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An integrated approach for the systematic monitoring of the indoor air quality and microclimatology at churches located in the Central Mediterranean region

Antonio Proto[1], Francesca Cannizzaro[2], Maria Ricciardi[1], Maria Letizia Amadori[3], Jgor Arduini[3], Oriana Motta[4], Paola Donato[2], Alfred Micallef[5], Sebastiano D'Amico[5], Adriana Alescio[6], Luigi Mondello[2,7], Danilo Sciarrone[2]

[1] *Department of Chemistry and Biology, University of Salerno, via Giovanni Paolo II 132, 84084-Fisciano (SA), Italy; aproto@unisa.it; mricciardi@unisa.it*
[2] *Messina Institute of Technology c/o Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, former Veterinary School, University of Messina, Viale G. Palatucci snc 98168 Messina, Italy; francesca.cannizzaro@studenti.unime.it; paolaagataeustochia.donato@unime.it; danilo.sciarrone@unime.it*
[3] *Department of Pure and Applied Sciences, University of Urbino, Piazza Rinascimento 6, Urbino, Italy; maria.amadori@uniurb.it; jgor.arduini@uniurb.it*
[4] *Department of Medicine Surgery and Dentistry, University of Salerno, via S. Allende, 84081 Baronissi, Salerno, Italy; omotta@unisa.it*
[5] *Department of Geosciences, University of Malta, Msida, MSD 2080, MALTA alfred.micallef@um.edu.mt; sebastiano.damico@um.edu.mt*
[6] *St John's Foundation, Malta, a.alescio@stjohnscocathedral.com*
[7] *Chromaleont s.r.l., c/o Messina Institute of Technology c/o Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, former Veterinary School, University of Messina, Viale G. Palatucci snc 98168 – Messina, Italy; luigi.mondello@unime.it*

***Abstract* – Air pollution is one of the main issues impacting the preservation of cultural heritage. As a matter of fact, the interaction of atmospheric pollutants with artworks may lead to their degradation. The present study concerns a preliminary investigation of indoor air quality and microclimatic conditions in sacral buildings located in the Central Mediterranean region, which is undergoing marked climatic changes and influenced by the long-range transport of atmospheric pollutants. The area is also experiencing a strong influx of visitors, which can directly impact indoor environments. Identification of the sampling locations and baseline microclimatic conditions at the monitoring sites, useful for a full indoor air quality assessment, was accomplished. To reach this goal, the monitoring strategy combined two real-time sensors that measure the concentration of particulate matter and microclimatic parameters with additional sensors for temperature, relative humidity, CO_2, and particulate matter. Some devices were installed at different heights to obtain vertical profiles of microclimatic parameters. Data collected inside and outside the monitored sites were processed in relation to the influx of visitors, providing insights with regard to the anthropogenic effects of visitors on the measured parameters.**

I. INTRODUCTION

It is well known that air pollution is of major concern in the preservation of cultural heritage [1]. Even more so in the case of works of art located in the historic centres of large cities, which are subjected to high levels of anthropogenic pollution [2–9].

Several air pollutants, including typical pollutants synonymous with urban and industrial areas such as carbon dioxide (CO_2), nitrogen dioxide (NO_2) [10], sulphur dioxide (SO_2) [11], and volatile organic compounds (VOCs), e.g. acetic and formic acid [12], can cause damage to cultural heritage, following exposure at certain concentrations for long periods [13–17]. Moreover, high concentrations of the said pollutants in indoor environments (e.g., churches) can pose risks to human health [18–21]. Consequently, the concentration of hazardous pollutants should be regularly monitored in order to safeguard both artworks and the health of workers and/or visitors.

Air monitoring can be performed using continuous, real-time instrumentation and active or passive sampling [22–24]. Active sampling is performed with air aspiration systems over short periods of time, whereas passive sampling can be easily carried out over long periods and returns time-weighted average concentrations, useful in air quality assessments.

The present work is part of a larger multidisciplinary project concerning a comprehensive assessment of the air quality in the Central Mediterranean region, and the effect of specific air pollutants on the state of conservation of the inestimable works of art at the location.

In particular, the project will involve the continuous assessment of key atmospheric pollutants that pose a risk to the conservation of the artworks. The pollutants to be monitored will include particulate matter (PM), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ammonia (NH_3), and volatile organic compounds (VOCs), all of which can accelerate the degradation of paint and canvas. Moreover, the concentration of contaminants introduced by visitors, such as dust, skin particles, and residues from personal care products, which can contribute to the accumulation of harmful substances on surfaces over time, will be also evaluated. Concurrently, microclimatic conditions (temperature, relative humidity, and light level), which are crucial for maintaining the stability of sensitive materials, will be constantly monitored.

For these purposes, small-size sensor units and passive air samplers will be installed inside and outside the churches. Furthermore, the conservation status of the artworks will be closely evaluated to avoid deterioration of different materials that necessitate careful management. This comprehensive environmental and material assessment will be vital for the preservation of the integrity of these significant cultural assets and preventing further decay.

Sacral Heritage Sites: Cultural Value and Monitoring Framework

This section addresses the importance of sacral buildings in the Central Mediterranean, which represent not only places of worship but also repositories of cultural memory and artistic heritage. Fig. 1 illustrates the geographical distribution of UNESCO World Heritage Sites in the Central Mediterranean region, distinguishing cultural sites (yellow), natural sites (green), and sites included in the list of world heritage in danger (red). The Central Mediterranean is a region undergoing marked climatic changes, with pronounced seasonal variability in temperature and relative humidity. These conditions strongly affect the hygrothermal stability of sacred interiors. The area is also influenced by the long-range transport of atmospheric pollutants, which can infiltrate and accumulate in confined spaces, thereby impacting both structural materials and works of art. From the perspective of conservation, these climatic and atmospheric factors represent critical challenges to the long-term safeguarding of heritage sites [25,26].

