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Micro-climatic investigation and particulate detection in indoor environments: the case of the historical museum of *Bersaglieri* in Rome

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Abstract
Museums, historical buildings mainly located in urban centers, may be seriously affected by pollution and other critical urban atmospheric conditions. In addition to museums, there are many other different cultural heritage indoor environments each having different characteristics, mainly depending on the type of preserved materials that are sensitive to pollution and urban conditions. In this contribution we report an investigation of the indoor air quality and some considerations about the conservation of historical artifacts located inside the Historical Museum of *Bersaglieri* in Rome. Specifically, we show the feasibility in the exhibition rooms of a microclimatic characterization to evaluate the air quality, a critical issue for many of the artifacts exposed in confined spaces. The work we carried out is the monitoring of the behavior of temperature and relative humidity and the presence of airborne pollutants inside the museum halls. Taking into account the regulations in force that control and protect the Italian museums, these measurements have been carried out by using a customized and flexible system based on low-cost multi-parameter sensors allowing the monitoring of several environmental parameters. In spite of the limitation of this preliminary test study, on the basis of the results and according to the different preserved materials, a set of indications, criteria and tools have been provided to the museum managers to implement an effective "conservative strategy".

Keywords Environmental monitoring · Low-cost device · Particulate matter · Temperature · Relative humidity · Indoor atmosphere · Cultural heritage

1 Introduction

In the recent years, a continuously increasing attention has been paid to the microclimatic conditions of cultural heritage indoor environments with the purpose being the long-term preservation of both the artifacts, but also of the location where they are hosted (Ascione and Minichiello 2010; Bacci et al. 2005). In the past, these exhibition locations were often characterized by less polluted and more stable microclimatic conditions. As an example, the heating systems and the artificial lighting, only two of the many factors potentially causing serious damage to the displayed art works, were limited and less powerful as those nowadays employed. In fact, parameters such as the internal air temperature, the relative/ specific humidity, and the lighting conditions significantly affect the indoor air quality inducing in many cases the deterioration of the artworks kept inside museums or other buildings hosting artworks and any other type of cultural heritage objects. Indeed, in

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addition to museums there are many different indoor sites, such as galleries, libraries and archives, historical palaces, archeological sites, etc., each having different types of environmental problems (Manuel Zarzo et al. 2011; Sileo et al. 2017; Smiełowska et al. 2017; Pereira et al. 2017; Sahu and Gurjar 2019; Lucchi et al. 2019) actually dependent by the type of preserved materials, opening conditions and number of visitors. A great number of these sites are located in dense urban areas, which are seriously affected by pollution and other critical atmospheric conditions. Although in the last decade in the main urban areas of the western countries we assisted to a significant reduction in the emissions of some environmental pollutants (Air quality report Europe, 2019), at variance, we observed in the same period an increase of airborne particulate matter (PM) (Bernardi 1990; Camuffo and Bernardi 1995; Grau-Bové and Strlic 2013; Pisello et al. 2014; Gozzi et al. 2017) and chemicals such as volatile organic compounds (VOCs), particularly in indoor environments (Kontozova-Deutsch et al. 2008; Cartechini et al. 2015). The latter, especially harmful for heritage materials, are produced by the museum framework itself and by the urban environment.

We are investigating the issue of the conservation of historical artifacts located inside museums, and, specifically, we carried out a microclimatic study in some exhibition rooms at the Historical Museum of Bersaglieri located in Rome. The project was initiated in the frame of the activities of the Master in “Experts in the evaluation and Protection of Cultural Heritage” at the University of Roma Tre. The original work was focused at examining novel procedures to monitor the behavior of the main parameters to keep under control in the exhibition halls of this museum, such as temperature, relative humidity and the presence of airborne pollutants. Based on a large corpus of scientific research, is it now clear that such environmental surveys allow understanding whether the buildings have suitable microclimatic conditions for the artworks or manufacts displayed, and eventually what might be the sources for the observed changes in the monitored parameters. Similar studies were already performed since 90s in several museums all around the world (Bernardi 1990; Camuffo and Bernardi 1995; Camuffo et al. 2001) using the technology available at the time.

