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Cultural heritage safeguard through multi-parameter air quality monitoring

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Abstract **– Artworks restoration and conservation awareness has risen in the last years. In this regard, it is important to conduct air quality studies to identify and quantify air pollutants that threaten works of art. In this study the results of a air quality monitoring campaign carried out at the *Beata Vergine dei miracoli* Sanctuary, in Saronno (VA, Lombardy Region, Northern Italy), during summer 2022, are presented. A multi-parameter monitoring system able to measure at the same time CO_2, NO_2, O_3 and PM10 was employed. A comparison with outdoor values for the same pollutants was performed with the purpose to understand how outdoor pollutants affect indoor air quality in the Sanctuary. This work is crucial in developing microclimatic conditions and air quality control strategies, to assure that the marvellous works of arts stored in the church will continue to inspire people for the times to come.**

I. INTRODUCTION

Microclimatic and air quality conditions are of extreme importance for the conservation of the works of art [1]. Historically, indoor air quality has been overshadowed by outdoor air quality. In fact, as regards outdoor environment, there are legal limits that must not be exceeded while for indoor environments (e.g. places where we live, schools, public buildings, museums and historical buildings) there are no limits. For places of historical and artistic interest, including museums, there are actually limits that are recommended not to be exceeded [2].

Ecclesiastic heritage is a tangible testimony of what each artistic vocation, with his artisanal creativity, has given to humanity in history. These works are expressions of the mercy and take on a specific meaning as they are devoted to evangelisation, worship and charity [3,4]. While it is evident the importance of safeguarding these works, unfortunately churches are not protected environments and their management is not easy to carry on because of some variables: the number of worshippers, that can obviously be very high during church services; the lack of air-conditioning systems, that can lead, together with poor ambient managements, to bad microclimatic conditions [5]; the presence of particular pollutants indoor sources related to ceremonies, like the use of incense and candles [6], that can cause high concentration peaks and can be problematic also in relation to their chemical composition. As an example, there are studies on metals deriving from candles [7].

The works of art are greatly affected by environmental conditions and air pollution [8,9]: some chemical reactions can take place leading to degradation phenomena, including colour changes or soiling. Mechanical ruptures due to physical parameters can also occur. The effects, that are in fact caused by all classes of pollutants, are usually synergic.

Fortunately, in recent times, the awareness on the conservation problems of the ecclesiastic heritage has risen. This research focuses on the air quality monitoring at the *Beata Vergine dei Miracoli* Sanctuary, located in Saronno (VA), in the Lombardy Region, Italy. The Sanctuary was built, following a miraculous event, between the 15th and the 17th centuries. Once the architecture was completed, it was decorated by some of the most famous and influential artists of the time. Bernardo da Luini decorated the apse and the presbytery with some masterpieces as the *Marriage of the Virgin*. Gaudenzio Ferrari frescoed the dome. Andrea da Corbetta and Alberto da Lodi gave birth to two sculptural groups: *Deposition* (1528-1529) and *Last Supper* (1531-1532) [10].

The present research is part of a study that began in

2020 with the aim to study the air quality and the microclimatic conditions in the Sanctuary [11,12].

In the present study both gaseous pollutants (NO_2, O_3 and CO_2) and PM10 (Particulate Matter formed mostly by particles with diameter lower than 10 micron) were monitored for about two months. The results of the summer campaign carried out at the Sanctuary between July 13th and September 1st, by means of two multi-parameter monitoring systems, namely Pullodrone system (Oizom), are presented. The monitoring stations were placed one inside the church and one outdoor. A comparison between indoor and outdoor values for the same pollutants was performed to understand how outdoor pollutants affect indoor air quality and what is the contribution of indoor pollutants sources.

It is worth noting that the possibility to perform a continuous monitoring of the main pollutants is crucial to highlight concentration variations and critical situations during particular periods. The high time resolution of the measurements allows to highlight critical short-term situations, that would be masked with classical sampling methods. This work is then helpful for establishing monitoring protocols, in order to evaluate the effectiveness of measures to reduce the pollution. Definitely, this work has an effective and concrete impact in protecting the marvellous works of art stored in the Sanctuary.

II. MATERIALS AND METHODS

For the monitoring purposes, two OIZOM Polludrone multi-parameter systems were employed. One system was installed indoor, near Last Supper sculptural group, while the other was employed to have reference high-time resolution outdoor data. The indoor position, near *Last Super* sculptural group, was chosen both for the importance of the sculptures and because the place is near to the main altar, that is the zone of highest passage of the church, because it leads to the Virgin Mary statue in the apse, to whom the Sanctuary is entitled. Regarding the outdoor system, the positioning was on the side of the Sanctuary.

