and has been extensively studied for water harvesting applications. Building on this concept, a new iron-based MOF, CAU-52 or $[Fe_3(\mu_3\text{-}O)(FDC)_3(OH)(H_2O)_2]\cdot 5H_2O\cdot H_2FDC$, was developed using the same V-shaped linker (CAU stands for Christian Albrecht University). In CAU-52, the well-known trinuclear $[Fe_3(\mu_3\text{-}O)]^{7+}$ cluster serves as the inorganic building unit (IBU), which is six-connected by FDC^{2-} linkers to form a primitive cubic (pcu) topology (Figure 5). This connectivity gives rise to two types of cubic cages, reminiscent of those found in soc-type MOFs, offering a promising porous architecture for further exploration in various applications.

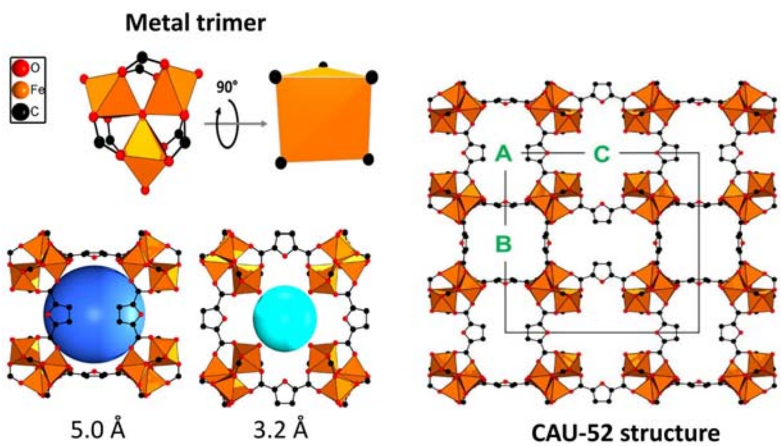

Figure 5. Crystal structure of CAU-52(Fe) showing the prismatic like Fe-trimer, cages A and C, and the 3D framework. Fe, orange polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity[28]

To the best of our knowledge, this MOF is primarily obtained under solvothermal conditions, and requires both a modulator (NaOH) and a co-solvent (acetic acid) to avoid the formation of an amorphous solid. Additionally, post-synthetic purification using DMF is necessary to remove any crystallized linker residing within the pores. In the context of the SIMIACCI project, CAU-52(Fe) is used as a benchmark for MOFs incorporating iron trimers and 2,5-furandicarboxylic acid (FDCA), as will be further elaborated in the following section.

4.3 MIP-21X(Fe) (Fe-FDCA)

The Fe-FDCA MOF (or MIP-21X(Fe), MIP stand for Materials from Porous Institute of Paris), is a novel in-house MOF recently discovered and studied at IMAP (unpublished yet). Its porous structure is built up from Fe-trimers connected via FDCA linkers to form 2-D layers (Figure 6A). The latter are linked together via acetate groups (AcO) binding at the vicinal positions of some of the Fe-polyhedra (Figure 6A). Overall, the 3D structure (Figure 6B), formulated $[Fe_3(\mu_3\text{-}O)(FDC)_3(OH)_{0.5}(AcO)_{0.5}(H_2O)_2]\cdot 5H_2O$, is endowed by micropores featuring a BET surface area of about 1320±10 m^2/g.

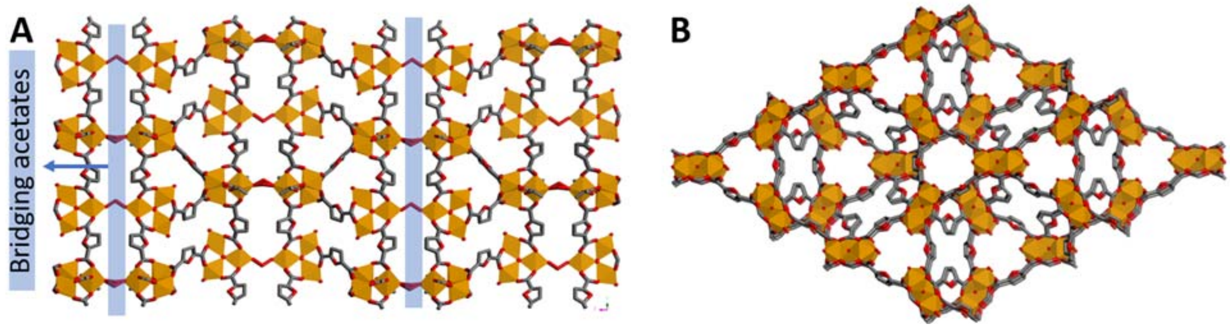

Figure 6. Crystal structure of MIP-21X(Fe) or Fe-FDCA, showing (A) the 2D-like structure where the pseudo-layers are linked by acetates and (B) the 3D framework. Color code: Fe, orange polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity.

Interestingly, this MOF can be obtained at the g-scale by direct reflux in ethanol, with potentially scalable to 100g. Preliminary studies conducted at University of Lisboa (M Pinto & A. Al Mohtar) revealed promising performances for the removal of acetic acid, although the activation/degassing procedure still needs to be optimized.

4.4 MIP-21Y(Fe) (Fe-MDIP)

The Fe-MDIP MOF (or MIP-21Y(Fe)), formulated $\{Fe_3O(OH)_xCl_{(1-x)}(MDIP)_{1.5}\}\cdot 4H_2O$, is also a novel in-house MOF recently discovered and studied at IMAP (unpublished yet). Its crystalline porous structure is built up from Fe-trimers connected via MDIP (3,3',5,5'-tetracarboxydiphenylmethane) linkers (Figure 7A) to form an open prismatic secondary building units (SBUs) (Figure 7B). These SBUs are connected together and yielding a 3D microporous structure with supermicropore of ca. 14 Å accessible via narrow windows (> 6 Å) (Figure 7C), promoting a BET surface area of about 1300 m^2/g. The Fe-MDIP was initially discovered using DMF-based solvothermal synthesis but the recipe was recently optimized to produce the MOF at the g-scale in more eco-compatible conditions (in isopropanol under reflux).

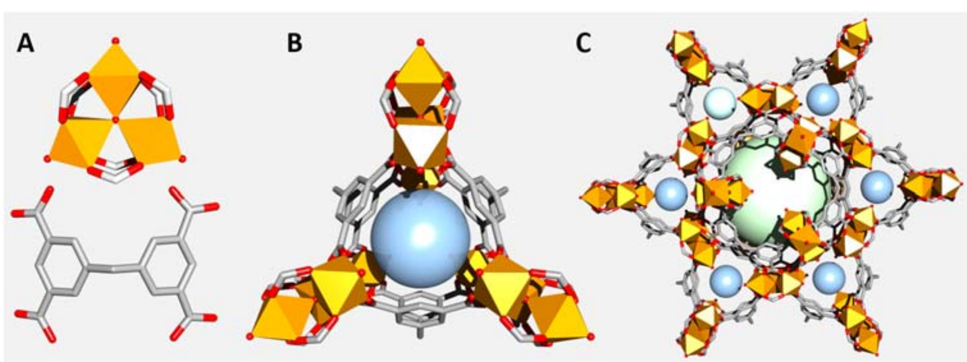

Figure 7. Crystal structure of MIP-21Y(Fe) or Fe-MDIP, showing (A) the Fe-oxotrimer and the MDIP linker, (B) the prismatic SBU and (C) the 3D framework. Color code: Fe, orange polyhedral; O, red; C, black; N, blue; H-atoms are omitted for clarity. The blue and green spheres represent the micropores.

Similarly to the previously described Fe-trimer-based MOFs, the Fe-MDIP represent a promising candidate offering the chemical prerequisite to promote VOC capture with minimal (in none) leak. In addition, it offers greater diversity to the MOF panel by introducing frameworks with relatively large pores and narrow apertures.

5. Challenges of MOFs Shaping

Despite their excellent intrinsic properties, MOFs are typically synthesized as fine powders, which severely limits their direct use in practical applications. As a result, shaping MOFs into mechanically stable and scalable forms is essential — but must be done without compromising their porosity or surface area[14].

Several strategies have been developed to address this challenge:

(i) **Granulation, extrusion, and pelletization**: Traditional shaping techniques that produce pellets, beads, monoliths, or foams, typically requiring the use of binders, solvents, or controlled processing conditions (e.g., pressure, temperature). Each porous material usually requires process-specific optimization to balance mechanical strength and adsorption performance[31, 32, 33, 34].

(ii) **Composite systems and hybrid materials**: Embedding MOF particles into polymeric or other continuous matrices (such as in mixed matrix membranes or composite monoliths) can combine the advantages of high porosity and mechanical flexibility. These approaches allow for higher MOF loadings, but also pose challenges related to particle dispersion, interfacial adhesion, and long-term mechanical performance[14, 35].

(iii) **Coatings and thin films**: Methods such as direct growth on supports, deposition of preformed nanoparticles (via dip-coating, spin-coating, or Langmuir-Blodgett), or layer-by-layer (LBL) synthesis can produce high-quality MOF films. While these approaches enable precise control over film morphology, they are generally more suited to applications such as gas separation, catalysis, or sensing and can face limitations in mechanical robustness and scale-up potential[36, 31, 37].

6. Toward Scalable and Sustainable Solutions

A key objective for the practical implementation of MOF-based air purification systems is the development of cost-effective, scalable, and environmentally sustainable shaping methods. Advances in process engineering, material formulation, and composite design will be critical to achieving this goal and ensuring that shaped MOF materials meet the specific technical and operational requirements of real-world applications.

The shaping of MOFs represents a decisive step in unlocking their full potential for air purification technologies. Whether in the form of pellets, monoliths, coatings, membranes, or other composite materials, each shaping approach offers unique benefits and faces specific challenges. The SIMIACCI project will evaluate these various strategies to identify the most promising and scalable solutions for enhancing indoor air quality in GLAMs environments.

6.1 Beads, Granules, Pellets: Shaping MOFs for Practical Applications

The shaping of MOF powders into larger, mechanically robust forms such as beads, granules, pellets, or extrudates is a critical step for their deployment in packed beds, filter cartridges, or reactors. These methods help improve handling, reduce pressure drops, and ensure efficient flow and diffusion in industrial systems[31].

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Granulation

Granulation is a widely used process to transform fine powders into larger agglomerates (typically 2–20 mm) for improved processability. Generally, formulations include MOF powder, one or more binders, additives like lubricants or plasticizers, and water or an organic solvent depending on binder solubility. Both inorganic (*e.g.*, silica, clays) and organic (*e.g.*, polymers) binders are commonly employed[38, 31, 39, 40].

Granulation techniques can be manual or automated, using devices that mix the formulation at controlled speeds on rotating plates to form spherical beads with narrow size distributions. The beads are then separated by size using sieves and thermally treated to enhance mechanical stability[38].

In extrusion-coupled spheronization, a mixture of powder, binder, solvent, and additives is pushed through a perforated die, producing calibrated extrudates. These are then shaped into spheres in a spheronizer equipped with a rotating, toothed plate that promotes collisions, followed by thermal treatment[31].

Notably, wet granulation involves spraying volatile solvents onto powders in a high-shear mixer, forming agglomerates, which are then rounded in rolling machines and dried. Dry granulation, by contrast, compresses powders at high pressures, followed by mild crushing and sieving. Reinforcement with binders (inorganic like clays[41], silica[41], alumina[42]; or organic like polyalcohols, carbohydrates[43] is often necessary to provide mechanical strength. For example, MIL-100 granules prepared with 10% silica binder showed superior NH_3 adsorption performance compared to pelletized counterparts, indicating that granulation preserves structural properties more effectively[44]. Similarly, MIL-100(Fe)@5PVB granules used in adsorption desalination combined good mechanical strength with satisfactory adsorption performance[45].

Pelletization

Pelletization, also referred to as compression or tableting, is one of the most commonly employed shaping techniques, both at the laboratory and industrial scales. It involves compacting powder by applying uniaxial pressure (typically several tens of MPa) using a punch in a die. Depending on the setup, one or both punches can be mobile, and in many configurations, a dwell time is included at maximum pressure to ensure optimal compaction[31].

This technique typically produces cylindrical or oblong-shaped bodies called pellets or tablets, whose size and shape can be precisely controlled. Its main advantage is its simplicity and the fact that it does not necessarily require binders, making it particularly attractive for small-scale tests. Moreover, it is cost-effective and relies on equipment that is relatively accessible at the lab scale.

However, the applied pressure must be carefully optimized. If the pressure is too low, the pellets will be fragile and prone to breakage; if it is too high, the crystalline framework of the MOFs may be damaged, leading to amorphization and loss of textural and adsorptive properties. The pressure ramp rate should also be controlled to avoid introducing internal mechanical stresses[46].

At the industrial scale, pellets are favored for packed-bed reactors, adsorption cartridges, and transport applications because they are easier to handle than powders, minimize pressure drops, improve mixing and bed homogeneity, and offer superior resistance to attrition and breakage. In some cases, adding binders (such as organic binders like starch, cellulose, polyvinyl alcohol, or inorganic binders like clays, silica, graphite) is necessary to enhance particle cohesion and mechanical strength. However, binders can modify both the physical and chemical properties of the material, as shown in examples like zeolites X and Y pelletized with bentonite or ZSM-5 zeolite shaped with kaolinite[47, 48].

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For MOFs, whose frameworks are generally more fragile than those of inorganic materials, such alterations can be particularly pronounced, and substantial porosity losses are frequently reported, especially when binders are used[31].

Extrusion

Extrusion is a continuous shaping technique widely used in the catalyst and adsorbent industries to produce well-defined forms such as rods, tubes, monoliths, or sheets (Figure 8). It involves preparing a paste composed of MOF powder, binders, plasticizers, and solvents, which is then forced through a die using a screw or a piston.

In screw extruders, the process operates continuously, while piston extruders work in batch mode but can handle pastes with higher viscosities. Plasticizers (such as polyethylene glycol or glycerol) are added to provide plasticity and facilitate flow through the die. After extrusion, the extrudates are cut to the desired length, dried, and often subjected to calcination or thermal treatment to remove plasticizers and harden the final shape[31, 38].

Extrusion offers numerous advantages: it enables the production of a wide variety of shapes with good reproducibility, scalability, and mechanical robustness, while maintaining controlled porosity. This technique is particularly attractive for industrial applications requiring high throughput and low pressure drop. For example, UiO-66-COOH extrudates have been successfully prepared and tested for ammonia removal, showing a good balance between mechanical stability and adsorption performance[33]. Similarly, Al-3,5-PDA MOF has also been successfully shaped into extrudates, showing good formaldehyde filtration efficiency[16].