The innovative aspect of the present study is the approach to survey carried out by means of a low-cost multi-parameter sensor system based on the Arduino open-source hardware and software platform. This approach is particularly suited for allowing a customizable and flexible system to monitor all needed environmental parameters. In this dedicated study, our customized device proved useful for the evaluation of the indoor air quality, a critical issue for the artifacts exposed for years in confined spaces. The design of the environmental monitoring took into account the specific regulations in force that control and protect the Italian museum collections (Gazzetta Ufficiale Serie Generale 2001), on the basis of which a series of indications, criteria and tools have been provided to the museum that hosted our study. We outlined a "conservative strategy" to be implemented (Sebastianelli 2015–2016) by means of the analysis within a finite period of time of the thermo-hygrometric conditions and the presence of airborne pollutants inside the halls of the Historical Museum of Bersaglieri. Airborne pollutants and PMs are a subject of great interest although they can be a quite elusive subject of study. Indeed, according to size, they display different properties and behaviors and may be originated from different sources (Gozzi et al. 2016).

In the field of the conservation of art works, a fundamental problem involves establishing a ‘suitable environment’, i.e., one with negligible variations and absolutely no sudden changes in the main parameters (e.g., temperature and relative humidity), which are the cause of many structural and chemical alterations. Many studies clearly demonstrates that changes in the microclimate are at the origin of observed alterations or damages and pointed out useful advices on how to control and improve the microclimatic conditions (Leissner et al. 2015). Indeed, even if the techniques for restoration developed to preserve artworks to the future generations are continuously improving thanks also to the modern analytical and imaging methods, each work of art can only be submitted to a limited number of ‘restorations’ and in many cases, especially in the last years, the physical condition of the cultural heritage has progressively and consistently deteriorated. Moreover, during the last 2–3 decades a continuously increasing number of people are interested in admiring paintings and other unique works of art. Paintings and other artifacts are now frequently transported from their original sites to galleries, museums, and temporary exhibition rooms. Many of these locations are not suitable for their conservation and are designed more for to ensure the safety of the objects, the comfort of the visitors, or the demands of aesthetics, than at providing a suitable microclimate for the conservation of artworks, which needs a constant microclimate and lighting with no or minor changes. Such conditions are hard or impossible to attain, while at the same time providing adequate heating, air conditioning, artificial lighting,” etc., to visitors.

The Historical Museum of Bersaglieri is one of the most valuable museums belonging to the Italian Army and is part of the monumental complex of Porta Pia, located in Via XX Settembre, within downtown. The foundation of this old building was commissioned by Pope Pius IV and was connected to a larger urban project that included the arrangement of several entrances to the city. The door was built to replace the oldest Nomentana gate and the project was entrusted to Michelangelo Buonarroti who worked there from 1561 to 1564. The new access to the city was not conceived as a simple arched opening but as a monumental complex (Fig. 1a) with a courtyard and two facades, one toward the city (Fig. 1b) and a second, external gate (Fig. 2) that, as shown in a drawing of the Alexandrine Registry (1660), presented a simple opening in the archway. The construction works were interrupted because of the death of the Pope in 1565. Additional interventions were carried out during the eighteenth century but concerned essentially the minor building inside the court and were connected to the customs and defense needs of the city entrance. A new phase of nineteenth-century interventions, followed by Virginio Vespignani, started after the Michelangelo door was damaged by a lightning in 1851. The restoration of the major damages involved the remaking of the entire central portion of the sixteenth-century facade. In addition to the restoration, the roman architect also completed the monumental complex, and followed the reconstruction of the external door in 1861–1868 done by several artists who contributed to the rich decoration. A few months after the final completion, the monumental site was overwhelmed by the war events. On September 20th 1870 the opening of a breach on the Aurelian walls between the IV and V towers caused significant damage to the entire complex; these deteriorations were later restored again by Vespignani, and completed in December 1870. During the urban reorganization of the Umbertine period, the decision to extend the tramway axis along via XX Settembre made the monumental complex lose its connection with the Aurelian walls because two sections of the adjacent walls were cut (1887–1889). In addition, the administration of Rome, which had become capital of Italy, changed the original use of the gate that was destined for the Carabinieri barracks. As a last and definitive change of use, the monumental complex was chosen to transfer the Historical Museum of the *Bersaglieri* that was previously housed in some rooms of the La Marmora barracks in Trastevere. The new Museum was inaugurated together with the location, in the square just in front, of the monument to the bersagliere (sharpshooter) (1932) by the sculptor Publio Morbiducci. New interventions were finally conducted from 1940 to 1942. The museum is part of the national heritage [Italian DLGS N.42, 22 January 2004] and has been included in the list of World Heritage sites of UNESCO, in September 1980.