Polludrone is a comprehensive smart solution for monitoring environmental parameters related to air quality (in the present study NO_2, CO_2, O_3 and PM10 data were analysed). It transmits the results over an IoT wireless network and the operability is thus really simple because it can be controlled off-site.

III. RESULTS AND DISCUSSION

The availability of high time resolution measurements allowed to manage data in a comprehensive way. In particular, in order to display the results obtained during the monitoring campaign, the daily average was calculated for each of the investigated parameters, as this time resolution still allowed to inspect the effects of short term critical concentrations events. Since some similarities were observed between the same week-days, the trend for a typical week was calculated.

Among the investigated parameters, carbon dioxide, that can only give a light acidic character to humidity, was actually quite interesting since it gave an idea of the number of visitors inside the Sanctuary. In fact, as can be seen from Fig. 1, indoor concentrations were always higher than outdoor concentrations. Indoor concentrations were the highest during Sundays, due to a great number of people participating in the celebration of services. During the other days, indoor daily average concentrations were still higher than the outdoor ones mainly due to the peaks related to the evening Masses, that are celebrated almost daily. It is interesting that, during the entire campaign, peak CO_2 values were within 1000 ppm, that is the guidance limit value for healthy air [13]. The error bars showed in the charts (Fig. 1 to 4) represent the standard error of the mean, with n = 7 or 8 depending on the weekday.

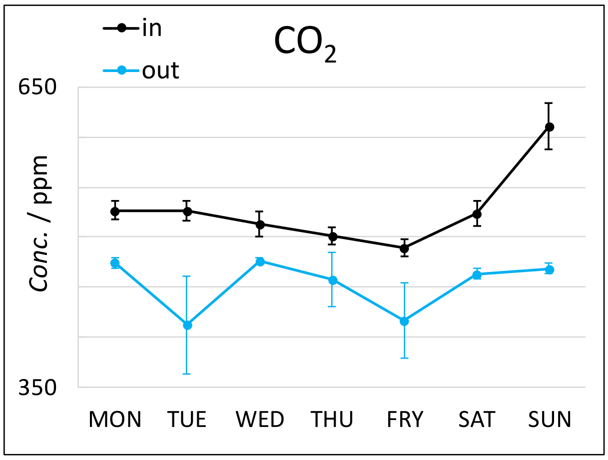

Fig. 1. Trend of CO_2 concentrations both indoor and outdoor the Sanctuary

Nitric oxide is potentially dangerous for the artworks because, in the presence of humidity, it forms nitric acid, a strongly acidic and oxidant agent. The effects on paintings are colour fading and yellowing [14]; it can also hydrolyse cellulose [15]. Indoor concentrations followed the trend of outdoor ones even if they were lower (Fig. 2). The source of nitrogen oxide comes from outside and is vehicular traffic. The Sanctuary is in fact located in the centre of Saronno and overlooks a motor roundabout. Moreover, the motorway is not far away. It is also interesting to note that indoor concentrations during the period investigated exceeded, greatly and constantly, the limit suggested for the protection of cultural heritage (4.7 μg m^{-3}) [2]. Nitrogen dioxide values measured indoors were in general agreement with what was observed in a previous measurement campaign [12] where, however, this pollutant was measured with passive diffusive samplers that weren't able to give high time resolution measurements, thus not distinguishing between the week-days. In that case, being the outdoor concentrations about 45 μg m^{-3}, the indoor ones were in the 10 - 20 μg m^{-3} range. The sampling campaign was carried out in wintertime, and this could explain the slightly lower indoor concentrations, as in winter air exchanges tend to be limited. In another study [15], that was conducted in April 2004 in the historical archive of Ca' Granda (Milan) the indoor concentration were comparable to those found in the Sanctuary (summer 2022), while the outdoors one were higher in Milan (71 μg m^{-3}), thus indicating a higher I/O ratio for the Sanctuary, that means a higher penetration of pollutants from outdoor with respect to the archive.