Figure 8. Integration of MOF beads into filter media. (Photo credit: ENSICAEN – O. Gherrak)

6.2 Advanced Membranes and Composite Materials

Porous membranes represent an attractive shaping strategy for porous materials like MOFs, combining high mass transfer efficiency with excellent permeability and selectivity. Mixed Matrix Membranes (MMMs) are among the most common membrane types, prepared by dispersing micro- or nanoparticles of porous solids into a porous polymer matrix. This results in freestanding, flexible, and stable membranes that are easier to handle, and process compared to pure powder forms[49, 50, 51]. MMMs have been successfully fabricated with porous solid loadings of 30–50 wt% using relatively benign solvents such as water, ethanol, and isopropanol[52, 53, 54].

At higher loadings, particle aggregation can occur, which affects polymer–filler adhesion and may influence selectivity, sorption performance, and mechanical stability. Common polymers used for MMMs, such as poly(vinylidene fluoride), polystyrene, or poly(ethylene-co-vinyl acetate) [55, 56] are often oil-derived, relatively costly, and can be challenging to process in green solvents, creating interest in more sustainable alternatives[14].

Cellulose-based composites

Cellulose, the most abundant biopolymer on earth, offers an appealing sustainable option for composite membrane fabrication. Derived from wood and cotton pulps, cellulose is biodegradable, affordable, hydrophilic, and chemically stable, making it well suited to environmental applications like air and water purification. Composite filter papers combining cellulose fibers and porous solids have already shown promise, offering a high surface area for adsorption.

Two main strategies are used to combine MOFs with cellulose:

(i) In situ synthesis, where MOFs are crystallized directly onto cellulose fibers.
(ii) Ex situ blending, where pre-formed MOF particles are mixed with cellulose fibers.

Reported examples include in situ synthesis of MOFs like $Cu_3(BTC)_2$[57] and γ-cyclodextrin-MOF on plant fibers with 6–23 wt% loading, as well as zeolite A deposited at 30–40 wt%[58, 59]. Higher filler content can affect the integrity of the cellulose fiber network and impact mechanical strength. As a result, conventional paper composites typically incorporate filler levels around 20–35 wt% to maintain structural performance[60, 61].

Nanocellulose reinforcement

Nanocellulose, particularly nanofibrillated cellulose (NFC), offers a promising reinforcement strategy for porous composites. With its nanometer-scale diameter, micrometer-scale length, and excellent tensile strength, NFC enables the formation of dense, robust networks. It is already industrially available and has been applied to activated carbon papers with up to 70 wt% loading[62, 63].

Recent advances have extended these methods to MOFs: In situ growth of ZIF-8, UiO-66, and MIL-53(Al) on TEMPO-oxidized NFC (TOCNF), achieving 75–90 wt% loading[64]. Ex situ blending of zeolites (*e.g.* ZSM-5, silicalite-1) with TOCNF and polyethylene glycol, resulting in composites with up to 97 wt% loading and good flexibility[65].

While these approaches show strong potential, some challenges remain, including partial pore blockage, multi-step synthesis protocols, and energy-intensive conditions (such as hydrothermal or solvothermal treatments), which may affect scalability.

Sustainable one-pot process with cellulose fibers and nanofibers

A sustainable one-pot process has recently been developed for producing MOF–cellulose paper membranes with high filler loadings[14]. This approach combines softwood bleached kraft pulp (SBKP) fibers for flexibility and NFC for mechanical reinforcement. The process relies on simple and rapid mixing in water at room temperature, followed by filtration and drying without the use of toxic solvents or high-temperature steps. Minimal energy input is required, and the resulting nanostructured paper-like composites retain both the mechanical and adsorption properties of the MOF while behaving mechanically like a sheet of paper[14]. This method offers a promising pathway for scalable production of functional materials, particularly in applications such as air purification.

The integration of MOFs into membrane and paper materials provides a versatile and scalable platform for developing high-performance composites. By combining the mechanical advantages of nanocellulose with the sorption capabilities of MOFs, these materials hold promise for a wide range of practical applications.

6.3 Coated Substrates for Air Filtration and Surface Immobilization of MOFs

The integration of Metal-Organic Frameworks (MOFs) into existing filtration and air purification systems is a promising approach to enhancing performance. Specifically, the deposition of MOFs directly onto pre-structured supports such as fibers, foams, metal meshes, honeycomb monoliths, or HVAC filter media offers a unique solution for air filtration and purification applications. This technique preserves open airflow channels, which minimizes pressure drop and facilitates smooth integration into established HVAC systems. Furthermore, it ensures superior mechanical stability, particularly in systems subject to high air velocities, making it ideal for industrial applications.

Several deposition techniques have been developed to coat substrates with MOFs, each providing distinct advantages depending on the application requirements. These methods allow for the creation of functionalized surfaces with controlled MOF layer thickness, and some offer considerable flexibility in adapting to diverse substrates. Below, we examine the most employed techniques for MOF deposition onto substrates[31, 36, 37].

In-situ Growth of MOFs

In-situ growth is one of the most widely used methods for creating MOF coatings (Hong 2018). This technique involves immersing the substrate in a solution containing metal salts and organic ligands, followed by thermal hydro- or solvothermal treatment to induce the crystallization of MOFs directly on the surface. Solvents such as water, ethanol, DMF (dimethylformamide), or DMSO (dimethyl sulfoxide) are typically used for the synthesis. In some cases, microwave-assisted heating has been employed to accelerate the process[66, 67].

The in-situ growth method can be particularly effective for producing MOF coatings with excellent adhesion to the substrate, as the MOF crystals grow directly onto the surface. Metal substrates, such as copper or zinc, can even act as a source of metal ions, which can then react with the organic ligands in the solution to form the MOF structure. By adjusting key parameters such as temperature, concentration, solvent properties, and pH, the properties of the MOF coating, including crystal size and morphology, can be controlled[68, 69, 70]. This method offers a simple and cost-effective approach for integrating MOFs into filtration systems, as demonstrated in studies where HKUST-1 MOFs were successfully grown on copper substrates[36, 71].

Dip Coating

Dip coating is a well-established technique for applying thin films of MOFs to various substrates. This process involves immersing the substrate into a solution containing MOF precursors and then withdrawing it at a constant speed. As the substrate is removed, a thin film of MOFs forms on the surface, which can then be dried. The thickness of the resulting film depends on several factors, including the withdrawal speed, the number of coating layers, and the drying process [36, 71].

This method is particularly advantageous because it allows for the rapid deposition of MOF films with thicknesses ranging from 40 nm to 1 µm, and the process can be easily controlled by adjusting the coating parameters. Dip coating has also been shown to work well for porous substrates, such as polymer sponges or metal meshes, and it can be enhanced using surfactant-assisted methods. These advantages make dip coating a versatile and cost-effective option for MOF deposition, particularly when large-scale production is required. Notable examples include MIL-100(Cr) and MIL-101(Cr) MOF films on alumina substrates[72, 73].

Spin Coating

Spin coating is another technique used to apply MOF films onto substrates. In this process, a small amount of MOF precursor solution is placed on the center of a rotating substrate, and centrifugal force spreads the solution evenly across the surface. As the solution spins, solvent evaporation leads to the formation of a thin film. The thickness of the film is primarily controlled by the spin speed and the evaporation rate of the solvent[74].

One of the key advantages of spin coating is the ability to create very thin and uniform layers of MOFs, often with thicknesses under 100 nm[75]. While spin coating is effective for creating ultrathin films, it does have some limitations. One notable disadvantage is that the MOF films may not always adhere strongly to the substrate, which can lead to issues with durability and long-term stability. However, the simplicity and speed of the spin-coating process, coupled with the possibility of functionalizing the MOF films, make it an attractive option for certain applications, such as optical sensors or catalytic layers. For instance, NH_2-MIL-88B photonic films and TiO_2-coated conductive glass substrates for photocatalysis have been successfully prepared using this method[76].

Layer-by-Layer (LBL) Method

The Layer-by-Layer (LBL) method is a more advanced technique for fabricating thin MOF films with precise control over thickness and structure. This method involves the sequential deposition of alternating layers of materials, often with opposite charges, onto a substrate. The process is typically referred to as liquid phase epitaxy and is widely used for producing highly uniform, crystalline MOF films with controlled thickness from nanometers to micrometers[31, 77, 78].

One of the main benefits of the LBL method is its ability to generate films with excellent crystalline orientation, which is particularly useful for applications such as membranes, drug delivery systems, and sensors[79, 80, 81]. The method also allows for precise control over the interpenetration of MOF structures, which can be beneficial for achieving specific performance characteristics. Substrates like metals, glass, and polymers can all be utilized in the LBL process, and the ability to vary the number of deposition cycles allows for fine-tuning the properties of the resulting MOF films[77, 78].

Spray Coating and Electrospray

Spray coating, including electrospray, is a versatile method that involves spraying a precursor solution onto a heated substrate to form a thin MOF film[82] (Figure 9). The sprayed droplets undergo solvent evaporation, resulting in the self-assembly of the metal ions and organic linkers. This method is particularly effective for large-scale production and can be used on a variety of substrates, including porous materials[31, 82, 83].

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One of the key advantages of spray coating is that it is a solid-state process, which reduces the risk of damaging the MOF during deposition. The process is also faster than other deposition techniques and can be adapted for use with large, irregularly shaped substrates. Additionally, spray-assisted methods, such as spray-assisted liquid-phase epitaxy, have been employed to produce oriented MOF films with applications in areas such as gas separation, catalysis, and sensing. For example, HKUST-1 thin films have been successfully prepared using a spray-assisted deposition process on various substrates, including silicon wafers and porous alumina[84, 85].

The development of various techniques for depositing MOFs onto substrates has significantly expanded the potential applications of these materials, particularly in the fields of air filtration, purification, and catalysis. The choice of deposition method depends on the specific requirements of the application, such as film thickness, uniformity, adhesion strength, and processing time. Techniques such as in-situ growth, dip coating, spin coating, layer-by-layer deposition, and spray coating each offer unique advantages, and their combination can lead to the creation of highly functionalized MOF-coated substrates. These innovations promise to improve the efficiency and scalability of MOF-based technologies in industrial air filtration and purification systems.

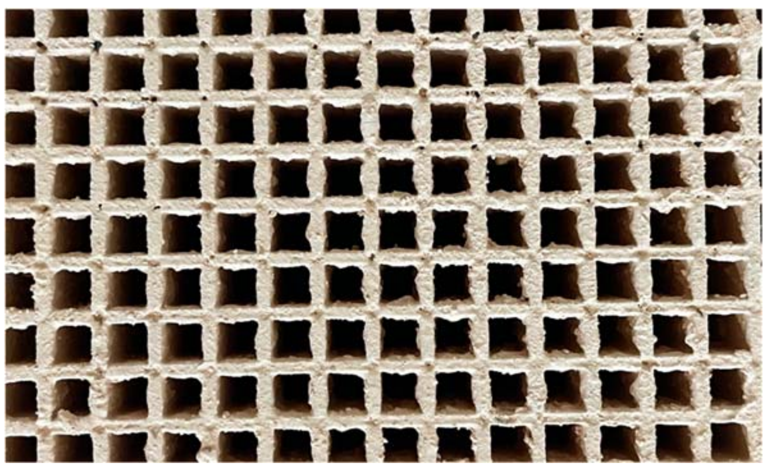

Figure 9. Illustration of a MOF Coating on a Solid Support (by SquairTech)

7. Integration of MOFs into HVAC and Air Purifiers for GLAMs Environments

The integration of Metal-Organic Frameworks (MOFs) into Heating, Ventilation, and Air Conditioning (HVAC) systems, as well as air purifiers, offers a promising solution for enhancing air quality management in GLAMs. These institutions house artefacts collections that are highly sensitive to air pollution, including volatile organic compounds (VOCs) like formaldehyde and acetic acid, nitrogen oxides (NOx), and hydrogen sulfide (H_2S). The ability of MOFs to efficiently adsorb these pollutants makes them ideal for addressing these challenges in GLAMs environments. However, successful integration requires addressing several critical factors related to physical compatibility, filtration performance, durability, and scalability.

7.1 Physical Compatibility

To ensure seamless integration of MOFs into HVAC systems and air purifiers, the MOF-coated materials must be physically compatible with existing filter slots and cartridges. MOFs need to be fabricated into forms that allow easy incorporation into standard HVAC filters and purifier cartridges without significant modifications to current infrastructure. This involves optimizing the size, shape, and structure of MOF-based substrates, enabling smooth integration into these systems. By doing so, filtration efficiency can be maximized without requiring costly alterations to existing hardware.

7.2 Performance Under Flow Conditions

The filtration performance of MOF-coated filters under dynamic airflow conditions is a key consideration. HVAC systems and air purifiers operate with varying airflows, and the MOF-based filters must remain stable and effective in capturing pollutants across these fluctuations. Additionally, the MOF deposition on filter substrates should minimize the pressure drop across the filter medium. A low-pressure drop is essential to maintain air circulation without overloading the system. This balance ensures that the filtration system functions efficiently without unnecessary energy consumption or strain on components.

7.3 Durability

The continuous operation of HVAC systems and air purifiers requires MOF coatings to exhibit excellent durability. These systems often undergo frequent cycling between adsorption and desorption processes, particularly when filtering gases and pollutants from the air. For the MOF-based filters to remain effective over time, they must be resistant to mechanical wear, as well as to fluctuations in temperature and humidity—conditions common in GLAMs environments. The long-term stability and reliability of MOF filters are critical to ensure that they continue to perform effectively, preserving indoor air quality and protecting sensitive cultural collections.

7.4 Factors to Consider for Industrial Production of Shaped MOFs

When scaling up the production of MOFs from laboratory synthesis to industrial-scale manufacturing, several key factors need to be addressed to meet the requirements of large-scale HVAC and air purifier applications in GLAM environments. These factors include production throughput, cost, environmental impact, and regulatory compliance.

7.5 Production Throughput

For industrial-scale applications, the throughput, or the quantity of MOF material produced per unit of time, is a key factor. Laboratory-scale synthesis typically produces small quantities of MOFs, often focusing on high crystallinity. However, for air purification in HVAC systems and air purifiers, large volumes of material are required. Therefore, synthesis methods must be optimized to produce MOFs in larger quantities without compromising their quality or performance. Developing scalable production techniques is crucial to meet the volume demands of HVAC and air purification systems in GLAMs environments.

