2022 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
University of Calabria, Italy, October 19-21, 2022

Evaluation of indoor environmental conditions in the Sanctuary of the *Beata Vergine dei Miracoli*

Andrea Bergomi[1], Valeria Comite[1], Vittoria Guglielmi[1], Mattia Borelli[1], Roberto Bonomi[2], Carola Ciprandi[2], Carlo Mariani[3], Antonio Faggiano[4], Maria Ricciardi[4], Antonio Proto[4], Paola Fermo[1]

[1] University of Milan, Via Golgi 19, Milan (MI), Italy, andrea.bergomi@unimi.it, valeria.comite@unimi.it, vittoria.guglielmi@unimi.it, mattia.borelli@unimi.it, paola.fermo@unimi.it
[2] Scuola di restauro ENAIP Botticino, Botticino (BS), Italy, 28roberto@libero.it, carola.ciprandi@libero.it
[3] Architect, Via Giusti 21/B, Seregno (MB), Italy, cm@carlomariani.eu
[4] University of Salerno, Fisciano (SA), Italy, mricciardi@unisa.it, anfaggiano@unisa.it, aproto@unisa.it

***Abstract* – Many studies concerned with the analysis of microclimatic conditions and air quality inside museums have been conducted through the years with the aim to protect and prevent degradation of cultural heritage. However, museums are not the only places in which artifacts of historic and artistic interest can be found. For instance, churches and sanctuaries often are the home to numerous works of art which require as much care and attention in order to be properly preserved. In this study, the microclimatic conditions and air quality were monitored inside the Sanctuary of the *Beata Vergine dei Miracoli*, located in Saronno (VA), Italy, which hosts several important artifacts such as frescoes by Bernardino Luini and Gaudenzio Ferrari, along with wooden sculptures created by Andrea da Corbetta and decorated by Alberto da Lodi. The results of the campaign showed that both the microclimatic conditions and the air pollutants' concentrations are higher than the ideal threshold values suggested for the conservation of the artifacts.**

I. INTRODUCTION

Microclimatic conditions and indoor air quality (IAQ) are two factors which play a crucial role in the conservation of artworks and manufacts of historic and artistic interest [1]. In this regard, it is widely accepted that the thermohygrometric parameters which pose the greatest threat are: temperature, relative humidity and lighting levels [2]. However, in recent years, several studies have focused also on gaseous pollutants (NO_x, SO_2, O_3, VOCs) and particulate matter (PM) as potential causes of deterioration [3–6].

The effects of uncontrolled microclimatic conditions and air pollution are strictly dependent on the type of artifact and on the parameter under consideration [2]. Imbalance in temperature and relative humidity can lead to dimensional changes, cracking, flaking, detachment and overall increased fragility of the work of art [1]. High concentrations of gaseous pollutants, especially NO_2, SO_2 and O_3, are known to cause material fading, deoxidation and corrosion of the substrate [2]. Instead, particulate matter, especially the fine fraction (aerodynamic diameter < 2.5 μm), can lead to soiling, blackening and, in combination with high moisture content in air, can give rise to potentially dangerous chemical reactions [4].

For these reasons, specific environmental conditions are required for the preservation of the artifacts [2,4]. In fact, national and international institutions have developed technical standards providing guidance for conservation. According to Italian law, the D.M. 10/05/2001 outlines threshold values and recommended ranges for the thermohygrometric parameters and major air pollutants in museums [7]. Table 1 shows the limit values for PM10, which is the fraction of particles with an aerodynamic diameter below 10 μm, and nitrogen dioxide.

Table 1. Recommended concentrations of pollutants indicated in the D.M. 10/05/2001

Pollutant	Concentration / μg m^{-3}
PM10	20 – 30
Nitrogen dioxide	< 5

Moreover, the UNI 10829:1999 technical standard establishes guidelines for monitoring microclimatic parameters (temperature, relative humidity and lighting) and also defines values considered acceptable for the proper conservation of the works of art, depending on the material [8]. Table 2 shows the values considered acceptable for conservation of painted wood, wall paintings and frescoes.

Table 2. Recommended ranges of temperature and relative humidity according to the UNI 10829 standard.