The museum is accessed from the northwest building. The two symmetrical buildings aside the courtyard host the collections that are organized into thematic sections, arranged following a general chronological sequence. All the museum's exhibition halls are equipped with radiators and an artificial lighting system composed of incandescent lamps on the ceiling. The two rooms located at the entrance on the ground floor are dedicated to the founder of the Corp, General Alessandro La Marmora; these host objects of different types of materials: textiles, metals, paper, paintings

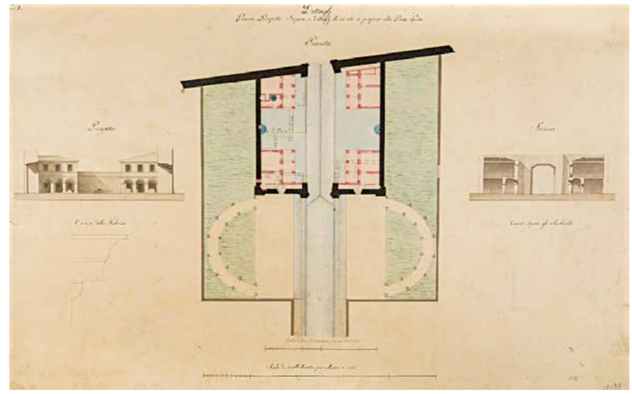

Fig. 2 The hystorical plan of the monumental complex of porta Pia by Virginio Vespignani 1851–1852 (from Istituto Nazionale di Archeologia e Storia dell'Arte, Fondo Rodolfo Lanciani, Rome)

Fig. 1 **a** General view of the monumental complex, from the external gate toward Via Nomentana. **b** the Michelangelo gate toward Via XX Settembre

on canvas, wooden artworks, polymaterial artifacts, etc., belonging to the nineteenth century. Many spaces in the exhibition areas are furnished with wooden cabinets of different sizes, where the most fragile and precious objects are kept: paper, textiles and metals (Fig. 3). The museum continues through the rooms on the first floor, which are dedicated to the Independence war, where most of the paintings preserved in the museum are shown. Following the passage obtained through the arch of the Vespignani gate, we reach the symmetrical building where the exhibition hall is dedicated to the First World War; here objects dating back to the first two decades of the twentieth century are located, including a large collection of photographs. The room on the upper floor houses an interesting collection of various types of artifacts from the African campaign. The museum ends with a room on the ground floor that collects objects from the Second World War.

Taking into account the conservative events of the building, the non-specific destination as an exhibition structure, and the location of the complex in the center of Rome,

Fig. 3 Some examples of the different manufacts on display in one exhibition in the Historical Museum of the *Bersaglieri*

affected by significant pollution and, finally, in consideration of the extremely varied typology of objects kept inside the rooms, the Historical Museum of the *Bersaglieri* represents a valuable site for carrying out microclimatic investigations including PM monitoring.

2 Methods

This original investigation within the Historical Museum of the *Bersaglieri* follows our previous research dedicated to the design and testing of a novel low-cost device for PM monitoring and sampling in urban areas. This device based on an Arduino microcontroller and a communication module was conceived to be easily transported and implemented with different sensors according to specific demands. Its original design is equipped with an air pump able to capture the particulate matter (Piazzolla et al. 2020) and it can be adapted to different means of transport, e.g., car, van, bicycle, bike, tram, by varying the dimension and the shape of the inlet system (Gozzi et al. 2016, 2017). It can monitor in real-time the mass concentration of different PM sizes, integrates a set of sensors probing the main meteorological parameters, i.e., temperature and relative humidity, and it is also ready to be equipped with additional commercial sensors, e.g. volatile organic compounds (VOCs). Real-time communication via smartphone through Bluetooth® or by a dedicated app for Android® and iOS® is possible. In mobile operation, data are also released with positioning information provided by the GPS. This device samples the airborne particulate on a polycarbonate filter for further morphological and chemical analysis.