7.6 Cost Considerations

Cost is an essential consideration when transitioning from laboratory-scale synthesis to industrial production. The overall cost of MOF production includes raw materials, energy consumption, labor, and equipment. While cost differences between various shaping methods may be negligible at the laboratory scale, they become more significant at the industrial scale. Special solvents, high-temperature processes, and non-automated equipment can drive up costs. Therefore, the MOF production process must be optimized to reduce costs while maintaining high-quality standards, ensuring the economic viability of MOF-based air purification solutions in GLAM environments.

7.7 Equipment Availability and Operational Complexity

For industrial-scale manufacturing, the availability of appropriate equipment is essential. Many laboratory-scale synthesis methods rely on specialized equipment that may not be easily adaptable to large-scale operations. Industrial-scale equipment must be capable of handling higher volumes of MOFs while maintaining consistent quality and efficiency. Furthermore, simplifying production processes and reducing operational complexity is vital to minimize human error and ensure the scalability of the process.

7.8 Requirements from Application Scenarios

In the context of the SIMIACCI project, the integration of MOFs into HVAC systems and air purifiers must meet the specific requirements of GLAM environments, particularly regarding filtration, adsorption, and de-NOx catalysis.

Filtration and Adsorption Applications

The primary objective for MOFs in GLAM environments is the effective removal of pollutants such as formaldehyde, acetic acid, H_2S, and NOx. The requirements for MOFs in filtration and adsorption applications include:

- **High Adsorption Capacity**: MOFs must possess high surface areas and many active sites to effectively adsorb pollutants like formaldehyde, acetic acid, and H_2S from the air. This ensures efficient air purification.
- **Selective Adsorption**: The ability of MOFs to selectively adsorb target pollutants is critical. For the SIMIACCI project, the design of MOFs must allow for the preferential removal of formaldehyde[16], acetic acid[18], and H_2S[17] while minimizing the interference from other substances in the air.
- **Low Pressure Drop**: To ensure optimal performance of HVAC systems and air purifiers, MOF-based filters must minimize the pressure drop across the filter medium. This ensures that air can flow freely through the system while maintaining efficient filtration.
- **Long-Term Chemical Stability**: The MOF filters must exhibit chemical stability over time, even in the presence of moisture and varying temperatures commonly found in GLAMs environments. This ensures long-term effectiveness without degradation of the material.
- **Regenerability**: MOFs should be capable of regeneration using practical and energy-efficient methods, such as mild heating, to enable multiple adsorption–desorption cycles. Alternatively, regeneration by washing with water at room temperature can be employed to enhance sustainability. Throughout these cycles, the MOFs must maintain high pollutant adsorption performance, thereby ensuring improved long-term stability and lowering overall operational costs—including energy consumption, maintenance, and material replacement—in real-world applications.

De-NOx Catalysis Applications

For NOx removal, MOFs with catalytic properties offer an additional advantage[13]. The key requirements for MOFs in de-NOx catalysis applications include:

- **High Catalytic Activity**: MOFs used for de-NOx catalysis must contain active metal sites that efficiently convert NOx into less harmful substances. The catalyst must function at ambient conditions and maintain high catalytic efficiency throughout the operational lifetime.
- **Durability**: Given the cyclic nature of de-NOx catalysis (adsorption and desorption), MOFs must maintain their catalytic activity over time, even under varying conditions of humidity and temperature.
- **Low Energy Consumption**: The de-NOx catalytic process should be energy-efficient, operating effectively at low temperatures without requiring significant energy inputs, aligning with the SIMIACCI project's objective to minimize energy consumption.

8. Summary

Table 1 summarises the key specifications of the MOFs mentioned in this report as well their key features and selectivity for given pollutants.

Table 1. Key specifications of the MOFs

MOFs	Formula		S_{BET} $m^2.g^{-1}$	Key feature		VOC / Pollutant / Gas			
	Linker	Inorganic building unit (IBU)		OMS	Azolate	AAc	NO_x	H_2S	FA
MIL-100(Fe)	BTC	Fe_3O trinuclear Fe(III) oxo cluster	~2000	✓	X	●●●●● 9 mmol/g	●●●○○ 4 mmol/g	●○○○○ N.D.*	○○○○○ N/A**
MIL-127(Fe)	TazBz	Fe_3O trinuclear Fe(III) oxo cluster	~1400	✓	X	●●●○○ N.D.	●○○○○ N/A	●●●●● 1.3 mmol/g	○○○○○ N/A
Al-3,5-pda	PDA	Single Al^{3+} coordinated with (OH^-)	~1200	X	✓	○○○○○ N/A	○○○○○ N/A	○○○○○ N/A	●●●●● 2.7 mmol/g
MIL-59(Fe)	IPA	Fe_3O trinuclear Fe(III) oxo cluster	~400	✓	X	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.
CAU-52(Fe)	FDCA	Fe_3O trinuclear Fe(III) oxo cluster	~1077	✓	X	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.
MIP-21X(Fe)	FDCA	Fe_3O trinuclear Fe(III) oxo cluster	~1100	✓	X	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.
MIP-21Y(Fe)	MDIP	Fe_3O trinuclear Fe(III) oxo cluster	~1200	✓	X	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.	○○○○○ N.D.

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10. Annex A. Expectations from the GLAMs: SIMIACCI Survey – ''How is your Indoor Air Quality management?''

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 place June 3, 2025 (Milestone 4).

The questionnaire was intended strictly for use within SIMIACCI and the main results to be communicated during the Focus Meeting. When evaluating the survey, qualitative statements were anonymised. To allow content related analysis, they were cross-referred with consecutive numbering. It was possible to match individual respondents to this number to study each respondent's answer with more detail.

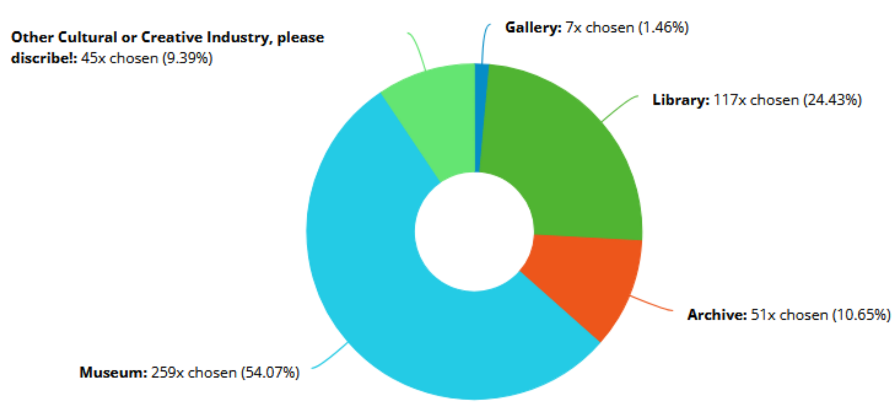
The results shown in this Annex are organized by question (Q1 to Q12) and are based on the total number of responses to each question. Whenever a comments box was available, the comments are gathered after the data analysis.

10.1 Results of the survey

10.1.1 Work context and acquaintance with IAQ

Q1 What type of organization do you work for?

Number of responses: 479

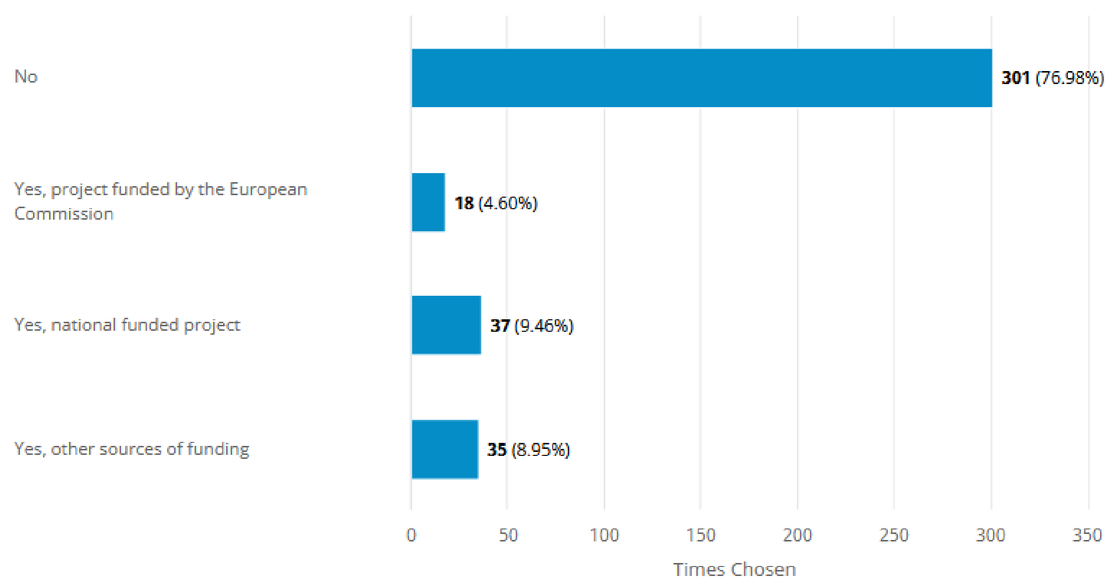


By far the largest number of responses was coming from museums (54%), followed by libraries (24%), archives (11%), other CCI (9%) and galleries (1 %).

Other CCI comprised: Conservation Laboratories (10), Research Institutes and Centers (7), Monuments (7), Combined (Library, Archive, Museum, other) Institutes (4), Universities (2), Museum support Institutes (2), Institution/Foundation managing several museums and historic buildings (2), Vendor/ Preservation & Digitisation (1), Consultant (1), Graduate student working at affiliate institutions and museums (1).

Q2 Are/were you/your organisation involved in projects related to IAQ/preventive conservation?

Number of responses: 391



The largest number of participants responded they had no involvement in projects related to IAQ / preventive conservation (77%). Then, a small number was involved in national funded projects (9%) or projects with other sources of funding (9%). Some respondents were already involved in projects funded by the European Commission (5%).

Q3 If yes, please describe briefly the project(s) and your role:

The following information given by the participants who responded ''yes'' to Q2 (each paragraph is the answer from one respondent unless specified from two respondents) is given ''as responded''. The 30 comments gathered indicate that, even if in small number in the GLAMs community, the persons involved in IAQ projects are extremely active and aware of the state-of-the-art situation.

EU funded projects:

- **MEMORI**: developing accessible dosimeters and reader. Our role WP leader in developing decisions support model, collating pollution damage information on acetic and formic acids, ozone and nitrogen dioxides and mitigation model for practical approaches.

* Two answers were given for: The project is an extension of Ki Culture's existing '**Getting Climate Control Under Control**' programme in France, with the aim of revising conservation standards, taking into account the specific characteristics of each museum institution, and reducing the energy consumption of these establishments.
* **JEWELS TOUR** - JEWish heritage as Leverage for Sustainable TOURism The City Council of Coimbra, in collaboration with partners from six European Union countries, is participating in the JEWELS TOUR – JEWish heritage as Leverage for Sustainable Tourism project, co-financed by the European Union, with the participation of the Regional Development Agency of Lviv, Ukraine. The common goal of JEWELS TOUR is to improve policy instruments to promote the valorization of Jewish cultural heritage, making it more accessible and attractive in terms of cultural, economic and tourist growth of the European cities involved.
* Two answers were given for: Interreg Europe – **CHARME:** The City Council of Coimbra, in partnership with four European cities and the University of Pavia (Italy), is participating in the **CHARME** project – Digital Cultural Heritage Activity across Multiple European Regions, co-financed by the European Union. In accordance with the Interreg Europe Programme, the aim of the CHARME project is to improve a policy instrument for each partner, aiming to implement regional development strategies and, ultimately, to resent solutions that benefit all citizens

Nationally funded projects:

* Principal Investigator of the **DBU project "Testing And Optimisation Of Specic Sorbents For The Preventive Conservation Of MalignantPlastics"** (https://www.dbu.de/projektdatenbank/37258-01/). The project aimed at identifying selective sorbents capable of taking up harmful emissions from degrading polymeric materials but with a reduced sanity for plasticisers
* We were involved both in **national and EU funded research projects**. The projects targeted on IAQ in museum showcases, mitigation possibilities by implementing adsorbent media (active/passive) and sensor technologies for monitoring IAQ on low-cost basis on-site. We were work package leader, performed main research activities and published the results in peer-reviewed journals and also presented them on conferences
* **Evaluating of the climate and atmospheric corrosivity in museum vitrines**, storage rooms and other museum objects (churches, historic buildings) using glass-dosimeters in order to get long-term integral information. **Glass-dosimeters** were developed, prepared and placed at the objects, and after exposure times between 3 and 12 month examined in our laboratories. At the end of the project, depending of the outcomes of the measurements, recommendations to ameliorate the storage-conditions in the vitrines were made.
* We have a unit for preventive conservation as well as one that works on **sustainability**. Both are working on projects in the field of preventive conservation. I think they are all nationally funded, but maybe some also European, I am not sure. Also the lab-department have a lot of projects, (nationally and European funded), it might very well be the case that they touch upon elements of preventive conservation as well.
* Project Coordinator of the Federal Strategy for the FSIs' Emergency Plans (**FEDERESCUE**). Coordination since 2021 of the 10 **Federal Scientific Institutions (FSI's) Emergency Plans** development. Through the setting-up of a formal coordination platform, our goal is to develop a common approach for the FSIs Emergency Plans within 5 years for better protect the people, our collections our data and our buildings. This project brings together more than 40 colleagues from the FSI's and the Federal Public Planning Service Science Policy (**BELSPO**). Project Manager of the KIK-IRPA strategy 'Heritage in Crisis'. Together

with Belgian actors in the heritage sector, we develop a national strategy for integrated risk management for heritage. This strategy emerged from the floods that severely hit Wallonia in July 2021, endangering more than 250 cultural institutions. The strategy includes coordination work, applied research and post-crisis analysis and recommendations. Project Manager of **Climate2Preserv** (2021-2025), a 4-year research project for the development of practical and state-of-the-art online tools to support Belgian museums in the sustainable improvement of the indoor climate management of their collection rooms (temperature & relative humidity mostly). Internal Emergency Plan Coordinator. I coordinate various working groups with representatives of the KIK-IRPA's departments (Building & Safety; Collections; Laboratories; Documentation, IT & Administration). The Plan includes the development of an internal emergency plan, the implementation of a staff training program and the building of local capacities and networks. Project Manager of Resilient Storage, a program for improving the efficiency of the HVAC systems in the context of Belgian museums. Project Coordinator of the **feasibility study for the KIK-IRPA building** renovation (2021-2022). Providing the requested information and organizing internal workshops for discussing KIK-IRPA's needs and vision with an eye to the 50 coming years.