Parameter	Painted wood	Wall paintings and frescoes
Air temperature / °C	19-24	10-24
Maximum daily temperature variation / °C	1.5	-
Air relative humidity / %	50-60	45-55
Maximum daily relative humidity variation / %	4	-

Amongst other technical standards internationally recognized there are those published by the British Standard Institutions (BSI) [9] and by ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers [10].

The current work deals with a monitoring campaign carried out in the Sanctuary of the Beata Vergine dei Miracoli, located in Saronno (VA), Italy. In this sanctuary numerous works of art are stored including frescoes by Bernardino Luini and Gaudenzio Ferrari and wooden sculptures created by Andrea da Corbetta and painted by Alberto da Lodi. The large number of visitors and the proximity to a highly-trafficked highway can lead to poor microclimatic conditions and air quality inside the sanctuary, therefore posing a significant threat to the conservation of the artifacts. The campaign was focused on the monitoring of microclimatic parameters (temperature and relative humidity) and particulate matter (PM10, PM2.5 and PM1), along with the determination of NO_2 and BTEX (benzene, toluene, ethylbenzene, xylenes) concentrations.

II. MATERIALS AND METHODS

A. Sanctuary of the Beata Vergine dei Miracoli

The Sanctuary of the Beata Vergine dei Miracoli is a marian sanctuary which was built between the XV and XVII centuries following a miraculous event. The whole complex was built in three stages: the apse, presbytery, ante-presbytery, dome, tiburium and bell tower were constructed between 1498 and 1516; in 1556 three bays were lengthened over three naves with the addition of the sacristy; and finally, from 1570 to the early 1600s two more bays were added and the facade erected. During the same period, the “Hostaria dell'Angelo" was built to accommodate pilgrims coming from afar, which later became a library and eventually a civic theatre [11].

B. Works of art

Some of the most important and renowned artists of the time were summoned to decorate the sanctuary. The first was Bernardino Luini, who completed numerous frescoes including *“Marriage of the Virgin”* and *“Jesus among the Doctors”*, which are found in the ante-presbytery, along with *“Adoration of the Magi”* and *“Presentation of Jesus in the Temple”* placed in the presbytery. Instead, Gaudenzio Ferrari was commissioned to paint the entire dome, which is now decorated with a fresco composed by three gyrations of festive angels and musicians who accompany Mary to the meeting with the Eternal Father [11].

Other artifacts of artistic interest are the wooden sculptures present in the two side chapels, created by Andrea da Corbetta and decorated by Alberto da Lodi. Together they form the two sculptural groups of the *“Last Supper”* and the *“Deposition”*. Andrea da Corbetta is also responsible for most of the sculptures present in the dome (crucifix, Eternal Father and the Saints), whereas the sculptures of the prophets and of the Sibyls were created by Giulio da Oggiono. All of the aforementioned sculptures were decorated by Alberto da Lodi [11].

C. Monitoring campaign

The monitoring campaign was carried out between 23/02/2021 and 28/12/2021 to determine the air quality inside the sanctuary. Three different sites were chosen corresponding to the two wooden sculptural groups (*“Last Supper”* and *“Deposition”*) on the ground floor and the *“Choir”* on the first floor. Figure 1 shows the location of the sampling sites within the sanctuary. These sites were chosen in order to determine the concentration of pollutants in close proximity to the works of art and to evaluate any possible dispersion by monitoring at different heights.

.

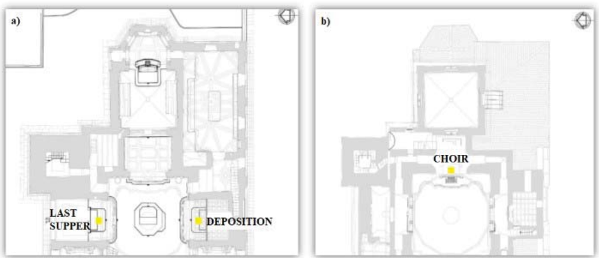

Fig. 1. a) Ground floor planimetry; b) First floor planimetry

Temperature and relative humidity were monitored in continuous mode using data loggers (USB Mini TH, XS Instruments). Particulate matter (PM10, PM2.5 and PM1) was also monitored continuously using an optical particle counter (P-Dust Monit, conTec Engineering Srl). Instead, gaseous pollutants (NO_2 and BTEX) were sampled with diffusive passive samplers (RING® radial diffusive devices, Aquaria Srl, Milan, Italy).