A customized version of this device assembled in the light of the foreseen permanent indoor air quality monitoring, was tested inside some halls of Historical Museum of the *Bersaglieri*. After the preliminary assessments, the system setup was modified with the purpose of collecting data uniquely for climatic parameters: temperature (T) and relative humidity (RH) and particulate matter (PM). For T and RH we used a commercial low-cost SHT20 sensor probe able to communicate via I2C protocol, with measuring range 0–100% for RH (accuracy 1σ: 3%) and − 40 °C to + 125 °C for temperature (accuracy 1σ: 0.3 °C), according to the manufacturer. For particulate matter we used the OPC-N2 particle device by Alphasense (UK) that allows monitoring $PM_{2.5}$ and PM_{10} dimensional classes with a satisfactory degree of confidence, up to 2000 mg/m^3. This particle device module is equipped with an integrated temperature and humidity sensing system and it is ready for data saving with on-board micro-SD memory and for data transfer via an SPI interface to Arduino. This particle module has been tested for accuracy against a professional platform equipped with the impacted system and proved to provide results well within the significance limit with respect all PM size classes (Gozzi et al. 2016). Due to logistic limitation, in this first test phase the assembled system did not allow sampling of the particulate for mineralogical/chemical analysis; this opportunity will be soon implemented to allow, besides quantitative measurements, also the qualitative characterization of the particles in terms of typology (inorganic vs. organic), mineralogy and chemistry (Piazzolla et al. 2020). This point is particularly important for a site that is located in the center of a highly-polluted metropolis like Rome, and kept materials spanning a large spectrum of typologies: paintings, wood, metals, but especially textiles including carpets, tapestries, old military uniforms, furs etc. that can contribute to the indoor environmental pollution. The system is powered by the electrical power network, but we decided to improve it with back-up batteries to continue operating in the presence of blackouts or when a loss of the power occurs.

The device we assembled is not limited to the above mentioned parameters and according to the location and objects to be monitored the system can be expanded with other sensors, and or adapted to the specific demands of the size and typology of indoor environment. As an example, to respond to recent demands, the device could implement also biosensors or sensors for persistent organic pollutants (POPs) to study the extent of chemical pollution and monitor the air quality breathed by visitors.

We tested our customized device within Historical Museum of the Bersaglieri along a period of ca. 70 days, from March 5th 2019 up to May 13th 2019. The necessity to setup the device and to verify its effective operativity during the testing period, resulted in a discontinuous data collection for this first indoor measurement campaign. With the aim to discuss the collected indoor data, and considering the need of minimizing the bias from a non-homogeneous acquisition, we follow this standardized workflow for data treatment:

(i) T, RH and PM measures were organized per day of acquisition;
(ii) Mean values of T, RH, $PM_{2.5}$ and PM_{10} were calculated for each complete measurement cycle of 60 min;
(iii) All calculated T and RH mean values for both March and April were then investigated using the "weighted average" routine in ISOPLOT4.1 excel spreadsheet (Ludwig 2003) following the statistic approach proposed in (Lucci et al. 2018);
(iv) Mean daily PM_{10} values were calculated to be compared to the respective outdoor PM_{10} values obtained by the 13 ARPA monitoring stations in Rome, and in particular by the "Villa Ada" station being the closest to our location (data available from the ARPA official website, https://www.arpalazio.net/main/aria/sci).

3 Results and discussion

Temperature is the major parameter correlated to "natural aging". Materials last longer at low temperatures and a rapid change in temperature, if the relative humidity is constant, may induce damaging effects on stressed metals, stone, films, plastics or wax, materials which belong to many collections. High temperatures may in fact increase deterioration reaction rates and melt heat-susceptible materials. There is no single relative humidity range that is ideal for all museum objects, however also the relative humidity (RH) should not fluctuate rapidly. Slow drifts are less harmful to structures and objects than abrupt changes. Indeed, fluctuating relative humidity (RH) causes stress on materials and also rapid humidity fluctuations may induce a higher damage of a wider range of museum objects than does temperature change. A change in RH causes dimensional alteration in hygroscopic materials, e.g., wood, ivory, skin, and other organic materials, resulting in warping, splitting, etc. of sensitive materials.

For mixed collections, a non-fluctuating relative humidity above 25% and below 65% is recommended. Lowering the temperature greatly increases the longevity of collections, but lower temperatures are not recommended for the comfort of visitors, so that many museums have set their relative humidity at 45% and gallery temperatures around 20 °C, see Table 1, which summarizes the regulatory recommendations of the Ministry for Cultural Heritage and Activities, D. Lgs. n.112/98 art. 150/6 (https://musei.beniculturali.it/wp-content/uploads/2016/04/Atto-di-indirizzo-sui-criteri-tecnico-scientifici-e-sugli-standard-di-funzionamento-e-sviluppo-dei-musei-DM-10-maggio-2001.pdf).