- **DSC-VOLATILE** project founded by the Bibliothèque nationale de France. The aim of the project is to test different analytical methods to identify volatiles molecules and particles in the library environments. I'm part of the supervision of the project.
- The project aims at **testing and optimizing various analytical methods for sampling VOCs surrounding heritage collections** (with a particular attention to pollutants harmful for the artworks) within our public institution. As conservation scientists, our role is to undertake this study and practical work in the laboratory
- We are planning new collection care center and I am responsible for **set up of indoor climate condition**
- Project on climatic setpoints for HVAC systems, focused on energy savings and conservation (project "**Prenons le contrôle du climat**", lanced by the French ministère de la Transition écologique et solidaire, program "Alternatives vertes 2") - Project on the development of transport crates made of cardboard rather than wood (project "**ça va cartonner**", by the French ministère de la Transition écologique et solidaire, program "Alternatives vertes 2)"
- US National Endowment for the Humanities grant on "**Integrating Risk Assessment for Pollutants into Energy- saving Strategies**"- designed and was awarded grant, served as PI for a year, subsequently served as consultant, co-author on publication
- small fund to purchase **OnGuard monitor** to assess rates of corrosion in environments- wrote grant, analyzed data and report on results
- **VOC monitoring in living museums with objects**. Manager of staff doing the research
- **Screening of IAQ in storage buildings**. Project leader. I designed and perform the monitoring campaign.
- The main objective was to **evaluate indoor climate and global warming potential** (GWP) for storage buildings in Denmark
- Our museum belong to Rede Portuguesa de Museus where we have access to **preventive conservation trainings**

Projects based on other sources of funding:

- I serve as the preventive conservator at a privately funded art museum and am involved in **Oddy testing, casework analysis**, etc.

- **Measurement of air quality in a selection of exhibition rooms and in display cases** to investigate emissions from display case material
- PI **Wildfires** are increasing in intensity and frequency, as seen recently in Los Angeles, posing significant challenges for cultural heritage preservation. A major obstacle to response and recovery is understanding how these spaces have been altered, especially by particulate matter (PM) which can have health impacts on patrons and staff as well as visual and chemical impacts on collections. PM is not well characterized or monitored within cultural heritage institutions, necessitating additional study and development of protocol essential for the continued longevity of collections. This project, using the **QuantAQ PM sensors**, aims to develop greater institutional understanding of outdoor air infiltration, HVAC functionality, and occupancy impacts on collections to **create data driven protocols for disaster response protocols**. These sensors are highly calibrated and easily deployed both indoors and outdoors to collect meaningful data. Additionally, cultural heritage institutions often over-regulate air quality, leading to excessive financial and environmental costs. By deploying advanced air quality sensors alongside a comprehensive energy usage study at Winterthur, we will gain critical insights into airflow dynamics. These findings will inform data-driven protocols for more sustainable climate control strategies. This project also serves as a training platform for undergraduate and graduate students through internships, summer research experiences, and environmental cultural heritage coursework. By equipping students with hands-on experience in sensor deployment and data analysis, we are preparing the next generation of professionals to be stronger advocates and stewards of cultural heritage.
- **Pilot study for IAQ monitoring using low-cost personal monitoring sensors and HVAC data**. I am a preventive conservation student and I partnered with an atmospheric chemist with experience in IAQ research.
- **Redevelopment of site and new strong rooms** attached to older extensions. Conservator.
- Our department is responsible for managing **storages for nitrate and cellulose acetate negatives**.
- Storage facilities at my institute are equipped with air conditioning and air monitoring systems as a preventive conservation mode. **Evaluation and process planning for preventive conservation in new permanent exhibitions Mitigation of gaseous pollutants from space suits on display.**
- KB National Library of the Netherlands **monitors T, RH, CO2 and light**. We tested some IAQ sensoring for future usage when we go to a passive solution for our storage in which no ventilation is present. We still research what we need to measure (off-gassing of paper and related materials).
- As part of my daily tasks, I monitor **indoor air quality using our Building Management System**. Additionally, during the Library's large-scale renovations, we assess any work that may affect air quality, aiming to minimize off-gassing.
- We took part **in a study of air quality when the ventilation system is switched off**. The study had two aims: - To find out what happens in the event of a fault and to take corrective action if necessary. - To investigate the possibility of shutting down the air handling system to save energy.
- IMLS (USA) funded **project relating indoor air pollutants to their source materials and observed corrosion**, with a focus being to **benchmark the Oddy test by creating reproducible standard test mixtures.**

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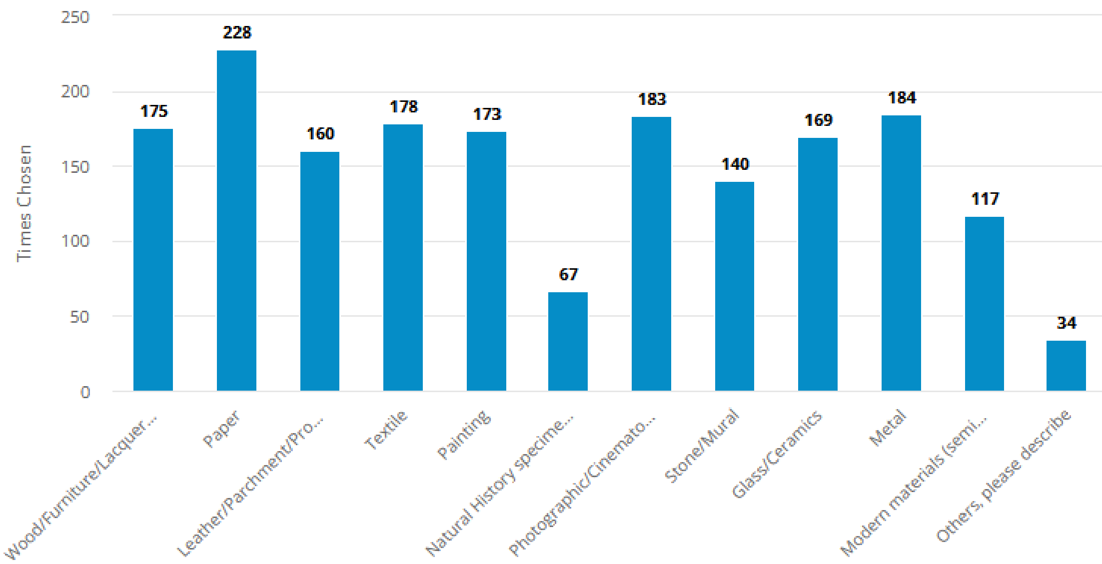
Q4 What type of artefacts/materials are held in the collections of your organisation?

Number of responses: 315



The largest group of collections are based on Paper materials (72%), followed by Metal (58%), Photographic /Cinematographic/Audio-visual (58%), and Textile (57%).

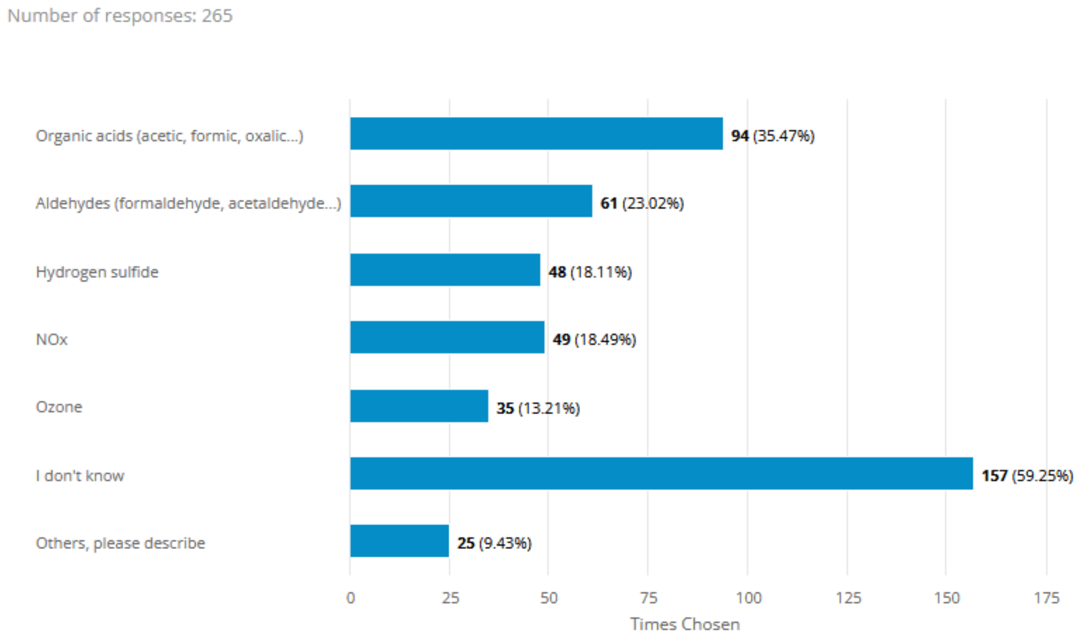
The number of objects categories (12) related to the total number of responses (1808) and the number of respondents (315) indicates that even when dedicated to one type of CH holding value (*e.g.* Archives and Libraries), as expected, the majority of the organisations conserve mixed materials collections. 32 organisations even indicate that they hold all of the artefacts and materials listed. More than 150 institutions hold at least five different materials. In conclusion, there exists a large variety of materials in individual collections, which is an important and notable factor concerning IAQ control and passive preservation issues in general.

''Others'' comprise**:** Organic materials (5x), Sculptures (4x), Archeological / ethnographic objects (4x), musical instruments (2x), Wax (2x), Whale bone/ ivory (2x), Audio Carriers (2x), Industry monuments (1x), Plastics (1x), terracotta/ clay (1x), Industrial objects (1), Historical buildings (1x), Hypermobile vehicles (1), Plaster (1x) and electronic equipment (1x).

In conclusion to Questions 1 to 4, The Collections in most GLAMs are varied and include organic as well as inorganic materials, which as described in section **Error! Reference source not found.** and **Error! Reference source not found.Error! Reference source not found.** of this report need different IAQ settings. The questionnaire was successful in targeting groups of professionals in a variety of GLAMs, CCIs and Research laboratories. The respondents who provided detailed information on their IAQ activities, correspond to the (minor) group (23%) who responded involvement in IAQ related project (Q2).

10.1.2 IAQ implementation

Q5 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?



The largest group (59%) of respondents indicate that they do not know what type of VOC or indoor gas pollutant are of concern for the preservation of the collections in their organizations. The reasons for such a lack of knowledge about pollutants might be on one hand, that it was likely not always the person responsible for preservation and IAQ issues who took the survey. On the other hand, there might be a lack of awareness on available devices and methods, but also a lack of availability and/or resources for measuring IAQ, or a low prioritization of the IAQ matter within the institution.

The pollutants of greatest concern are: **Organic acids** (35%), **Aldehydes** (23%), **NOx** (18%), **Hydrogen sulfide** (18%) and **Ozone** (13%). The first four pollutants being the ones that are targeted in SIMIACCI, the survey fully confirms this choice. Additionally, **high humidity levels** were mentioned as problematic by two respondents. This can seem anecdotic but it can be noted that since the survey did not include T/RH management issues questions, one did not expect comments on T/RH. However, T/RH management is a major issue in GLAMs, and the highest priority before pollution management. This can be an additional explanation to the large number of "I don't know'' responses (59%).

Other VOC's of concern comprise:

Sulfur dioxide (SO_2) and Sulfur trioxide (SO_3) / SOx (mentioned 6x). **Particulate Matter (PM) was mentioned 3x, and CO2 (2x).** Furthermore, the following VOCs of concern were mentioned one time each: NH_3, HNO_3, Carbonyl sulfide, Dimethyl sulfide, Toluene, Isobutylbenzol, 1,4 Diethylbenzene, Vanillin, Pesticides, Organic solvents used in restoration work, Plasticizers, Petroleum based solvents, Resin adhesives, Naphthalene and Arsenic.

Comments Section

The respondents had the option to give their comments, and 31 persons commented on this question.

The following information was given by the participants of the questionnaire (each paragraph represents one answer):

- We carried out a background survey for the pollutants noted above in 2022. In 2023 we had an incident in a showcase from what turned out to be **acetic acid off-gassing** from case furniture (a podium) affecting a limestone object. We also have had problems in showcases with growths of **crystals of 2,2,6,6-tetramethyl-4-piperidinol** (TMP-ol) but not on objects. In general we are always concerned about **H_2S** because of the low threshold for tarnishing.
- We don't have pollutant meters. However, the museum I work for is next to the sea, where you can see a lot of **saltpeter** inside.
- There are a few others **piperidinols** and **morpholines**, that people have had issues with, but we've avoided so far
- We were also interested in **Particulate Matter** measurements as we wanting monitoring to also determine infiltration of **soot/ash during wildfires**.
- exhaust/**odors from cafe kitchen** (in corridors not necessarily in collection rooms)
- These types of analyses have never been done or requested, so I don't know specifically what I should ask for analysis. The ones I selected [organic acids, aldehydes, NOx] will certainly be found due to the various types of materials that make up this very particular collection.
- The Central Bohemian Museum is adjacent to the **wastewater treatment plant** and the VUAB, Pharma, a. s. [**pharmaceutical plant**]
- **Mold/Mildew, Metal Particles, Asbestos**
- We have tested for the above plus general VOC levels. We are most concerned about **organic acids** and **H_2S**
- We emphasize the use of only inert materials that do not emit VOCs. The depository is designed this way. If necessary, we **check the corrosivity of materials with Oddy tests**.
- In our institute we have an HVAC system in multiple spaces. Others however work solely on dehumidifiers and humidifiers. Since we do wet- and dry treatments and since our objects consist out of so many different materials and come from so many different heritage institutions etc in Belgium (and sometimes from abroad), I think we are confronted with a **multitude of indoor air pollutants**. This is for the conservation studio's and lab department (these are also all spaces where we cannot open windows due to the risk of other agents of deterioration... But also our office spaces have some issues here and there, for our building was very cleverly and beautifully constructed in - state of the art materials and design - around the 1950's-60's and elements like flooring (some kind of linoleum) really smell and it is necessary to open windows before starting to work in these spaces.
- Particulate matter, atmospheric particulate matter from pollution in urban area
- I do not think that the products of outgassing from the decay of recording tape have been widely studied. We think we know that "**vinegar syndrome**" from decaying cellulose acetate is "contagious" and can "infect" (more properly catalyze, I think) nearby elements of similar structure. There has been little study on the decay products of PET and other base films to the best of my knowledge.
- **Asbestos** from modern-era building construction, e.g., found in linoleum and insulation
- The Aircon system are not functioning optimally, and we struggle with too **high heat** for periods of times which have an effect on the legacy material (e.g. open reel tapes) which we can smell is busy degrading.

