Indoor Air Quality in the Uffizi Gallery of Florence: sampling methodology and preliminary results

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Indoor Air Quality in the Uffizi Gallery of Florence: sampling methodology and preliminary results

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Abstract. In museums, indoor air quality plays a fundamental role in the visitors and staff well-being as well as in the deterioration processes of the exhibit objects. Due to some complaints dealing with poor air quality conditions reported by the occupants, a preliminary survey in some rooms of the Uffizi Gallery in Florence was carried out. To assess indoor temperature, relative humidity, chemical and microbiological pollutants in the museum, a methodology of investigation and evaluation of the results was defined and applied to several rooms of the Gallery. The survey aim is to underline the presence of critical issues in order to determine the pollutant concentration and compare the sampled values with the limits reported in Italian standards, technical regulation and guidelines. The preliminary results can be used to plan a deepen investigation with a more detailed sampling of specific pollutants. In this paper the results regarding a representative room are shown and discussed.

1. Introduction

Museums play an important role in society, not only in cultural terms but also because the increasing cultural tourism can be a way to achieve also financial sustainability; so it is necessary to ensure and improve indoor air quality (IAQ), conditions to preserve the artefacts [1] [2] and provide well-being to visitors and staff [3].

Frequently it is hard to manage the conflicts and to reach a compromise between IAQ, well-being, preventive conservation and energy efficiency, since conservation requires by definition a very stable climate with short fluctuations, which imposes high demands to the air conditioning systems in order to meet those requirements and to reduce the process of exhibits degradation [4].

As for IAQ and well-being, the expectancy of museum visitors is different from the one of the staff due to several reasons related for example to the duration of the visits, personal factors (clothing level and metabolic rate) and pattern of use of the visitors greatly different from those of the staff.

The quality of the air inside museums has become a matter of growing concern because airborne pollutants can cause potentially health complains and discomfort of the occupants and adverse effects on the collections.

To characterize indoor quality and the related exposure to air pollutants, emissions from various sources, such as occupants, building materials, maintenance products and equipment including heating, ventilation and air conditioning systems (HVAC), must be considered. Also, the duration of the exposure must be considered, especially for the workers in the museum.

From a management point of view airborne pollutants rarely can be controlled and monitored individually; so, some pollutants are identified as key pollutants for museum environment [5].

Most relevant pollutants inside museums are water vapour, carbon dioxide (CO_2), other inorganic pollutants, volatile organic compounds (VOCs) and biological agents; the effects of these pollutants can be even increased by indoor high levels of temperature, relative humidity (RH), human activity and ventilation effectiveness.

Water vapour is included ad a key airborne pollutant as high RH can be related to mould growth.

Carbon dioxide is a gas emitted from human breath together with water vapour. Although CO_2 is a good indicator of pollution caused by human beings, it can also be used as an indicator of human bio effluents and of the effectiveness of ventilation in the museum. Carbon dioxide in its gas phase has very little adverse effect on collections while its concentration above 1000 ppm can cause adverse effect on human health.

Volatile organic compounds in museum indoor air occur in many species from various sources: occupants (metabolic products, personal care products), cleaners and waxes (cleaning products with solvents, etc.), paints, pesticides (mould inhibitors, insecticides, fungicides, household disinfectants, etc.), adhesives, furnishing and clothing (carpet finishing components, tapestry, draperies, tissues, etc.), building materials (construction materials, furniture, etc.), HVAC systems sections and air inlet grids if near to pollution sources (vehicular exhaust, etc.), outdoor air [6]. VOCs are formed by numerous chemical compounds, belonging to classes of aromatic, halogenated and aliphatic hydrocarbons, aldehydes, esters, alcohols, ketones, terpenes, carboxylic acids, etc.

Exposure to VOCs can result in both acute and chronic health effects; main health effects are: severe irritation of eyes and respiratory track, heart diseases, damages to central nervous system up to possible human carcinogen. Health effects can be related to a fast-increasing pollutant concentration and to an extended exposure.