Nitrogen dioxide was determined with UV-Vis spectroscopy (Varian Cary® 50 UV-Vis spectrophotometer) following water extraction with a Griess-Saltzman reaction. Instead, BTEX were extracted with carbon disulfide (CS_2) and quantified using gas chromatography with flame ionization detector.

The specific sampling periods for each of the monitored parameters are shown in Table 1.

Table 1. Sampling periods

Monitored Parameters	Sampling site	Sampling period
Temperature	*"Last Supper"* *"Deposition"* *"Choir"*	23/02/2021-29/03/2021
Relative Humidity	*"Last Supper"* *"Deposition"* *"Choir"*	23/02/2021-29/03/2021
Particulate Matter	*"Last Supper"*	25/03/2021-25/04/2021
Particulate Matter	*"Deposition"*	02/03/2021-25/03/2021
Particulate Matter	*"Choir"*	27/05/2021-05/06/2021
Nitrogen dioxide	*"Last Supper"*	02/03/2021-23/03/2021
Nitrogen dioxide	*"Deposition"*	23/03/2021-02/04/2021
Nitrogen dioxide	*"Last Supper"* *"Deposition"* *"Choir"*	14/12/2021-28/12/2021
BTEX	*"Deposition"*	23/03/2021-02/04/2021

III. RESULTS AND DISCUSSION

D. Temperature and relative humidity

Figure 2 shows the daily temperature and relative humidity average values registered in the three different sampling sites. Temperature values fall within the recommended range for the conservation of wall paintings and frescoes for the entire sampling period. However, the opposite is true for painted wood: in this case, the values are constantly below the specified range. Instead, relative humidity values are almost always above the upper limit indicated in the UNI 10829 standard for the conservation of wall paintings and frescoes, whereas the days in which the threshold for painted wood was overrun were less.

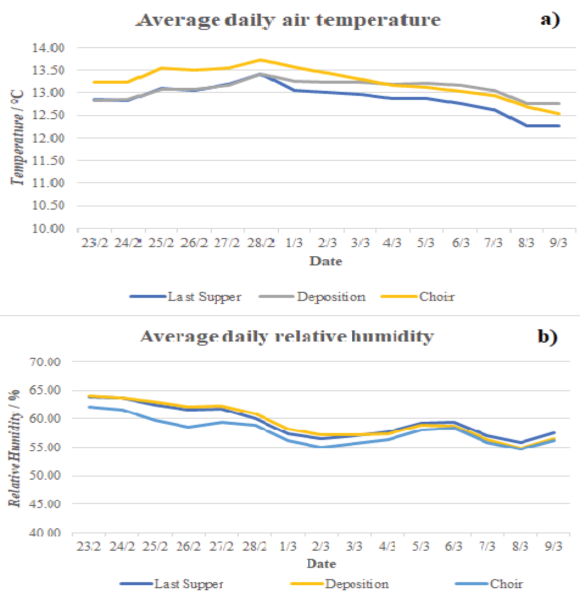

Fig. 2. a) Trends in average daily air temperature; b) Trends in average daily relative humidity. Date format: "dd/m"

Another important factor to consider is the maximum daily variation of the thermohygrometric parameters. In this case, the UNI 10829 norm gives recommended values only for wood paintings. Figure 3 shows the data collected compared to the limit indicated in the technical standard.