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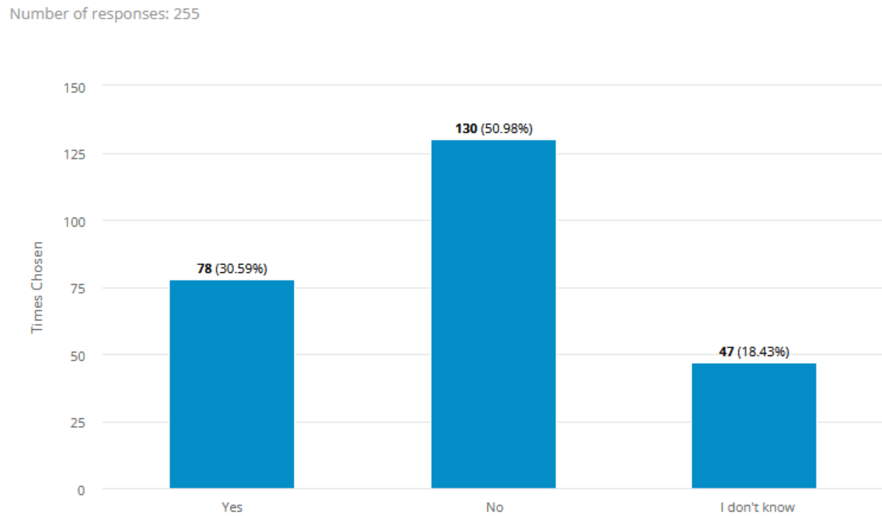
- We have earlier been involved in a project developing adsobents, the company Adsorbi that was a spin-off from a **ERC-funded project**, **APACHE**
- we have carried out a background survey of the pollutants above, our main concerns **are organic acids and hydrogen sulphide**
- While it is easy to list those above, in my experience we find a significant amount of **other VOCs** which could also do damage to collections. Often these areas are bespoke, and while they might have the listed compounds, they are also filled with others at ratios that are unique to their own spaces
- In case of no ventilation, we might encounter **gasses that are now missed due to the tiny amounts** in relation to others. We intend to research a new method especially catered for robotised, passive storage solutions.
- **Organic solvents** for conservation and restoration work
- **Organic solvents** (consolidation, cleaning processes)
- Our storage conditions are not optimal, so we are mostly concerned with **outdoor air pollution**.
- We have carried out a survey of typical museum pollutants in galleries, storages and showcases including **all of the above plus SO_2**. Our baseline levels are largely within 'safe' levels however we have had issues with **organic acids** from objects and case furniture and are also always concerned about **H_2S** as the thresholds for tarnishing are so low.
- High levels of **formaldehyde** were detected in off-site storage rooms, due to crates made up of fiberboard.
- **Sulfuration (tarnishing)** of silver objects was observed on collections in permanent exhibition
- We've had off-gassing issues, as well as **speculated particulates/sulfate concerns from a coal train** that passes nearby.
- **Plasticizers**
- We are mainly focusing efforts on mitigating risks from **indoor pollutants from the building**, display case and storage furniture and artefacts themselves
- Unfortunately, an analysis of the air quality in the museum to identify VOCs was never carried out. But since the museum is located in an area of the city of Lisbon with a lot of **road traffic**, very close to the river and with exhibition equipment made with very old materials, we suspect the presence of VOCs inside the museum.
- Some **traffic pollution**.
- Despite the notorious presence of pollutants in the museum's air, with **widespread deposition of particles**, no analyses have yet been carried out to identify them. We are located under a viaduct, inside a metro station, next to two intersections with **heavy traffic**. Being very close to a football stadium, every week we have food trailers (fried food, etc.) near one of the museum's emergency exits and the metro station's vents. Also, the club's football fans set off petards and vary-lights near the museum's entrance.
- **Subway pollution** and **road pollution**.
- **Ozone**, if not filtered for, via active ventilation

Q6 Does your organisation use adsorbents in showcases, public rooms or repositories?

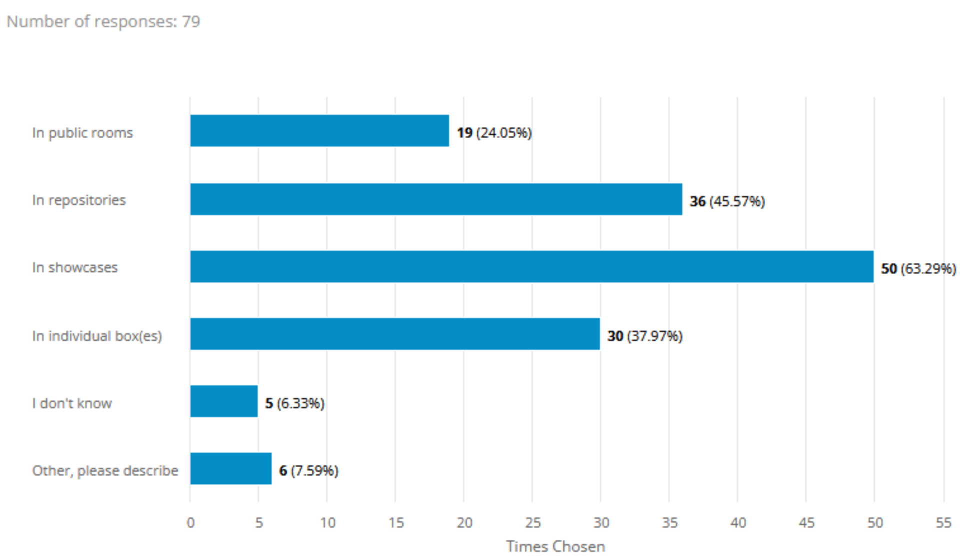


The question was answered by 255 participants, whereof 31% indicate the use of adsorbents, while 51% do not use them and 18% do not know if adsorbents are in use in their CCI.

The analysis shows that the large majority of GLAMs using adsorbents are Museums (52x), while Libraries (9) and Archives (8), as well as some other institutions (Laboratories, Universities) barely use adsorbents.

The next few questions were designed to gain more information about the specific details and characteristics, as well as the locations where the adsorbents are implemented.

Q6a Where are the adsorbents implemented?

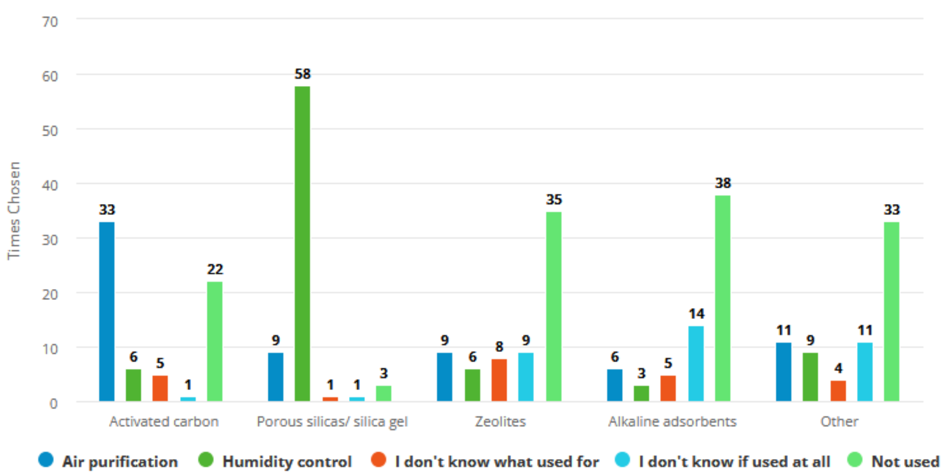


This and the following 3 questions were available only if ''yes'' was answered to Q6. Of the 79 answers given, 63% of the respondents indicated that adsorbents are used in showcases, followed by the use in repositories (46%), in individual boxes (38%) and in public rooms (24%). Only five respondents (6%) did not know where adsorbents were used, and 6 persons (8%) indicated other adsorbents were used, such as

carbon filter on an active humidity control system (''miniclima'') in a problematic showcase with acetic acid vapours, **mobile air purifier** with activated carbon designed to clean the indoor environment in the dioramas of one exhibition; for **storage packaging** and **in fire proof safes.**

Q6b If adsorbents are implemented, please specify:

Number of responses: 67



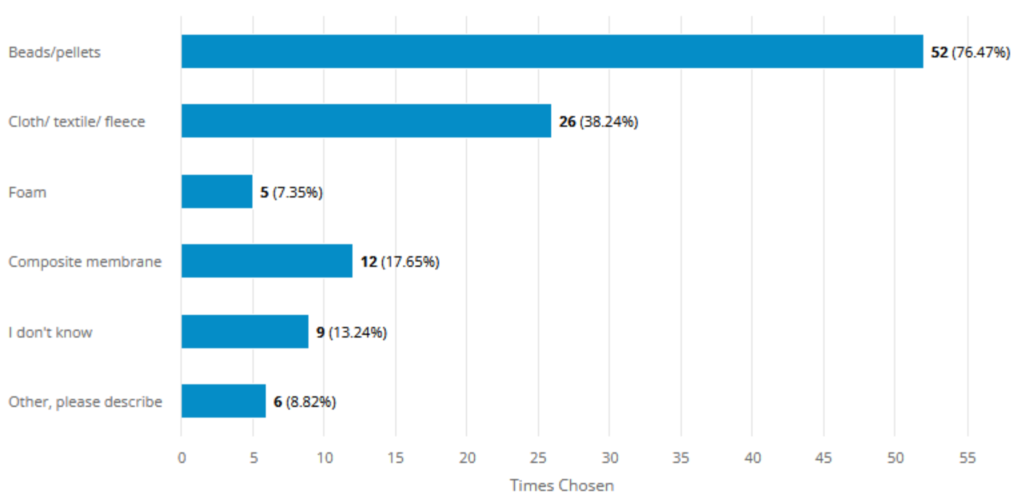
Of the 67 answers given, the most common is the use of

- **porous silica gel for humidity control** (81%)
- **activated carbon for air purification** (49%)

Other adsorbents (17%) as well as zeolites (13%) are seldom used, occasionally for air purification or humidity control.

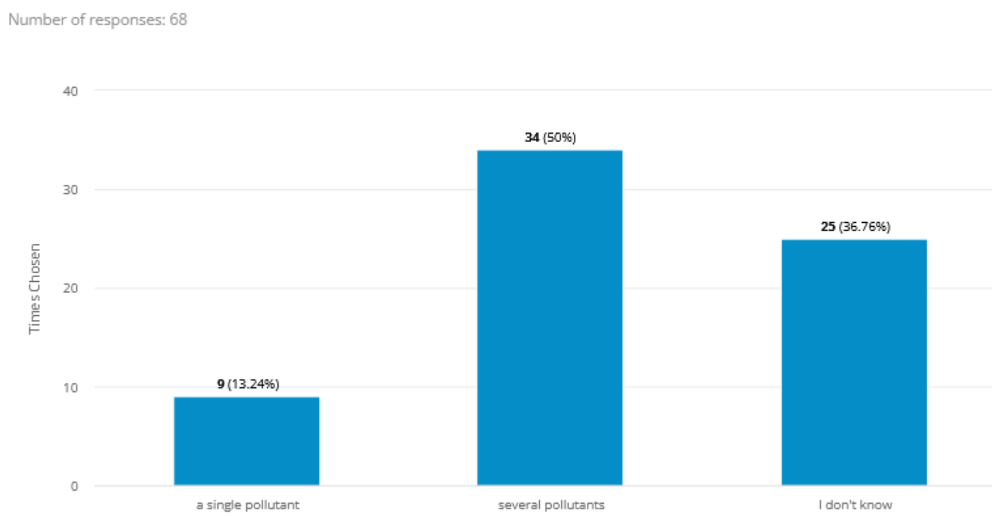
Q6c Which shapes of adsorbents are used?

Number of responses: 68



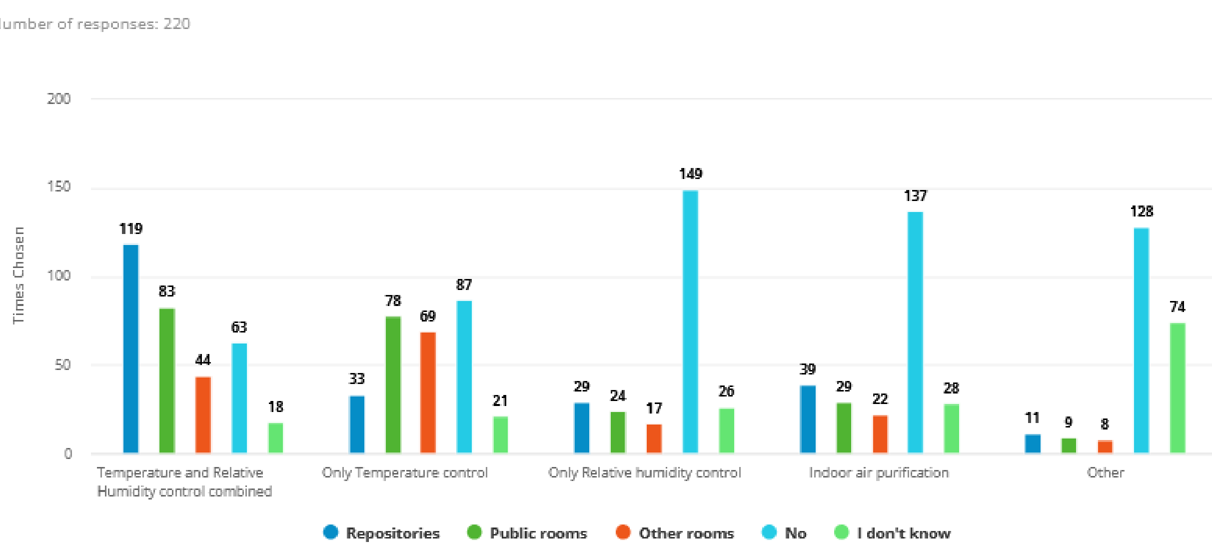
Of the 68 answers, the majority (76%) indicates **beads/pellets** as the preferred shape. This is the overwhelming answer since this is the adsorbents are most commonly commercialized in these shapes. Cloth/textile/fleece are a popular product as well (38%). The few ''Others'' (9%) refer to powder.