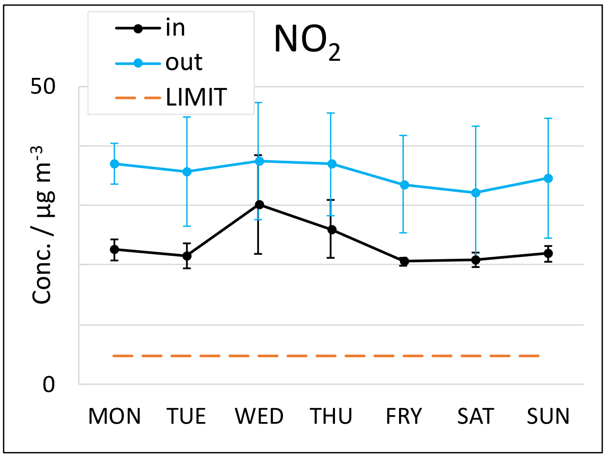

Fig. 2. Trend of NO_2 concentrations both indoor and outdoor the Sanctuary

While nitric oxide is a primary pollutant, ozone is of secondary origin, as it is formed in the photolysis of nitric oxide [12]. Ozone is a powerful oxidant and is deleterious for paper since it induces the formation of peroxide groups in the presence of moisture. Moreover, it can break double bonds in organic chains, disrupting a wide range of materials [15]. Ozone showed a low weekdays dependency, with a fairly constant daily-average value. Indoor ozone concentrations, which are lower than the outdoor ones (Fig. 3), are quite high compared to what has been found in the aforementioned historical archive [15]. In fact, the average concentration for the entire campaign in the Sanctuary (Summer 2022) was 18 ± 9 μg m^{-3} (being the uncertainty the standard deviation of 1199 hourly measurements), while in the archive (Milan, April 2004), the concentration was found to be <2 μg m^{-3}. It is to note that in that case it was spring and not summer, and that outdoor concentration was 32 μg m^{-3}, while the values found in the present study were between 40 and 50 μg m^{-3}. It is worth to notice that the limit suggested by the ministerial directive [2], 2 μg m^{-3}, for the protection of works of art are greatly and constantly exceeded for this pollutant.

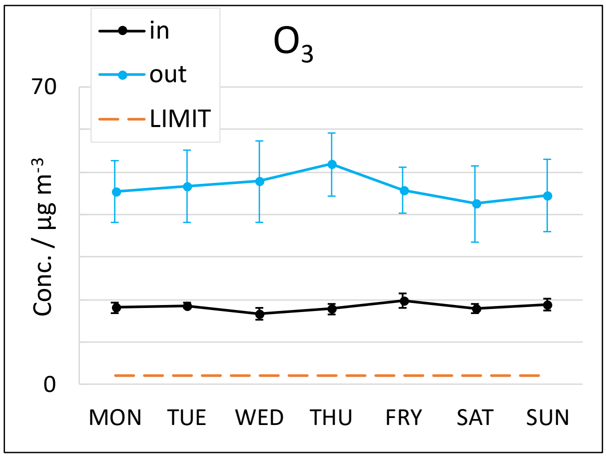

Fig. 3. Trend of O_3 concentrations both indoor and outdoor the Sanctuary

The effect of PM is the soiling of the artworks, leading to the darkening of the surface [16], or some degradation phenomena due to chemical reaction depending on the PM composition. Furthermore, the smaller the size of the particles, the easier they can adhere to the artwork. It is reported that infiltration from outdoor, visitor debris, cleaning activities, resuspension and the use of incense and candles are among PM sources in churches [6].

In this campaign, as regards PM10, the indoor trend was similar to the outdoor one (Fig. 4) with a change starting on Saturdays, when the concentrations began to increase. On Sundays the concentrations became comparable with the outdoor ones; the maximum was reached on Mondays, as these days were still affected by the events of the previous days and, also, there were some special events like funerals. The increase in the concentrations was most likely to be attributed to an increase in the number of worshippers, visitors and celebrations during the weekend. This fact therefore attests the presence of an indoor source consisting precisely of particles input by people, together with the mentioned use of incense. Candles were not take into account as in this Sanctuary only low-smoke candles are used and in a very limited way.

On a daily average basis, PM10 values did not exceed the limits suggested for works of art protections (20 and 30 μg m^{-3}, as evidenced in Fig. 4). The situation is reversed during the cold season, as it was clear from the previous campaign, when also outdoor concentrations were higher [12].