The major categories of biological particles which can affect IAQ in museums are dust mites, fungi and bacteria. The highest number of mites in indoor environments comes from human skin and are usually found in upholstered furniture, carpeting, tapestry, draperies, tissues, etc., and shows a wide seasonal difference. High total bacterial load (TBL) can be also related to the presence and growth of pathogen micro-organisms. As the mould's growth is increased by high relative humidity values and air temperature higher than 25°C, it can also be an indicator of poor ventilation quality. Among the numerous species of fungi only some of them are of prime interest in museum indoor environments [6]. When temperature and relative humidity range is fitted, some species can use many organic materials to grow: plants, animal, cellulose paints, and even building materials when superficial condensation conditions are met, for bad or insufficient insulation of the building envelope. In indoor air of museums, the main sources of bacteria aerosol are usually human being even though bacterial aerosol can also be generated by disturbing settled dust. The humidifiers, filters and drainage fans of the HVAC systems can also be a potential source of airborne bacteria.

These pollutants form a bioaerosol that can cause rhinitis, asthma, allergies, atopic allergic dermatitis, infections; moreover, mycotoxins in airborne particles can be potentially hazardous for humans.

Even if there are not specific laws for IAQ there are technical standards (mandatory or voluntary), guidelines and studies (national and international) that can be taken into account to establish a relationship between pollutant concentration, quality indicators and health effects or even discomfort conditions [7].

One of the most important Standard concerning IAQ is ASHRAE Standard 62.1 that defines acceptable indoor air quality [8]. Many standards deal to indoor air quality by means of minimum ventilation rates [9] [10]. Some Italian Reports of Istituto Superiore di Sanità (ISS) dealing with indoor air quality are also available [11]. Different occupational patterns of museums (workers and visitors) are included in different laws and standards from MIBAC (Ministero per i Beni e le Attività Culturali) [12]. Other guidelines establish maintenance protocols (inspection, cleaning) for Air Handling Units (AHU) and ductwork of HVAC systems; moreover, limit values for dust, bacterial ad fungi in

ductwork are available. NADCA guidelines and international standards and those of AIISA (Associazione Italiana Igiensti Sistemi Aeraulici) are very important as there is a strong relation between indoor air quality and ductwork [13].

There are some fundamental documents that rule air quality and that can be adopted in museums [9][10][12][14]; in particular, UNI EN 13779 Standard classifies IAQ in four classes (from high quality to low quality) corresponding to minimum air flow rates, while in UNI EN 15251 the expected percentage of people dissatisfied are related to IAQ levels. For CO_2 concentration, ISS Report 16/15 [15] recommends a maximum indoor concentration of 1000 ppm, that can be taken as limit value for museum environments equipped with mechanical ventilation systems (table 1).

Table 1. CO_2 concentration values

CO_2 concentration	**CO_2 assessment**
CO_2 beneath 1800 mg/m^3 (1000 ppm)	Acceptable level, harmless
CO_2 between 1800 mg/m^3 (1000 ppm) and 3600 mg/m^3 (2000 ppm)	High level
CO_2 higher than 3600 mg/ m^3 (2000 ppm)	Unacceptable level

For VOCs concentration, European Standards suggest limit values for total VOCs; those can be used as reference values for museum IAQ assessment [16] (table 2).

Table 2. VOCs concentration values

VOCs concentration	**VOCs assessment**
< 0.200 mg/m^3	Comfort level
0.200 - 3 mg/m^3	Acceptable level
3 - 25 mg/m^3	Discomfort level
> 25 mg/m^3	Unacceptable level - toxicity

These guidelines suggest a total VOCs concentration of 0.300 mg/m^3 as threshold value; moreover, any component can exceed 50% of the value identifying its class.

European guidelines suggest limit values for biological pollution (bacteria and moulds) for non-industrial destinations and can be taken as reference values also for ductwork hygienic conditions in proximity of air inlet grids [16] (table 3).

As regard human well-being, UNI EN ISO 7730 [17] points out acceptable values in moderate thermal environments for dry bulb temperature (20-26°C), relative humidity (40-60%) and air velocity (< 0.23 m/s).

Table 3. Recommended values in CFU/m^3 of biological concentration

Biological pollution level	**Bacterial pollution (CFU/m^3)**	**Mould pollution (CFU/m^3)**
Very low	< 50	< 25
Low	< 100	< 100
Intermediate	< 500	< 500
High	< 2000	< 2000
Very High	> 2000	> 2000

On the basis of these premises, and due to some complaints dealing with poor IAQ reported by the occupants (museum staff and visitors), the Director of the Uffizi Gallery decided to carry out a preliminary IAQ survey in some rooms of the museum to verify their suitability.

To assess indoor temperature, relative humidity, chemical and microbiological pollutants in the museum, a methodology of investigation and assessment of the results has been defined and presented in this paper. The survey aim is to underline the presence of critical issues in order to determine the pollutant concentration and compare the sampled values with the limit values reported in Italian standards, technical regulation and guidelines. The preliminary results can be used to plan a deepen investigation with a more detailed sampling of specific pollutants.