Q6d is the implemented adsorbent selective of...



The majority of the respondents (50%) indicate that the adsorbent in use is not selective and adsorbs several pollutants. This is consistent with the number of responses for the use of activated carbon (Q6b). A 13% indicate the use of adsorbents selective of a single pollutant. However no further specification was given as to which pollutant nor as to what sorbent. It is also noteworthy that 37% of the respondents do not know if the adsorbents used are compound-specific or not, which underlines the need for information.

Q7 Does your organisation use Heating, Ventilation and Air Conditioning (HVAC systems) or other climate control systems in exhibition/ public rooms and/or repositories?



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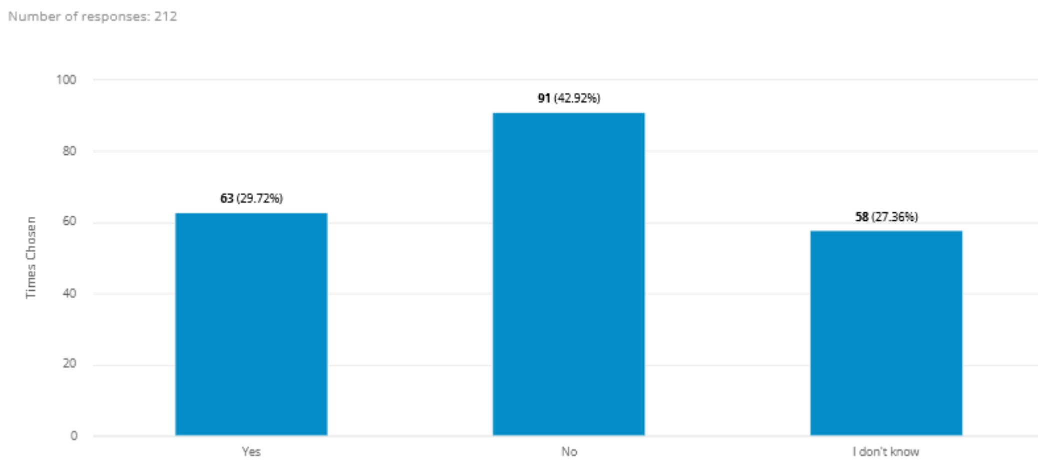
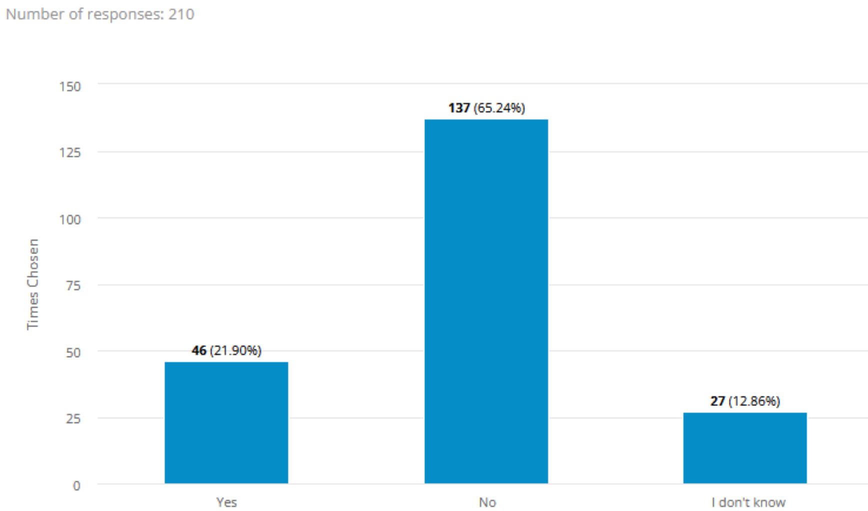
Among the 220 responses, while most public rooms have some kind of air control (97%) - either temperature (T) and Relative Humidity (RH) (with or without air purification) or T only - the repositories are in majority T and RH controlled (54%) and seldom they have additionally an air purification system (17%). The control of only RH is very infrequent, but in some cases applies to public rooms and repositories. However, overwhelmingly, **indoor air purification systems are absent** (62%). This large percentage underlines the need for more sustainability, and low-energy consumption in GLAMs.

Q8 Is your organisation adapting new trends towards relaxation of Temperature (T) and Relative Humidity (RH) recommendations?



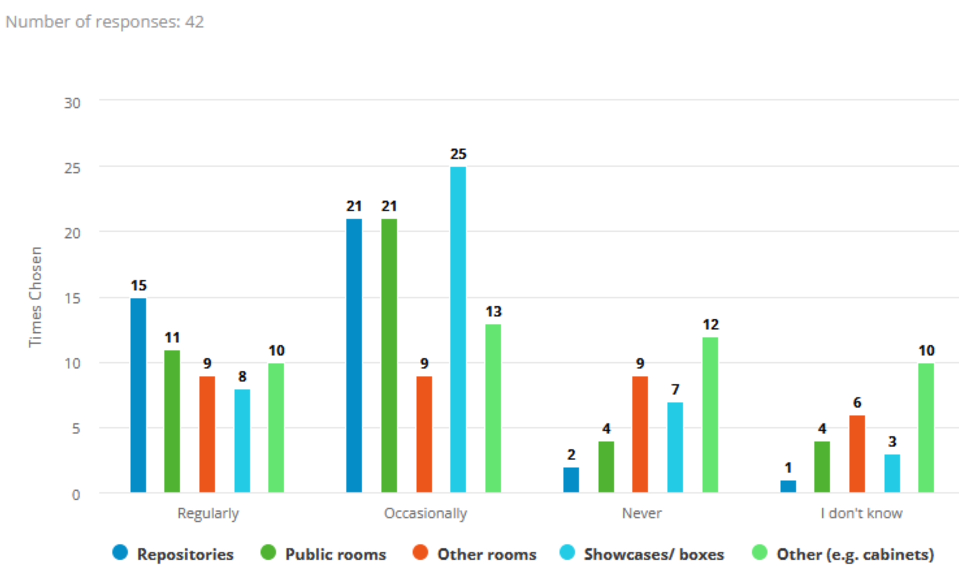
In recent years research has shown that CH collections can tolerate greater variations in RH than previously thought, as reflected in the Bizot Green Protocol[37] and the joint declaration by IIC and ICOM-CC[38] (see section **Error! Reference source not found.**). To the question of adapting new trends, 43% of the respondents answered negatively and 27% did not know. However, the interesting result that **confirms the relevance of the question posed** is that 30% answered positively. This shows that a large number of CCIs are aware of the new trends and are acting upon them, which indicates their awareness and sensitivity for sustainable CH preservation.

Q9 Does your organisation measure/ analyse indoor air pollutants in showcases, public rooms or repositories?



A total of 210 answers were given, whereof 21% indicate the measurement and analysis of indoor air quality in showcases, public rooms or repositories. The large majority (65%) do not measure gas pollutants and 13% do not know whether the latter are monitored in their institutions. Putting these results in parallel with Q6 (a-d) shows that if about 50% of the respondents do use adsorbents for RH air purification (AC), they do so as a preventive conservation measure but they do not measure their impact using sensors or dosimeters.

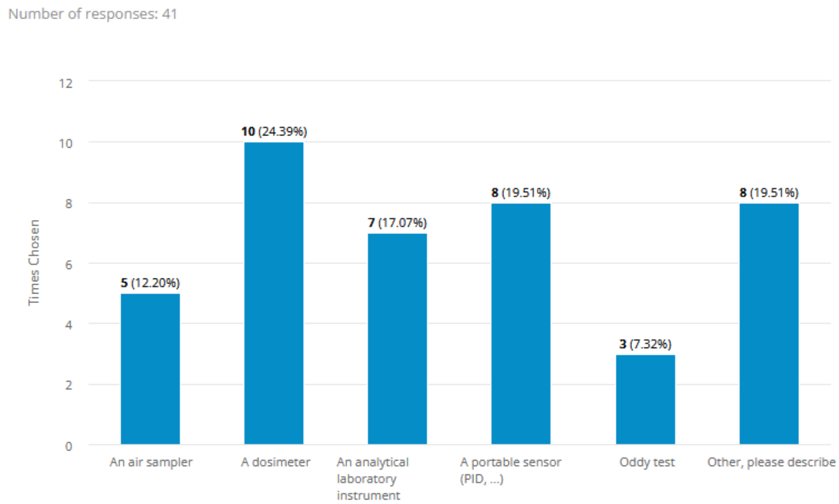
Q9a Where and how often does your organisation measure/ analyse indoor air pollutants?



This and the following 2 questions were responded only by those who answered ''yes'' to Q9. **Occasional monitoring** of IAQ is most commonly carried out in public rooms, showcases and repositories, rather than regular monitoring. The cost of continuous monitoring, the lack of specific damage observed on artefacts or the lack of trained personnel can explain this.

When regular monitoring is preformed, it is predominantly in repositories, followed by public rooms, others (e.g. cabinets) and showcases.

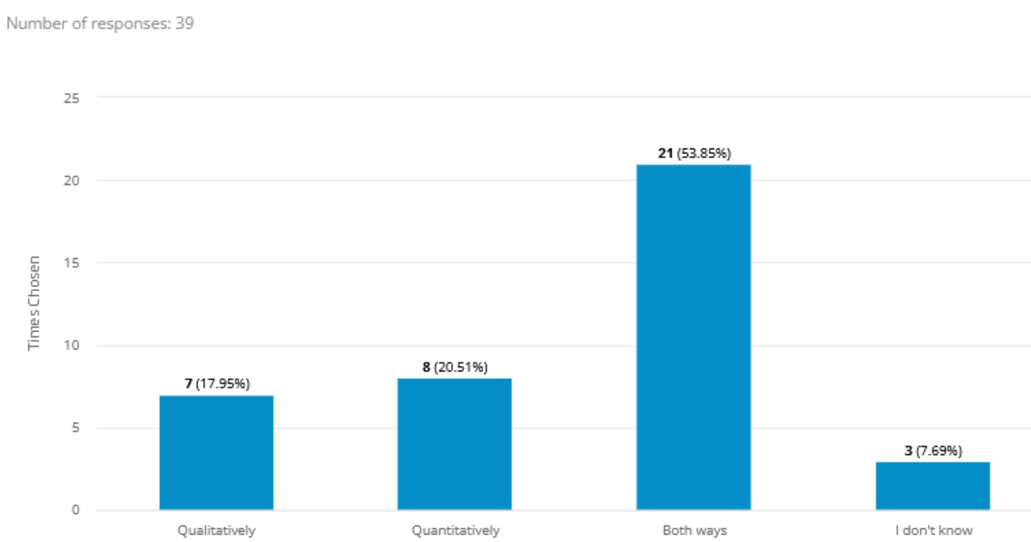
Q9b Is the device used for indoor air pollutants measurement/ analysis...



The 41 answers to this question relate only to those respondents who declared doing occasional or regular IAQ monitoring. The majority of devices in use are **dosimeters** (24%), followed by **portable sensors** (20%) and other devices (20%). Analytical laboratory instruments are used by 17% of the respondents, followed by air samplers (12%). The Oddy test only gathered 7% of the answers, which could be paralleled with its drawbacks despite its popularity (see section **Error! Reference source not found.**).

Other methods were commented upon such as AD-strips (2x), as Corrosion Classification Coupons (Purafil) (1x), and Corrosion sensor AirCorr (1x) (see section **Error! Reference source not found.**). Some institutions declare using a combination of several monitoring systems (4x).

Q9c Does the device work...



Out of 39 responses, more than half (54%) indicated that the device in use works both qualitatively and quantitatively. This information might also contain the information from the institutions using several systems concomitantly. A quantitative measurement method is used by 21% and 18% use a qualitative measurement.

The comments to this question by 26 respondents allowed a closer description of the methods in use. It shows that the devices are mostly used in combination, respectively in parallel with other monitoring systems, to fulfill the needs of the individual materials stored in the collections, rooms, showcases or boxes.

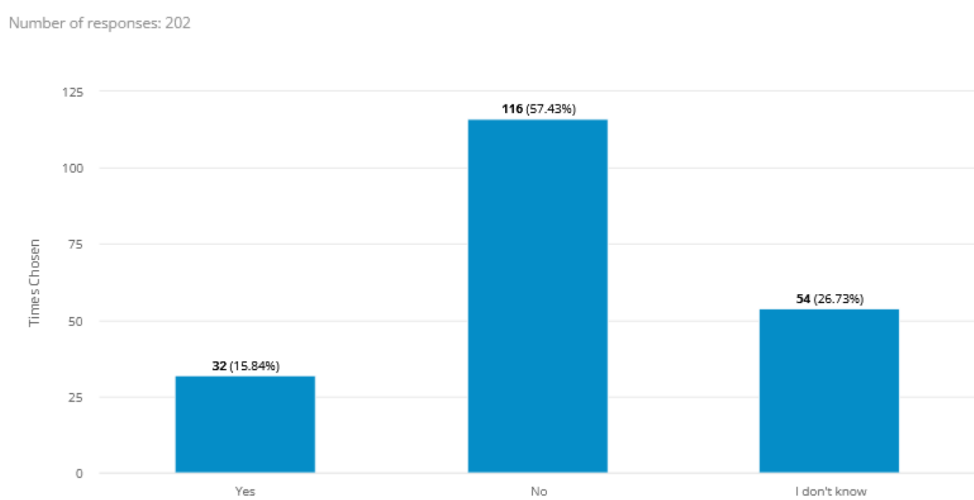
In detail, the numerous following comments were given that show the diversity and capabilities of sensors and dosimeters options described in section **Error! Reference source not found.**are well-known by this small proportion of respondents who are involved in IAQ monitoring:

- In the galleries showcases and storages we have used **IVL dosimeters** (passive diffusive sampler) **Radiello dosimeters** (passive diffusive sampler) **Purafil metal strip** air quality sensors and a digital device regularly but with much higher thresholds.
- As we are a research institute, we use sophisticated instruments with high resolution (qualitatively/quantitatively). Unfortunately, most of the questions before do not rely to research organizations but to classic collections. This is why I answered " I do not know" as an answer was mandatory.
- Different types of **glass-dosimeter** with different selectivity as well as sensitivities were developed and are still in use. Also, the location to be investigated (existence of biologic microorganisms like fungi, in-door/out-door etc.) are relevant for the selection of the proper dosimeter. Commercialisation by Fraunhofer ISC/IZKK, Würzburg/Germany.
- Loopshore (https://loopshore.com/)
- Bluetempos and dataloggers managed and analyzed by Collections Managers and BAS control system managed by engineers
- QuantAQ PM and CO2 sensor, AMS, VOCUS
- Oddy tests, diffusion tubes, active sampling, Tenax tubes (externally analysed), A/D strips, metal coupones and electrochemical stripping, Onguard, Air Corr, online NO_2, O_3, VOC, CO2, CO sampling units
- Air conditioning unit CIC H5, filter type EU75 - processing and control of air 3500m^3/hr - 7 pieces, for each floor separately, measuring device is integrated in the unit and anylyzed by Siemens program, hygrometer portable thermometer Comet D3120
- We had a series of tests carried out by students from UCL institute for sustainable heritage.
- We have used Gastec colorimetric tubes, IVL passive dosimeters and Radiello passive dosimeters also Purafil pollution monitoring strips. We are setting up Oddy testing for the future.
- Corrosion monitoring, ISA Standard 71.04-2013
- A/D strips, sensors across repositories and some working areas.
- We have used Gastec colorimetric diffusion tubes but with limited success. also IVL diffusive samplers and Radiello diffusive samplers. Also Purafil strips - the copper alloy and silver ones. we have AD strips but have never really used them and will try to set up oddy testing this year.
- SPME-GCMS, also swapping for pesticides
- We did a test with Polygon, using ExactAire sensors. Offices seemed just as clean as repositories, while offices do not have filtering and much more people polluting the air. Device was a black box and did not measure individual components. Not suitable for our current situation, let alone the new passive one. The service is provided by an external institution and we are monitoring microbiological activity

only (once every two years). It is part of the Building Management System. It measures the Particulate matter.