In Fig. 4 we display an example of the typically observed T and RH variations over a monthly period against the recommended maximum T and RH conditions in indoor museum structures, indicated by the broken line (see Table 1). In details, the statistical evaluation of the data shows that the trend observed in March 2019 is characterized by:

(i) hourly mean temperature values of 15.0°–21.5° ± 0.3 °C with a weighted mean value of 18.4° ± 0.3 °C ($1\sigma = 1.6\%$, MSWD = 20; $n = 88$; outliers = 6 in the range 8.0°–29.2° ± 0.3 °C);
(ii) hourly mean RH values of 26–63 ± 3% with a weighted mean value of 42.5 ± 2.3% ($1\sigma = 5.4\%$, MSWD = 13; $n = 88$; outliers = 3 in the range 8–69 ± 3%);

while the trend in April 2019 is characterized by:

(i) hourly mean temperature values of 17.0°–23.0° ± 0.3 °C with a weighted mean value of 20.2° ± 0.2 °C ($1\sigma = 1.0\%$, MSWD = 18; $n = 166$; outliers = 5 in the range 4.0°–16.5° ± 0.3 °C);
(ii) hourly mean RH values of 36–57 ± 3% with a weighted mean value of 45.6 ± 0.7% ($1\sigma = 1.5\%$, MSWD = 2.0; $n = 166$; outliers = 12 in the range 4–60 ± 3%); T and RH outliers, identified through the Tukey rules, correspond to less than 5% of the total dataset and will be excluded at this stage from discussion because a larger dataset would be needed to a better understanding of their meaning (i.e., true extreme values vs. bad data).

Table 1 Recommended T and RH values for the different materials in museum collections (https://musei.beniculturali.it/wp-content/uploads/2016/04/Atto-di-indirizzo-sui-criteri-tecnico-scientifici-e-sugli-standard-di-funzionamento-e-sviluppo-dei-musei-DM-10-maggio-2001.pdf)

Cultural heritage materials	Temperature (°C)	Relative humidity (%)
Weapons and iron armors	N.R	< 40
Ceramic products cooked at LT;	19–24	< 45
Gold, metals and polished alloys, silver brass, pewter, Pb and Cu	N.R	
Fabrics, carpets, tapestries, fabric upholstery	19–24	40–60
Mineralogical collections, marbles and stones;	< 30	45–65
Furs, feathers;	15–21 (4–10)*	
Painted wood, polychrome sculptures;	19–24	
Plaster	21–23	45–55
Paper, Papier-mâché;	19–24	50–60
Leather, skins, parchment; manuscripts;	14–20	
Organic material in general; pastels, watercolors, drawings, prints	19–24	
Paintings on canvas	19–24	30–45
Photographs (b/n)	2–20	20–30