2. Materials and methods

A general evaluation of the Uffizi Gallery (general data, condition of rooms and equipment, number of visitors, drawings, building materials, HVAC system and other equipment, objects exposed) was carried out with site inspections and interviews with the technical staff.

The HVAC system was investigated both from a theoretical point of view and with direct inspection (technical rooms, spaces for the passage of pipes, duct, etc.) in order to analyse the effectiveness of the system to maintain acceptable indoor air quality in the museum environment.

As the presence of visitors was very important, air pollution in the museum was sampled, for some representative rooms, both with the museum closed (used to define "reference" values) and the museum open.

Main pollutants were selected, and a proper methodology of monitoring was developed concerning the strategy of monitoring and the set of instruments, the reference air pollution values from guidelines, standards and specific laws for human well-being.

In particular, the investigation strategy was performed stepwise:

- collection of general data;
- definition of the monitoring strategies (sampling objectives, rooms of the museums to assess, set of instruments, time of sampling, duration and frequency of sampling, sampling location, active and passive sampling strategy);
- sampling of thermo-hygrometric parameters (air temperature, relative humidity, air velocity measured in the room and in proximity with the air inlet/outlet grids);
- sampling of organic (VOCs) and inorganic pollutants (CO_2);
- sampling of bacteria aerosol (bacteria and moulds);
- collection of reference values for the sampled pollutants;
- sampling analysis to determine chemical and microbiological pollutants. In particular, microbiological analysis aimed at the total bacterial load (including bacteria that grown at a temperature range of 30-37°C) and the total Colony Forming Unit (CFU) in the bioaerosol;
- comparison between the measured values and the recommended values from guidelines, laws, technical standards, scientific studies;
- pollutants critical analysis and their correlation with possible pollution sources (HVAC system, maintenance procedures, cleaning procedures, etc.).

The described methodology was applied on several rooms of the Uffizi Gallery, chosen according to the importance of the artworks exhibited, the number of visitors, the air conditioning system and the potential critical issues for artworks conservation and for occupants well-being related to indoor air quality.

The Uffizi Gallery entirely occupies the first and second floors of the large building constructed between 1560 and 1580 and designed by Giorgio Vasari. It is famous worldwide for its outstanding collections of ancient sculptures and paintings (from the Middle Ages to the Modern period). The collections of paintings from the 14th-century and Renaissance period include some absolute masterpieces: Giotto, Simone Martini, Piero della Francesca, Beato Angelico, Filippo Lippi, Botticelli, Mantegna, Correggio, Leonardo, Raffaello, Michelangelo and Caravaggio, in addition to many precious works by European painters (mainly German, Dutch and Flemish). Moreover, the Gallery boasts an invaluable collection of ancient statues and busts from the Medici family, which adorns the corridors and consists of ancient Roman copies of lost Greek sculptures.

In every room of the Gallery the instruments were positioned in an appropriate location with the aim of collecting representative data and, at the same time, limiting visitors interaction and ensuring the correct fruition of the room.

To sample environmental parameters a microclimatic station with datalogger, positioned to a high of 1.6 m from floor, was used; the data were collected every minute for 2 hours and the following parameters were measured: dry bulb temperature (t_{db}), wet bulb temperature (t_{wb}), relative humidity, air velocity and CO_2 concentration.

The VOCs monitoring was carried on in close proximity to the microclimatic station with active sampling of a 5 litres air volume collected in nalophan bags, afterwards sent to an external laboratory to be analysed; quantitative and qualitative VOCs analysis was carried out according with Gas Chromatography-Mass Spectrometry (GC/MS) method (EPA TO-15-1999 method). For VOCs the cut-off value was settled at 1% of the air sample, as established by the CE Reg. 1272/2008.

Biological analysis (TBL and moulds) was carried on both with active and passive sampling methods. During active sampling air flow was collected with a surface air system impactor with a sampling rate of 100 l/minute positioned in close proximity to the microclimatic station, to a high of 1.60 m from floor. Sampling rate and consequently the total air volume (0.3 - 0.5 - 1m^3) varied for different occupational pattern of the museum room. In order to collect information about biological pollution due to the passage of people and the air flows from the ventilation systems, the total biological pollution was also collected by passive sampling for 2 hours, using Petri dishes positioned near the microclimatic station (Φ=90mm, Plate Count Agar for microbial growth and Sabouraud Dextrose Agar for mould growth). Both sample dishes (active and passive sampling) were sent to an external laboratory to be incubated at proper temperature-time range (three days at 30°C for TBL and five days at 25°C for moulds) and afterwards analysed to determine the CFU both for bacteria than for moulds according to ISS Report 13/37 [18].