- A/D strips from Image Permanent Institute, SPME PA, PDMS/DVB, CAR/PDMS, CAR/PDMS/DVB from Supelco Biocollector from Grosser on Monotrap from GL Sciences
- Sensor lora lan
- We have used Gastec diffusion tubes with limited success and IVL passive dosimeters which have provided better information. We also deployed Purafil corrosion strips one time. We plan on setting up Oddy testing and also will have GCMS capability in the coming year
- SPME Fibre in place for one week alongside short and long term Oddy coupons
- Mainly IVL passive/diffusion samplers for organic acids, ozone, NO2 and H2S Also occasionally Purafil/Camfil corrosion coupons (Ag and Cu). Also occasionally AirCorr corrosion loggers with Pb and Ag sensors
- Oddy, GC/MS, dosimeters, VOC sampling using TD
- Oddy test and A/D strips
- Data logger
- IVL passive samplers

Q10 Is your organisation actively aiming at limiting the level of gaseous indoor pollutants?



Among the 202 respondents, 57% answered ''No'' and 27% ''I don't know''. It can be concluded that managing gaseous pollutants is not an issue for the majority of GLAMs, which aligns with the answers to previous questions.

Some of the comments given from the 32 respondents (16%) who answered ''yes'' are copied below. They show that the publication by the Getty Conservation Institute (Grzywacz, 2006) is the quite popular among the guidelines and recommendations listed in **Error! Reference source not found.**.

- We use those specified by the Getty in their 2006 publication - Monitoring for gaseous pollutants in museum environments Cecily M Grzywacz Removal of Formaldehyde using selective adsorbents.

- We aim (not always achieved) for the following values: Acid gases - General collections: 100–600 ug/m^3 for acetic acid, and 10–38 ug/m^3 for formic acid. Sensitive collections: <12 ug/m^3 for acetic acid and <9.6 ug/m^3 for formic acid. VOC- A limit of 300 ug/m^3
- The goal is to understand how the space is functioning before implementing a threshold depends on material, base levels given at https://www.english-heritage.org.uk/learn/conservation/collections-advice-and-guidance/ MANAGEMENT OF SHOWCASES > MEMORI
- A study of specific VOC or gas phase pollutants has not been undertaken, only overall VOC and PM measurements. A CO_2 study showed very low levels suggesting high levels of air turnover by HVAC.
- Through incoming air filtration.
- We go by the recommendations in the Getty Publication - C. Grzywacz Monitoring for Gaseous Pollutants in Museum Environments (GCI 2006).
- For a repository with master drawings with lead white highlights we are planning HEPA + active carbon filtering
- Using the ATCD© 3.0 GreenRestore© Accurate Thermal Chamber, we reduce the amount of toxic substances (insecticides used from the 1960s to the 1990s) contained in wooden collectibles. The released VOCs are captured by activated carbon filters.
- I assume via the filters in our HVAC-controlled spaces? One studio also has a system to actively filter mold-particles from the air. This is also a system that was developed via a European project, some years ago.
- Use of solvents and chemicals are restricted under vacuum system, local or portable. Rooms are ventilated every day. We don't have any AC system. We use less plastic and synthetic stuff than before
- I hope the results of this study will be published as this is a great opportunity to learn and then spread knowledge.

  We generally use Getty guidelines from Grzywacz- Monitoring for gaseous pollutants in museum environments, GCI, 2006
- We would like to know threshold levels, but there is not much info for collections.
- Planning filtration system in our new Collection care center. Limits for each gas was not set up yet.
- We do not have a threshold but are trying for example to select materials used in construction that do not emit indoor are pollutants.
- We have been using the threshold limits indicated by GCI publication - Monitoring for Gaseous Pollutants in Museum Environments Cecily M (Grzywacz - Getty Conservation Institute 2006)
- In small areas- for example, we're trying to reduce off-gassing of a wooden cabinet with absorbents, but don't have a specific threshold we're aiming for.
- As a starting point we follow the recommendations given by the ASHRAE Guidelines (2023)
- We created a separate room for the negatives that are off-gassing acid acetic gas in order to not damage the rest of the collection.
- Organic acids < 100 microgram/m^3, NO_2 < 5 microgram/m^3, Ozone < detection limit

Q11 Does your organisation have an Indoor Air Quality or Climate Management Group or Department?

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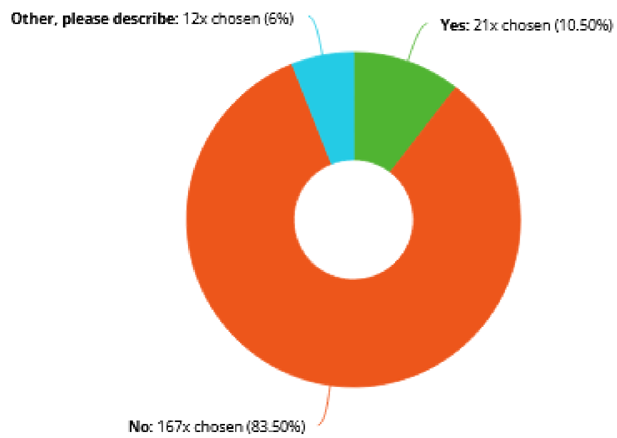
Number of responses: 200



Among the 20 respondents, 84% answered ''No'' and only 11% responded positively. This result underlines the fact that most GLAMs who answered are small scale, which does not call for a specific department dedicated to IAQ/HVAC engineering. This is a positive outcome for SIMIACCI since the new sorbents, which will be developed will be especially designed to be low-cost and to function passively for air purification, so they can be location-specific and manage micro-environments, only where air purification is needed. Similarly, the sensors to be developed shall also meet these requirements.

Some of the comments attached to this question, from the group who answered ''yes'', indicate that IAQ is the responsibility of the Preventive Conservation groups in the GLAMs who have such groups among their conservation divisions. These comments are copied below.

- There is a preventive conservation team
- Collections management and Facilities work together.
- I believe it falls under general facilities dept. but not sure
- We do not really have this group, but for many years we've have a strong preventive conservation unit that always guides and supports where needed.
- Conservation is one of the Institute's main tasks. Prevention currently presents many critical issues and is in urgent need of adjustment.
- Not sure, but they have an aircon department
- Climate Management is part of the conservation lab
- A group with facilities and conservation personnel have occasional meeting, but it is not very formalised
- The climate is managed by the technical department of the institution. They don't sample nor measure the concentration of particular VOCs.

Q12 Have you heard of the EC project SIMIACCI?

To this question, the answer was overwhelmingly ''No''. This is not surprising since SIMIACCI had started a mere 3 months before the survey was launched. The Focus Meeting (M4) held on June 3, 2025 has without a doubt helped in increasing the awareness of the CCI community interested in IA issues about SIMIACCI goals and efforts.

10.2 Synthesis of the survey analytics

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 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 the report D4.1 (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.

10.3 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: *

Funded by
the European Union

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

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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

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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?

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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!

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11. Annex B. Identifying the main barriers and challenges for effective IAQ management in GLAMs

11.1 Introduction

Members of WP4 of the consortium of SIMIACCI (Horizon Europe funded project – Sustainable Intelligent Management of Indoor Air Quality for the Culture and Creative Industries - 2025-2029) reached out to 4 leaders of past EC-projects dedicated to developing sensor and dosimeter devices or sorbent materials specifically to be used in GLAMs. The discussion was geared towards the outcome of each project from the perspective of the respondent (mostly project coordinators or WP leaders) about the exploitation/communication strategies adopted and the actual implementation of the products in the GLAMs community. These interviews are meant to advise SIMIACCI about the greatest challenges in the implementation of sorbents and sensors for GLAMs at a high TRL, and give a perception of the market strategies to adopt to reach a successful wide distribution once at a commercial level.

The tables below gather the key information about the projects, the questions from SIMIACCI and the answers provided during/after the interview, for dosimeters (

Table 2), for sensors (Table 3), for sorbent materials (Table 4) and one for adsorbent materials and sensors (Table 5).

11.2 Discussions with past EC-projects coordinators and WP leaders

Table 2. Dosimeters for GLAMs

EC project	**PROJECT TITLE: MEASUREMENT, EFFECT ASSESSMENT AND MITIGATION OF POLLUTANT IMPACT ON MOVABLE CULTURAL ASSETS – INNOVATIVE RESEARCH FOR MARKET TRANSFER** **ACCRONYM: MEMORI** **EU FP7 supported Collaborative project** **Grant agreement 265132.** **Project period 2010 –2013**
Coordinator	Elin Dahlin, NILU-Norwegian Institute for Air Research, Norway.
Date of contact	22-04-2025
Date of exchange	24-04-2025
Name of person contacted / job / employer/ e-mail	**Terje Grøntoft**/ retired from NILU / terjegrontoft@gmail.com
Description of project	MEMORI developed a dosimeter technology to measure indoor air quality and its impact on cultural heritage objects. The technology includes the MEMORI dosimeter, a handheld reader, and a web-based platform for data analysis and risk assessment. The project also investigated damage caused by organic acids on

	various materials such as paper, leather, textiles, pigments, and varnish. Results showed that even low concentrations of acetic acid and formic acid can accelerate the degradation of these materials. Strategies were developed to control and reduce pollution levels in protective enclosures using adsorbents like activated charcoal.
Intended use	The MEMORI dosimeter technology is intended for use in cultural heritage institutions to monitor and assess the impact of indoor air quality. The result helps conservators and museum staff evaluate the risk posed by pollutants to various materials, including paper, leather, textiles, pigments, and varnish. The dosimeter consists of a holder, which includes two sensitive materials: a Glass Slide Dosimeter (GSD) and an Early Warning Organic (EWO) polymer. The GSD is sensitive to organic acids generated indoor, while the EWO responds to oxidizing pollutants like nitrogen dioxide and ozone from outside. Both materials also react to climate factors such as temperature, relative humidity, and UV light. The GSD was developed by the Fraunhofer Institute. A portable device measures the changes in the dosimeter after exposure to the environment. Users upload measurement results to the MEMORI web-based platform, where they can analyse the data and assess the risk to heritage materials. The platform provides a "traffic light" system (green, yellow, red) to indicate the level of risk based on the dosimeter readings. The dosimeter technology measures acetic and formic acid, NO_2 and Ozone.
Context of use (experimental in the lab, limited level in museums, or commercial level)	Confidential level distribution in museums / commercial level
Can the results be accessed directly by the end-user, or is there an extra analytical step needed?	The MEMORI dosimeter technology is designed to be user-friendly and can be used directly by the end-user without the need for extra analytical steps.
Was an user-interface developed for accessing data?	The end-user places the MEMORI dosimeter in the indoor environment they wish to monitor for a specified period, typically three months. After the exposure period, the end-user uses the handheld MEMORI dosimeter reader to measure the changes in the dosimeter. The measurement data is then uploaded to the MEMORI web-based platform. The platform analyzes the data and provides a risk assessment using a "traffic light" system (green for low risk, yellow for moderate risk, red for high risk).