* Thermohygrometric recommendations issued in Italian UNI 10829:1999

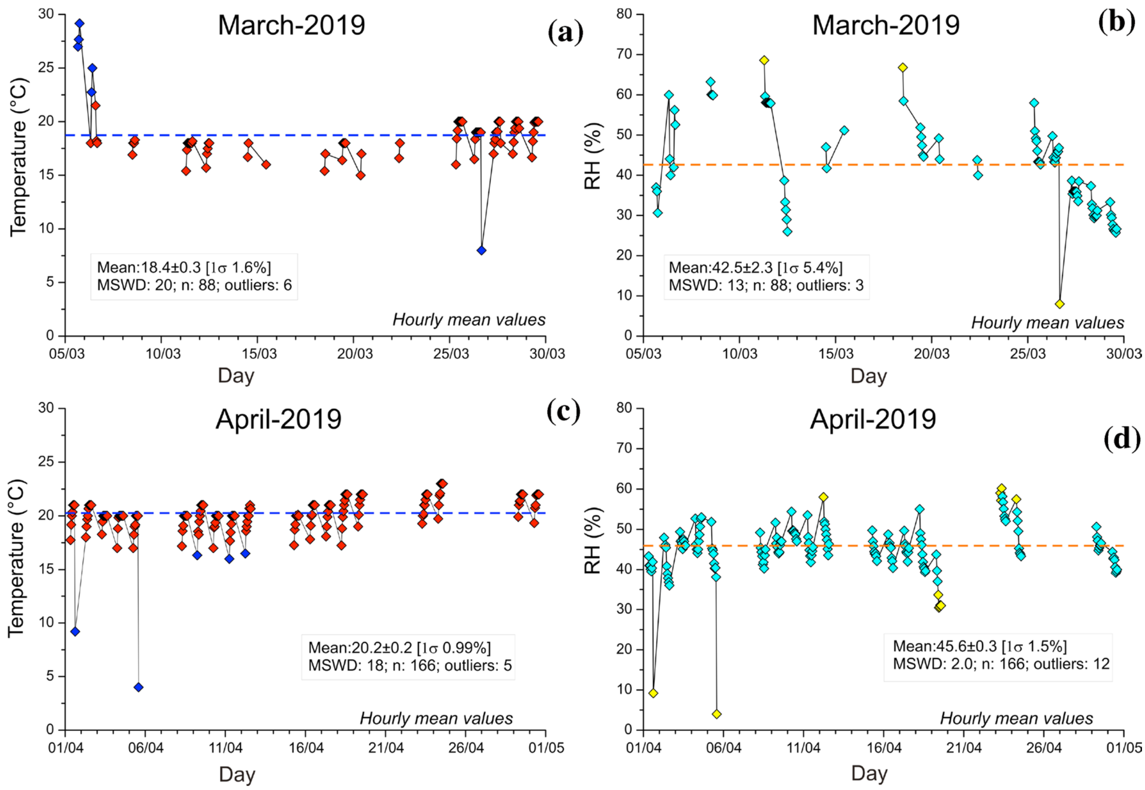

Fig. 4 Plots showing the variation of T (left) and RH (right) inside one of the hall of the museum monitored in the period from early March to the end of April 2019

Concerning the environmental indoor conditions, data point out that the building where the museum is located is characterized by consistent daily temperature (ca. 6 °C) and RH (up to 40%) variations, with T and RH showing an inversely correlated trend. It is clear therefore that, due to the ancient topology of this historical building and the lack of any buffering system for the temperature and humidity within the exhibition halls, the microclimatic environmental conditions are extremely variable during day and night (and seasonally), with maximum values significantly exceeding the recommended values.

Table 1 lists the ideal thermohygrometric conditions for a proper conservation of different type of cultural heritage materials. As an example, some damages observed in the museum collections are probably due to the uncompensated fluctuations of the climatic conditions. An example is displayed in Fig. 5, where severe cracks in a wooden frame are evident.

In addition to temperature and relative humidity, we collected also the indoor concentration of particulate matter (PM). Figure 6 shows selected results of the particulate matter variation during the monitored period. Statistical analysis of the data shows hourly mean $PM_{2.5}$ and PM_{10} values of 2.2–42.9 μg/m^3 (mean 9.8 μg /m^3) and 4.4–125.6 μg /m^3 (mean 15.5 μg /m^3), respectively, for March, and hourly mean $PM_{2.5}$ and PM_{10} values of 2.2–28.7 μg /m^3 (mean 9.0 μg /m^3) and 2.6–30.4 μg /m^3 (mean 11.0 μg /m^3), respectively, for April. Although discontinuous, the data set shows that the museum si characterized by a low and generally constant $PM_{2.5}$ (ca. 9–10 μg /m^3) and PM_{10} (ca. 11–16 μg/m^3), however anomalus high values were registered in several days, see for example March, 11th (PM2.5: 33–43 μg/m^3; PM10: 95–126 μg/m^3), or March 25th ($PM_{2.5}$: 26–32 μg/m^3; PM_{10}: 26–37 μg/m^3).

With the aim to verify the meaning of these peak-values, we decided to compare the museum indoor daily mean PM values with the correspective daily data from the whole ARPA monitoring system of the city of Rome (Fig. 7). It is possible to observe that the indoor trend (red points) follows closely the trend outlined by both the closest “Villa Ada” ARPA station (blue line) and the averaged behavior for all stations (lilac shaded field). However, two differences are immediately evident: (i) the indoor trend measured within the museum building shows systematically lower values with respect to the outdoor ones and (ii) on March 11th the ARPA stations registered an anomalously high peak; the same peak is detected by our sensors, but appears delayed of two days with respect to the ARPA sensing network. Further investigations are required to identify indoor/outdoor correlations and to calibrate with a higher confidence level our low-cost

Fig. 5 Examples of existing damages: a severe cracks suffered by the wooden framework on display in one of the exhibition halls

system against the professional systems used by the Government Agencies like ARPA. However this study, although preliminary, allows to conclude that the use of customized low-cost devices is consistent, feasible and low cost. Moreover, if arranged in larger connected networks do provide an interesting support for the continuous monitoring of both outdoor and indoor (historical buildings, museums, etc.) environments in metropolitan areas.

4 Conclusion

In order to preserve the state of conservation of cultural heritage objects and to deepen their knowledge, scientific methodologies combined to new technologies have to be considered and applied. The project of micro-climatic investigations and particulate detection described in this short contribution using Arduino, a commercial open source system was developed from scratch and was tested in the Historical Museum of Bersaglieri. The use of Arduino combined with low-cost devices allowed the monitoring of some parameters that may directly affect the conservation of manufacts present in this museum.