Collected data were reported in tables (with minimum, maximum and average values of the parameters) and graphs, depending on time for every sampling location; reference values (guidelines, standards and cut-off values of different pollutant concentrations) were also underlined. Temperature and relative humidity ranges were highlighted together with recommended values for object proper conservation [12]. In table 4 main features of the microclimatic station probes are presented.

Table 4. Main feature of probes

■ Psychrometer	
SENSOR	Pt100 (1/3DIN)
Accuracy	0.10°C (0°C); 0.13°C (20°C) 2% (15÷40%); 1% (40÷70%); 0.5% (70÷98%)
Response time (T90)	90'' (operating fan)
Measure range	t_{db}: 25 ÷150°C; t_{wb}: 0 ÷ 60°C RH: 0÷100%
◆ Anemometer	
SENSOR	Tungsten wire Ø 9.45 µm
Accuracy	0.05 m/s (0÷0.5 m/s); 0.1 m/s (0.5÷1.5 m/s) 4 % (>1.5 m/s)
Response time (T90)	0.1''
Measure range	0÷20 m/s
✱ CO_2 probe	
SENSOR	Absorption infra-red cell
Accuracy	3% measure range
Response time (T90)	<30''
Measure range	0 ÷ 3000ppm

3. Preliminary results and discussion

In this paper the results regarding the Room X of the Uffizi Gallery are shown and discussed.

The Room X, located on the second floor of the museum, has a floor area of 146.34 m^2, height of 8.93 m and a volume of 1306.82 m^3; the marvelous Primavera by Sandro Botticelli, a tempera painting on wood dated 1478 - 1482, is exposed in the room. The room has only an external wall, without windows, facing east and is equipped with an HVAC system for the control of temperature and relative humidity, managed by a remote monitoring and control system. The AHU, housed in an attic room, allows the air treatment with centralized air recirculation, both for heating and cooling, and is equipped with air inlet and outlet funs with variable flow, with a nominal air flow of 8000 m^3/h and a nominal air exchange rate of about 6.12 vol/h. The air inlet and outlet take place through linear grids placed under the top skylight.

Figure 1 shows the IAQ monitoring system inside the room, which was placed near the Primavera. The monitoring was carried out on 05.06.2019 from 10:00 to 12:00, during the opening hours of the museum in correspondence with the greater number of visitors.

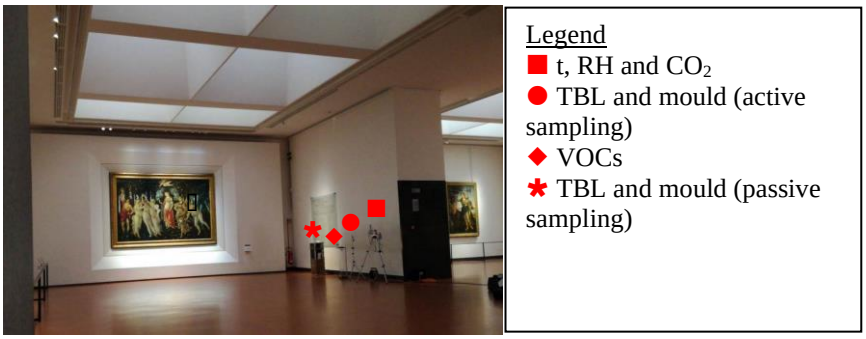

Figure 1. Picture of the Room X with the IAQ monitoring system

Table 5 summarizes the preliminary results of the monitoring carried out, as regards temperature, relative humidity, carbon dioxide, volatile organic compounds, total bacterial load and mould. As regards biological monitoring, the results expressed in CFU/m^3 refer to active sampling, while those expressed in CFU/PT_{90} to passive sampling of total bacterial load and mould.