	The platform also offers detailed evaluation tools, such as two-dimensional diagrams that help diagnose the sources of pollutants and assess the overall environmental risk.
What was the intended distribution? Wide scale by the cultural heritage community // small scale distribution/limited // close-to-market solution	The MEMORI dosimeter technology was intended for wide-scale distribution within the cultural heritage community, with a focus on making it accessible and practical for a broad range of institutions and professionals in the field.
Was the foreseen distribution level reached ?	No The dosimetry system is today out of supply. The German/Fraunhofer ISC part (GSD-Glass slide dosimeter) was made unavailable for MEMORI only one year after finalization (about 2015) whereas the EWO (Early organic) was available until Terje Grøntoft retired from NILU in September 2024. The environment and conservation quality evaluation was finally made to be an open access system and can today be used very simply by inputting the environment values from for instance passive samplers (pollution, climate, light) on the front page on https://memori.nilu.no/, and simply see the result there by clicking "add result".
If not, what would you do differently (if you would have had that chance) to improve the outcome?	For a future product, for a deliverable which depends on several partners input and obligations, then its delivery for an extended period beyond the one year of the EU contract should be formally/legally agreed during the project before final delivery to the commission, with the signatures of the partner companies.
What are in your opinion the minimal requirements to meet for a successful large scale distribution?	A challenge is the profitability of a product. If this is questionable it is likely that everything will, after end of project, be left to the researcher, who have to do the communication, marketing, sales etc. It seems typical in the field of conservation that the marketing people think of the likely customers in the thousands (and millions) whereas the reality is some hundreds (or even less) - but depending, of course. So a realistic idea about market size / willingness to pay for a product is important. It, may for example, be that the MEMORI dosimeters, that were quite technically demanding and expensive to produce would not anyway in the end have been sold much besides the connection with research and research projects
Did you encounter pitfalls that should be avoided in terms of business strategy, communication, implementation costs, and energy consumption?	See above

Table 3. Sensors for GLAMs

EC project	**PROJECT TITLE: Preventive Solutions for Sensitive Materials of Cultural Heritage** **ACCRONYM: SENSMAT** **H2020 Research and innovation programme** **Grant agreement No 814596** **Project period 2019-2022**
Coordinator	CEA-ARC-Nucléart (FR)
Date of contact	11-04-2025
Date of exchange	24-05-2025
Name of person contacted / job / employer / e-mail	**Gilles Chaumat** / Res. Ing. / CEA / gilles.chaumat@cea.fr
Intended use	SensMat aimed to develop and implement a complete ''product'' to be used in **preventive conservation in GLAMs for environmental surveillance**. The website claims the development of effective, low cost (< 20 – 30€ for the basic integrated platform), eco-innovative and user-friendly sensors, models and decision-making tools, as well as recommendations and guidelines to enable prediction and prevention of degradation of artefacts as a function of environmental conditions. A **network of connected sensors** for T°, RH, VOCs, corrosiveness, particulate matter, light, shocks and vibration was produced (hardware and software): - VOCs measured: acetic acid, formic acid, formaldehyde (Silicon carbide sensors) - Corrosivity measurement with sacrificial anodes (measures resistivity) The communication portal was based on Low-Rank Adaptation (LoRA) – internet-based gateway, data stored on CEA servers to which end-users had access (on the long run, this was designed to be subscription fee-based) Key parameters Improved during the project: efficiency to monitor environment and/or to predict material degradation, cost of tools, size of sensors systems, and accessibility of the technology for non-specialized personnel (training provided), user-friendliness. The monitoring systems were designed be adapted easily to different configurations, with a standardization of computer codes to improve interoperability, mutualisation, for sharing of knowledge and practices
Context of use (experimental in the lab, limited level in museums, or commercial level)	The TRL at the start of the project was already high (TRL5) for some of the sensors to be integrated since the technology already exited (T, RH, light) and reached TRL7 at the end of the

	project. TRL for corrosion and VOCs sensors was lower and for dust, vibration and shocks sensors even lower. The integrated solution was tested on-site (10 demonstrators case studies in various museums across Europe, which represented about 100 sensors fabricated and distributed). In-loco measurements were carried out over one year for seasonal monitoring. Service support for the installation and training was provided to ensure production of useful and uniformed data.
Can the results be accessed directly by the end-user, or is there an extra analytical step needed?	Yes, results accessible to the end-user through a restricted access to the server, free of charge during the project. There was a miniaturised and real-time wireless sensor node (integrated software framework for some sensors). The goal was to provide support and consultancy service to GLAMs end-users through a subscription fee to help small and medium-sized museums to control their environmental parameters.
Was a user-interface developed for accessing data?	The integration of the different components was developed through the specific objectives into the SensMat system. It was intended as a modular system that could be adapted to any sensor. It was thus possible to use existing sensors and implement them in the system. Integrated software accessible to end-users.
What was the intended distribution? Wide scale by the cultural heritage community // small scale distribution/limited // close-to-market solution	A decision-making engine based on contextual data and a ''knowledge database'' were intended and customized for each small and medium museum with management tools. Intention to develop a user-friendly **all-in-one solution** that could ''reduce or eliminate the need for overly expensive restoration through preventive conservation (PC)''. However: the development stayed in an experimental phase and the distribution went only to the end-users in the project and during the project. The integrated solution was not fully finished at the end of the project due to the different TRLs on the individual sensors part of the integrated system.
Was the foreseen distribution level reached?	Yes, technical (sensors) and scientific (prediction model) goals met. There is no follow-up after the project ended, the solution stayed ''lab level'', and no commercial level was reached. There is no current prospect to evolve towards a commercialisation after the project. The different industrial partners (hardware and software) were different private companies and are currently each developing their own separate solutions. These companies were competitors even before the project started. It resulted difficult to make them agree on one solution fits all at the end of the project, each company willing to do their own further developments to reach their own private market.

If not, what would you do differently (if you would have had that chance) to improve the outcome?	Nothing. Industrial partners had experience with EC funding system. They had competing projects. They accepted being part of SENSMAT because their own submissions to the call were rejected – Arc-Nucleart was able to coordinate the project as a ''neutral'' academic partner to avoid the competition between the partners during the project.
What are in your opinion the minimal requirements to meet for a successful large-scale distribution?	The need for a higher TRL and maturity at the start of the project would enable to find/reach the shift of paradigm to initiate commercialization and pervade the market. The solutions are now in the hands of the industrial partners (private companies).
Did you encounter pitfalls that should be avoided in terms of business strategy, communication, implementation costs, and energy consumption?	The task dedicated to the Multiscale modelling (tool to help in preventive conservation decision-making) could not be integrated in the solution. The pitfalls were: indoor vs outdoors climate modelling (HVAC on/off).

Table 4. Sorbents materials for GLAMs

Name of IAQ system	**PROJECT TITLE: Active & intelligent PAckaging materials and display cases as a tool for preventive conservation of Cultural Heritage.** **ACCRONYM : APACHE** **Horizon 2020 research and innovation programme - NMBP-33-2018 | Innovative and affordable solutions for the preventive conservation of cultural heritage (IA)** **Grant agreement No 814496** **Project period 2019-2022**
Coordinator	CSGI – Consorzio Interuniversitario per lo Sviluppo dei Sistemi a Grande Interfase (Firenze, IT)
Date of contact	07-04-2025
Date of exchange	22-04-2025
Name of person contacted / job / employer / e-mail	Antonio Mirabile / Private Conservator/ www.antoniomirabile.com, antonio.mirabile@gmail.com
Intended use of the adsorbents	Showcases, boxes, cabinets
Context of use (experimental in the lab, limited level in museums, or commercial level)	VOC absorbers were developed during APACHE. The goal was to create sustainable, passive solutions for mitigating volatile organic compounds (VOCs) in museum and heritage environments. Two different types of absorbers were designed and tested. Both absorbers were initially evaluated under controlled laboratory conditions, followed by validation in selected museum settings under confidentiality agreements. As of today, one absorber has progressed to commercial availability and is being offered through Adsorbi AB, a spin-off company of the project. The absorber is based on PU/Castor oil and remains at a pre-commercial, experimental stage, with further anticipated development.
Can the results be accessed directly by the end-user, or is there an extra analytical step needed?	Yes- No extra analytical step
Was an user-interface developed for accessing data?	No user interface is needed
What was the intended distribution? Wide scale by the cultural heritage community // small scale distribution/limited // close-to-market solution	The ambition was to enable a broad distribution within the museum and cultural heritage sector, offering a scalable, accessible solution to indoor air quality (IAQ) monitoring and mitigation, specifically targeting VOCs through passive adsorption.

Was the foreseen distribution level reached?	While the scientific and technical objectives were successfully achieved, the ambition of wide-scale distribution across the GLAMs sector has only been partially fulfilled. Of the two VOC absorber materials developed, one has since been commercialized and is currently available through Adsorbi AB. However, the adoption within the GLAMs community remains limited, due in part to strategic and operational challenges, such as the absence of strong industrial partnerships during the transition phase, and the need for sustained outreach and support tailored to CH professionals. The second absorber material, although validated in pilot studies, remains at a pre-matured stage.
If not, what would you do differently (if you would have had that chance) to improve the outcome?	Despite the successful development and validation of the VOC absorbers developed, broad commercialization and uptake within the GLAMs sector have been constrained by several interrelated factors. One key challenge was the lack of an industrial partner to support the scale-up and market deployment phase, which limited the ability to transition from prototype to a widely available product. In addition, there were insufficient resources for post-project activities, such as long-term field validation, user training, and maintenance support, which are essential elements for building trust and adoption within heritage institutions.
What are in your opinion the minimal requirements to meet for a successful large scale distribution?	To make the VOC absorbers widely available and used across the GLAMs sector, key conditions need to be met. First, a strong performance data is needed from real GLAMs environments, not just from the laboratory. To be adopted by the GLAMs community the product also needs to fit easily into existing preventive conservation practices, without requiring major changes or complex tools. A scalable and affordable production process is essential to keep costs reasonable for CCIs of all sizes. In addition, having reliable partners for distribution and technical support would help users feel confident in adopting the product. Lastly, the benefits of the absorbers should be explained in clear, practical terms, with a focus on how they help in daily preventive conservation work, not just technical features.
Did you encounter pitfalls that should be avoided in terms of business strategy, communication, implementation costs, and energy consumption?	Several challenges were faced in bringing the VOC absorbers to a wider audience. At first, the product was presented as a high-end, research-focused solution, which made it seem inaccessible to many potential users. The communication and dissemination material was too technical, making it hard for some stakeholders to quickly understand the benefits. Some users also found the cost of replacement and maintenance to be a concern. Although the absorbers are passive and do not consume energy, a more flexible, modular design could have made them easier to adapt to different settings.

Community involvement	Conservators, preventive conservation specialists, and collection care professionals were involved from the early stages of development through interviews, informal discussions, and collaborative workshops. Their practical insights were essential in shaping both the design and deployment of the VOC absorbers. While a dedicated application was not developed, the feedback from these key user groups directly influenced decisions on usability, format, and integration into day-to-day conservation practices. However, since the project was funded and approved based on a predefined proposal, it was difficult to significantly change direction during development, even when some feedback suggested alternative approaches.
Pilot activities	Pilot studies were a key component of our development and validation process. The materials were tested in real museum environments, allowing to assess their performance under realistic conditions and gather meaningful user feedback. These demonstration pilots were conducted in collaboration with museum professionals, including conservators and collection care teams, who provided valuable insights on practical handling, placement, and perceived effectiveness. The pilots played a crucial role in building trust with potential users.

Table 5. Sorbent materials & Sensors for GLAMs

EC project	**PROJECT TITLE: Innovative packaging solutions for storage and conservation of 20th century cultural heritage of artefacts based on cellulose derivative.** **ACCRONYM: NEMOSINE** **European Union's Horizon 2020 research and innovation programme** **Grant agreement 760801** **Project period 2018 –2022**
Coordinator	AIMPLAS - ASOCIACION DE INVESTIGACION DE MATERIALES PLASTICOS Y CONEXAS, Spain
Date of contact	22-04-2025
Date of exchange	24-05-2025
Name of person contacted / job / employer/ e-mail	**Abeer Mohtar**/ Researcher from ISTID / abeer.mohtar@tecnico.ulisboa.pt **Moisés Pinto**/ Researcher and team leader from ISTID / moises.pinto@tecnico.ulisboa.pt
Description of project	NEMOSINE aimed to improve the traditional storage solutions, such as freeze storage (below 5ºC), by developing an innovative package with the main goal of energy saving and extent conservation time. To achieve this objective NEMOSINE worked on developing various areas. 1. Active acid adsorbers based on Metal Organic Framework (MOFs) able to capture acetic acid at low concentrations under moisture in addition to incorporating these MOFs in composites. 2. Gas detection sensors to monitoring acetic acid. 3. Multi-scale modelling to correlate degradation & sensors signals. 4. Packaging with modular design to fulfil the technical & economical requirements of the different CH made by cellulose derivates.
Intended use of the adsorbents	The adsorbents were to be used on the NEMOSINE packages (in pouches with Tyveck bags or incorporated in composites) to capture the emissions of acetic acid.
Context of use (experimental in the lab, limited level in museums, or commercial level)	The TRL of the main technologies developed within the project started at TRL 4 and reached TRL 6: "Prototype tested in a relevant environment." The objective was to develop and validate the technologies in the lab, followed by validation in archive environments. For the sensors, a sensor array selective to acetic acid was developed and validated within the project as part of the prototype. However, we unfortunately lost contact with the company responsible for sensor development, and we have no information about the current status of their commercialization. Regarding the adsorbents, two MOFs highly selective for acetic acid were developed within the project. One was based on MOF hydrophobicity and high affinity for acetic acid—namely, MIL-53-CF_3. The other, MIL-100(Fe), is based on

	open metal sites and is extremely efficient for acetic acid capture under moist conditions due to its higher selectivity. Today, MIL-100(Fe) is available commercially through SquairTech, a spin-off company.
Was an user-interface developed for accessing data?	Yes, a user-friendly interface was developed to monitor the acetic acid concentration as well as it enables the user to simulate different scenarios and see the effect of storage parameters.
Can the results be accessed directly by the end-user, or is there an extra analytical step needed?	The results can be assessed directly nevertheless the user should know some information about the film to give better estimation of the future degradation of the films.
Was the technology patented or open source?	The developed adsorbents based on open metal sites in addition to the sensor array were patented. The developed prediction models as well as the developed of MOF composites in addition to the final results of the project (https://doi.org/10.1016/j.culher.2023.11.013) were published in open access.
What was the actual outcome? (intended ambition reached or not?)	The actual outcome was very satisfactory, with impressive results, and the major objectives of the project were met. However, some objectives were not achieved due to technical challenges with certain industrial partners. These included the development of nanofiber-based carriers with incorporated antifungals, where the industrial partner was not able to adapt their existing technology to meet the NEMOSINE objective. Also, the development of nanosensors to monitor NO gas, which was hindered by the instability of NO. In addition, the original project considered cellulose derivative artefacts, but this was refined at the very beginning to focus specifically on cellulose acetate artefacts.
If not, what would you do differently (if you would have had that chance) to improve the outcome?	Reallocate the budget of the industrial partner responsible for electrospinning to another partner with more appropriate technology. The validation tests were delayed due to the COVID-19 pandemic, and no extension for the project was requested, resulting in a reduction of the validation period from four months to one month. The results would have been more robust with a four-month validation test.
What are in your opinion the minimal requirements to meet for a successful large scale distribution?	Collaboration among the supply chain. A strong validation across multiple GLAM entities worldwide. The industrial production needs to be developed at several kg scale/day. The academic partners should develop the technology for pollutants capture at relevant concentrations (acceptable limits for GLAMs).
Did you encounter pitfalls that should be avoided in terms of business strategy, communication, implementation costs, and energy consumption?	We only engaged the end users at a very late state. The costs of the solutions that are being developed need to be understood earlier to see if this can be a barrier for the cultural sector to adopt the solutions.

List of abbreviations

MOFs – Metal-organic frameworks

VOCs – volatile organic compounds

H_2S – Hydrogen sulfide

NOx – Nitrogen oxides

GLAMs – Galleries, Libraries, Archives, and Museums

IAQ – Indoor air quality

MIL – Materials of Lavoisier Institute

PDA – Pyrazole dicarboxylic acid

FA – Formaldehyde

AA – Acetic acid

BTC – Benzene tricarboxylate

STY – Space-time yield

HF– Hydrofluoric acid

IPA– Isophthalate

IBU– Inorganic building unit

CAU– Christian-Albrechts-University

pcu– primitive cubic

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