In this study, we monitored for several weeks the thermo-hygrometric conditions and the presence of airborne pollutants inside halls in the ancient building hosting the Historical Museum of Bersaglieri. Large fluctuations in the monitored parameters were observed. This behavior may significantly compromise the preservation of many of the artifacts hosted in the museum. As an example, fluctuations in temperature and relative humidity may affect the correct preservation of hygroscopic materials, some of which are extremely sensitive to variations in the relative humidity, such as gypsum, but also paintings, paper documents, ancient photos and other manufacts preserved in this museum, e.g., the wooden table display case showed in Fig. 3, since the double flap opening is not properly insulated from the external environment. In this case the moisture factor may contribute with other deterioration factors to the degradation of materials placed inside.

Very interesting is also the behavior of the PMs monitored in the same period inside the museum. Indeed, PM monitoring is performed outdoor where we have primary sources of pollutants such as vehicles, heating systems, industrial emissions, soil resuspension due to traffic, etc. Monitor of PM indoor is a quite recent area of research since the composition of the indoor atmosphere depends by many internal sources of contaminants, physical–chemical transformations, deposition of substances, number of persons present in the indoor environment, e.g., daily visitors in the case of a museum, and also the level of atmospheric contamination of the outdoor environment. In this context,

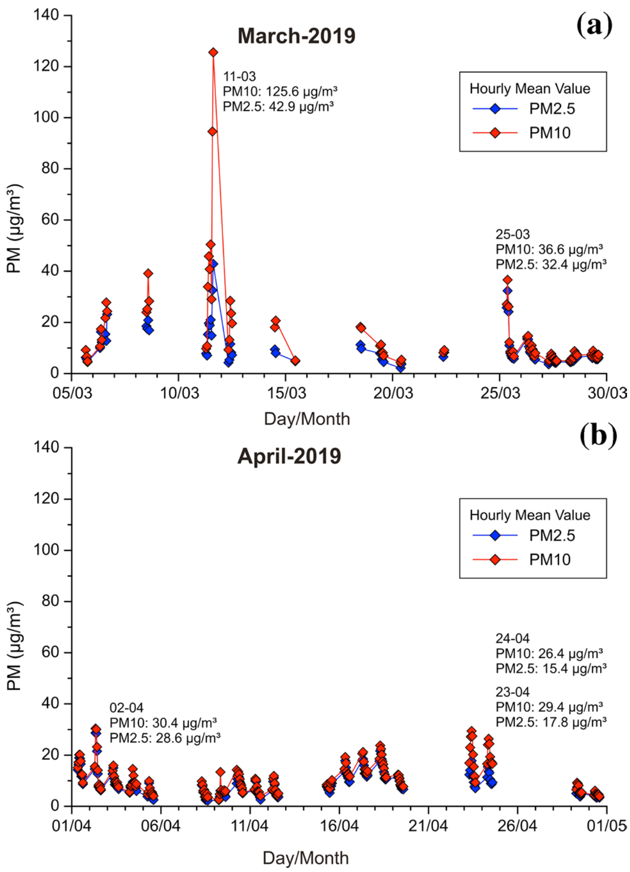

Fig. 6 Comparison of the measured values for PM2.5 (blue) and PM10 (red) during March (top panel) and April (bottom panel) of 2019 in the hall on the first floor of the museum dedicated to the Independence War

the type of air exchange used, practices for indoor air quality management, gates and windows all play a special role. This issue requires attention, not only on account of human health considerations, but regarding the deterioration of materials conserved in cultural heritage sites: museums, archives, galleries, libraries, etc., since the degradation of artifacts resulting from PM depends on particle size, concentration and composition.

All data collected in this short campaign were analyzed to draw conclusions regarding the maintenance and conservation of the different assets. The values measured in the test campaign were never the ideal ones and significant variations in temperature and relative humidity have been recorded in all rooms even within the same day. After the evaluation and the comparison of the measured parameters with those considered optimal for a good conservation of the different materials in the museum halls, we identified actions aimed to establish suitable conditions for the conservation of the different exposed materials. The humidity stabilization was strongly recommended and, in particular, considering the different materials exposed in the museum, it is advisable to maintain the temperature in the range 18–20 °C in all exhibition halls.