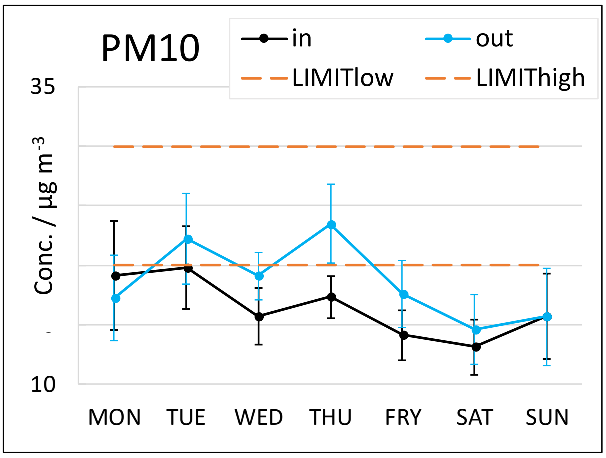

Fig. 4. Trend of PM10 concentrations both indoor and outdoor the Sanctuary

Basing the affirmations on the observed data, it can be hypothesised that CO_2 mainly accounts for visitors' presence, while PM10 is mainly linked to the use of incense. In Figure 5, the indoor/outdoor ratios of the hourly averages of the measured parameters during Monday are shown. This particular day was chosen because, unlike weekends days, there were two celebrations that, as can be highlighted from the chart, had different characteristics. The first one, starting from the middle of the morning, showed only a slight increase in CO_2 levels ratio but a strong PM10 ratio peak. The second one, in correspondence of the evening Mass, showed a peak in CO_2 ratio, while PM10 ratio did not increase significantly.

The increasing ratios in both cases were caused by increased indoor concentrations over constant outdoor ones (this wasn't the case for example for the slight ozone peak in the night, caused by a constant indoor over lowered outdoor). This situation indicated the presence of indoor sources or transportation from outdoor. Since transportation from outdoor can bring the ratio I/O to 1, the ratios greater than 1 indicate an indoor source. It is reasonable to assume that few people participated to the first event and that the PM10 ratio peak is related mostly to the use of incense. In the second event, more people participated but no incense was used. The observed PM10 incense ratio peak is in accordance with literature values, in particular for a study conducted in a gothic roman church in Germany [17]. The use of incense, according to guidance limits [2], thus create potentially dangerous situations for the works of art [18] at the hourly average scale that can be detected only by means of high time resolution instruments.

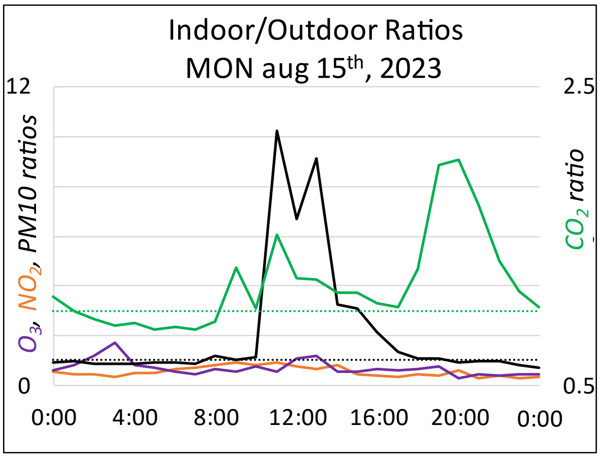

Fig. 5. Indoor over outdoor ratios for ozone, nitrogen dioxide, PM10 (primary axis, black dotted line is the unit reference) and CO2 (secondary axis, green dotted line is the unit reference).

The present study was conducted in summer. As mentioned during the discussion, the time of year do affect the concentrations of the measured pollutants, since in winter there are more combustions thus leading to increased CO_2, NO_2 and PM10; O_3 is instead lower in winter due to a limited photochemical action. Furthermore, changes in temperature and relative humidity can affect pollutant deposition [18] and the degradation phenomena, yet they do not affect greatly the measurements systems.

IV. CONCLUSIONS

In this work a monitoring campaign of the air quality inside a church, the Sanctuary of Beata Vergine dei Miracoli, Saronno (VA), Italy, was carried out. Two multi-parameter continuous high time resolution analysers (Polludrone, Oizom) were employed. A typical week trend was calculated for the pollutants CO_2, NO_2, O_3 and PM10. Carbon dioxide was used as a proxy to trace the presence of visitors; its concentrations were, on average, higher indoor. Nitrogen dioxide and ozone were found to be the pollutants of major concern as their indoor concentrations are, greatly and constantly, above the limits suggested for the safeguard of cultural heritage. PM10 was instead below the limits, when observed at the daily average scale, yet at the hourly average scale potentially dangerous situations were highlighted. Worshippers' presence and the use of incense were hypothesized to justify higher particles concentrations in the weekends. Finally, this work contributes to set-up monitoring protocols that would allow to suggest measures for the protection of the precious artworks stored in the Sanctuary.

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