In addition to environmental stressors, the region attracts a strong influx of visitors, both tourists and worshippers. Human presence contributes directly to indoor microclimatological variations, including fluctuations in carbon dioxide concentration, relative humidity, and particulate matter, as will be discussed in Sections III and IV.

The interplay of such factors underscores the importance of preliminary monitoring campaigns aimed at characterizing the unique sub-microenvironments of sacred and cultural buildings in the Central Mediterranean, providing essential data for preventive conservation.

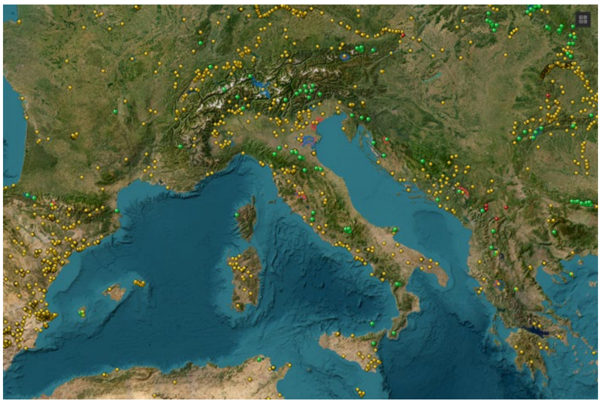

Fig. 1. *Map of UNESCO World Heritage Sites in the Central Mediterranean region. Yellow markers represent cultural sites, green markers natural sites, and red markers sites are those included in the List of World Heritage in Danger (Source: https://whc.unesco.org/en/interactive-map/ September 2025).*

II. MATERIALS AND METHODS

Four types of instruments were deployed in selected churches during the monitoring campaign. Two identical devices were used to measure carbon dioxide (CO_2) concentrations (A01 and A02), while another pair was employed to measure particulate matter (PM1.0, PM2.5 and PM10), labelled PM01 and PM02. In addition, eleven loggers for temperature and relative humidity (Parkside, model PKDL A1), labelled TH01 to TH11, were employed. Some of the devices of the latter lot were installed at different heights in order to obtain vertical profiles of microclimatic parameters inside the monitored sites. These instruments were distributed across the various sub-microenvironments and architectural levels to achieve the most comprehensive coverage possible. Furthermore, two Sensy S1 air quality sensors were installed at different locations in one of the churches that was being monitored, one indoors and the other outdoors. These sensors were developed by Sense Square (WIPO 2018/225030AI). They are laser scattering instruments that allow the continuous measurement of PM10, PM2.5 and PM1.0 concentrations, with a high temporal resolution. They also measure microclimatic parameters such as temperature (T), atmospheric pressure and relative humidity (RH). The main characteristics of these sensors are summarised in Table 1.

Table 1. Main characteristics of the Sensy sensors.

Parameter	**Accuracy**	**Technology**
T	±0.3 °C	Band-Gap
RH	±2%	Capacitive
PM10	±5 μg/m^3	Laser scattering
PM2.5	±5 μg/m^3	Laser scattering
PM1.0	±5 μg/m^3	Laser scattering

III. DISCUSSION

This preliminary investigation involved the identification of the sampling locations and baseline microclimatic conditions at the monitoring sites, which are useful for a comprehensive indoor air quality assessment. Fig. 2 illustrates some of the instruments used during brief preliminary campaign. In Fig. 2a, a Sensy sensor is shown, installed outdoors at one of the monitoring locations. Fig. 2b depicts a monitoring set-up comprising a Sensy sensor, a temperature and relative humidity logger, and a CO_2 sensor, positioned indoors to provide complementary information. Finally, Fig. 2c shows a close-up of a particulate matter sensor placed in proximity to ornamental surfaces in order to assess the localized effects of human presence.

To monitor airborne pollutant levels, such sensors were employed at different locations, both indoors and outdoors. The instruments recorded particulate matter concentrations (PM10, PM2.5 and PM1.0), temperature, relative humidity, and CO_2 concentration on a continuous basis.

***Fig. 2**. Location (circled in red) of the monitoring devices: (a) Sensy sensor installed outdoors at one of the monitoring sites; (b) indoor monitoring set-up including a Sensy sensor, a temperature and relative humidity logger, and a CO_2 sensor; (C) particulate matter sensor placed in proximity to ornamental surfaces.*

The data will be processed in relation to the influx of visitors in order to assess the resulting anthropogenic effects. This analysis is essential for the identification of pollution sources.

Indoor air quality is strongly linked not only to outdoor pollution but also to the presence of large numbers of visitors, who may act as carriers for volatile organic compounds and particulate matter. Furthermore, specific pollutants, even present in low concentrations, can cause substantial damage over long exposure periods, and hence the associated assessment is crucial for the preservation of cultural heritage.

IV. CONCLUSIONS

This brief and preliminary investigation highlights the importance of systematic monitoring of air pollutants and microclimatic parameters in churches located in the Central Mediterranean region, which is strongly influenced by climatic changes and increased tourism. The results demonstrate how the integration of real-time sensors placed also at different heights, together with passive samplers, can provide essential baseline information for assessing environmental risks. These data will support the development of appropriate strategies for the protection of artworks and the optimization of conservation practices in cultural heritage sites exposed to both climatic variability and anthropogenic pressures.

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