The approach used in this investigation in this museum can be further implemented with additional devices to detect other particularly harmful pollutants such as VOCs, which can be released from wooden showcases, and to measure the illumination value (lumens/square meter). With the monitor of these additional parameters and the reconstruction of the microclimatic dynamics with further campaigns, it will be possible to obtain an exhaustive description of the status and of the effective risk factors (related to the different objects and materials) on display in the exhibition halls of the Historical Museum of Bersaglieri.

The results achieved with the compact and low cost monitoring system assembled and used in this study, point out usefulness and feasibility of the installation of similar systems in a large number of public and private cultural heritage sites. This will certainly represent a significant step further in the preservation of the world wide cultural heritage.

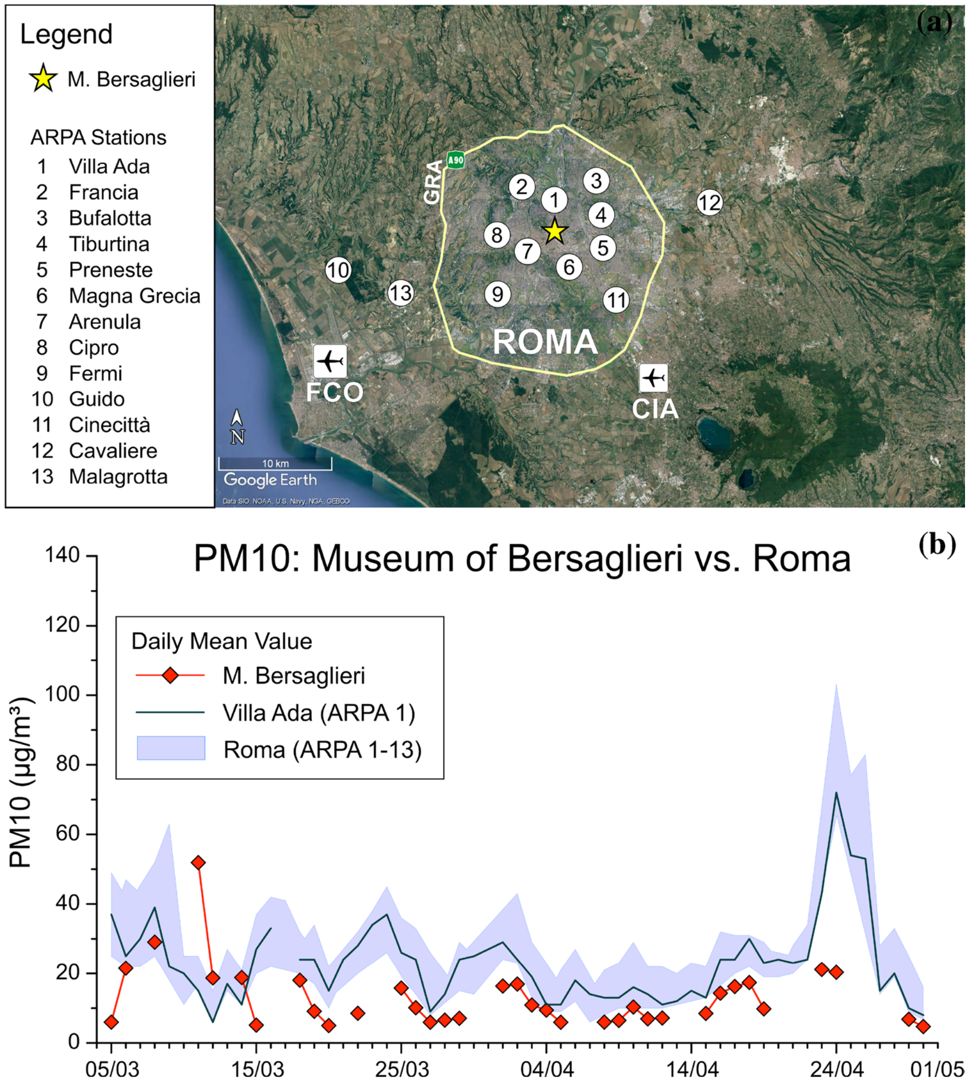

Fig. 7 **a** The location of Historical Museum of the *Bersaglieri* (yellow star) in Rome with respect to the 13 ARPA stations; **b** the average daily content of particulate matter (PM10) collected within the museum building (red diamonds) compared with the average daily content measured by all ARPA stations in the city of Rome (shaded field)

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Compliance with ethical standards

Conflict of interest We declare no potential conflict of interest.

Human/animal rights All research has been performed in compliance with ethical standards. This research is not involving human participants and/or animals.

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