Table 5. Preliminary results of the IAQ monitoring carried out in Room X

Monitored parameter	**Minimum value**	**Maximum value**	**Average value**
t (°C)	21.9	24	22.8
RH (%)	48	56	51
CO_2 (ppm)	1312	1568	1442
Monitored parameter		**Sampled value**	
VOCs (mg/m^3)		0.354	
TBL (CFU/m^3)		180	
mould (CFU/m^3)		19	
TBL (CFU/PT_{90})		64	
mould (CFU/PT90)		3	

Figure 2 shows the values of temperature and relative humidity measured outdoor and in the room for the whole acquisition time compared with the acceptable values for the occupants well-being (yellow box) and also with the acceptable values for the conservation of wood paintings (gray box) [12].

Indoor CO_2 concentration is connected to the presence of occupants (staff and visitors), exceeding the recommended limit value of 1000 ppm when the museum is open.

All the measured VOCs values are within the acceptable level, according to the classification expressed by the European guidelines reported in table 2. The substances with the greatest presence

within the environment were the class of aldehydes, followed by that of alcohols (both components mainly associated with furnishings, finishing treatments, products for cleaning and fragrance).

As regards the microbiological parameters, based on the reference values shown in table 3, the total bacterial load concentration is to be considered in the intermediate level pollution category (less than 500 CFU/m^3), while the mould concentration is to be considered in the low pollution category (less than 100 CFU/m^3). In particular, moulds grown on Sabouraud dishes (both with active and passive sampling) belongs to Aspergillus (flavus e fumigatus) e Penicillium.

The air velocity never exceeded the value of 0.1m/s meeting the occupants well-being range.

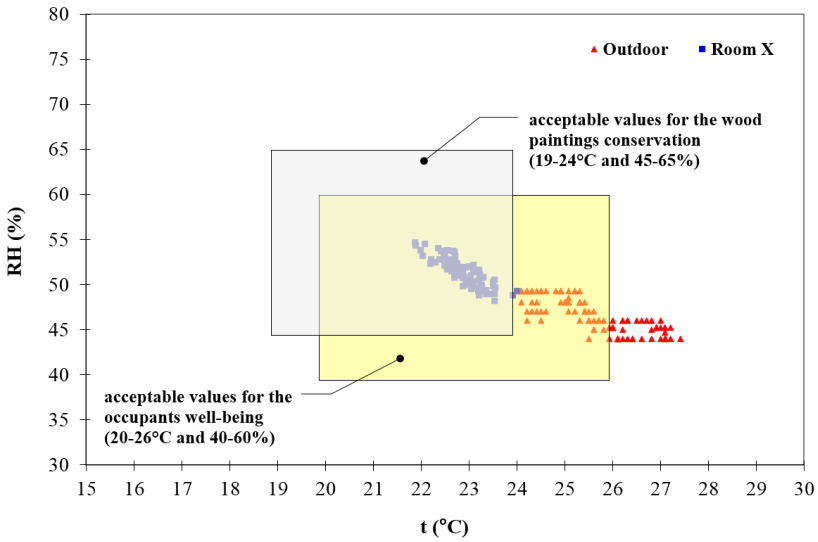

Figure 2. Values of temperature and relative humidity measured outdoor and in the room X for the whole acquisition time compared with the acceptable values for the occupants well-being (yellow box) and for the conservation of wood paintings (gray box)

4. Conclusions and future development

A preliminary IAQ monitoring was conducted in some rooms of the Uffizi Gallery of Florence.

Data collected in room X suggest a general agreement with the acceptable limit values, excepted for CO_2 that exceeded the recommended limit value of 1000 ppm. For VOCs the substances with the greatest presence within the environment were the class of aldehydes, followed by that of alcohols. As regards the microbiological parameters, the total bacterial load concentration is to be considered in the intermediate level pollution category, while the mould concentration is to be considered in the low pollution category.

The future development of the research involves a deepen analysis of the IAQ inside the Uffizi Gallery. As regards VOCs, an investigation should be carried out to underline the relationship between some specific pollutants and the pattern of use and maintenance of the museum, for example achieving cleaning, paints, varnishes, glues and disinfectants products composition to determine the presence of specific pollutant classes. This information can be useful to determine specific VOCs Threshold Limit Value concentration both as Time Weighted Average (8 hours) for the staff and as Short-Term Exposure Limit (15 minutes) for the visitors. As for the biological pollution specific bacteria and moulds can be sampled in order to underline potentially dangerous pollutants both for occupants and the exposed objects. Moreover, an analysis of the hygienic maintenance of HVAC ductwork should be studied in deep.

IAQ monitoring in the museum can also be useful to plan different strategies to improve occupants well-being, good conservation of the objects exposed without overlooking the building energy efficiency.

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