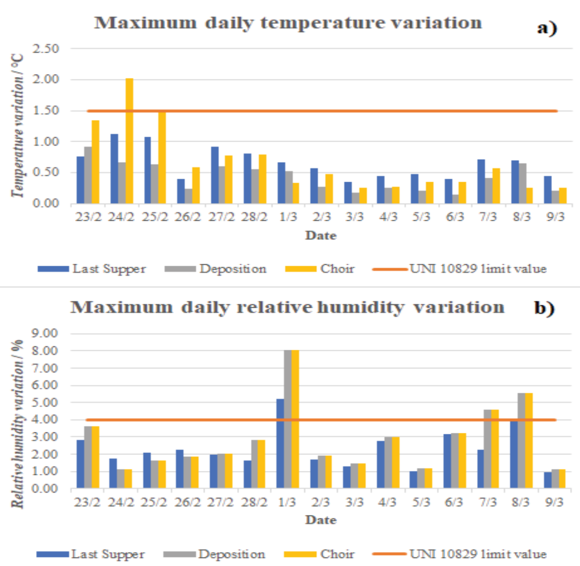

Fig. 3. Maximum daily variation of: a) temperature; b) relative humidity. Date format: "dd/m".

For both parameters the days of overrun are few, and both temperature and relative humidity show a limited daily variation during the entire sampling period. Moreover, no significant differences are highlighted between the different sites.

E. Particulate matter

The PM10 concentrations observed during the monitoring campaign differed depending on the site under consideration. Figure 4 shows the concentration trends observed in the three sampling sites.

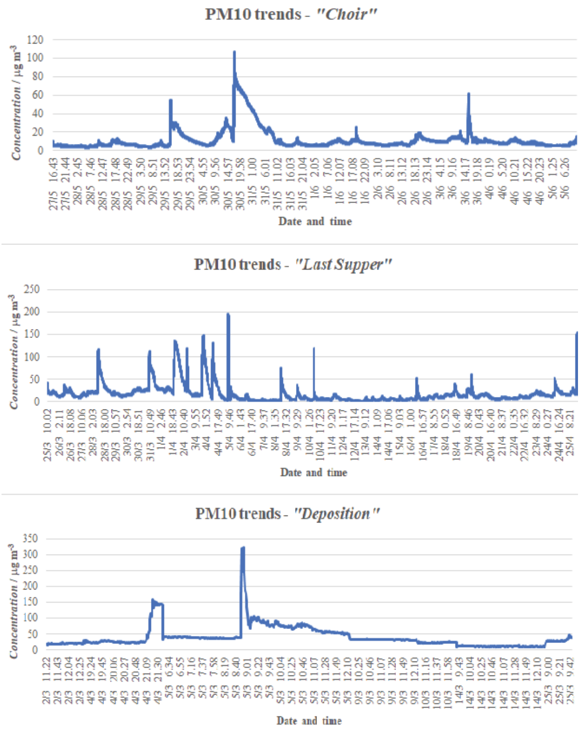

Fig. 4. PM10 concentration trends in site a) "Choir"; b) "Last Supper"; c) "Deposition". Date and time format: "dd/m hh:mm".

All of the sites are characterized by steady concentrations between 10 and 30 μg m^{-3} with the presence of sharp peaks associated with specific events which trigger a rapid increase in the concentration of PM10. With regards to the *"Choir"* site, the peaks were observed during the weekend (29/05 and 30/05). This is probably due to the fact that Saturday and Sunday are typically the days which attract a larger number of worshippers attending religious services. In fact, visitors are known to act as vehicles for the transport of particles from outdoors to the indoor environment [1,2,4], therefore contributing to the increase in concentration of particulate matter.

This effect can be particularly appreciated considering the results from the *"Last Supper"* site. In this case, part of the monitoring campaign was carried out during the Holy Week (28/03 - 04/04), which is known to attract a very large number of people. In fact, almost every day of the Holy Week was associated with a spike in the concentrations of PM10, underlining the impact of visitors on the rise of particulate matter concentration levels.

This effect was less appreciable in the *"Deposition"* site, which showed two peaks in the concentration of PM10, however not associated with weekends or other religious holidays. These apparently anomalous spikes in concentration are probably due to cleaning activities which regularly take place in the sanctuary and which are known to contribute to the enhancement of particulate matter concentrations [12].

The data regarding the contribution of the fine fractions (PM2.5 and PM1) shows that PM2.5 and PM1 constitute a large proportion of the total particulate matter. Figure 5 shows that this is true for all the sites and for almost all of the days in which the monitoring was carried out.

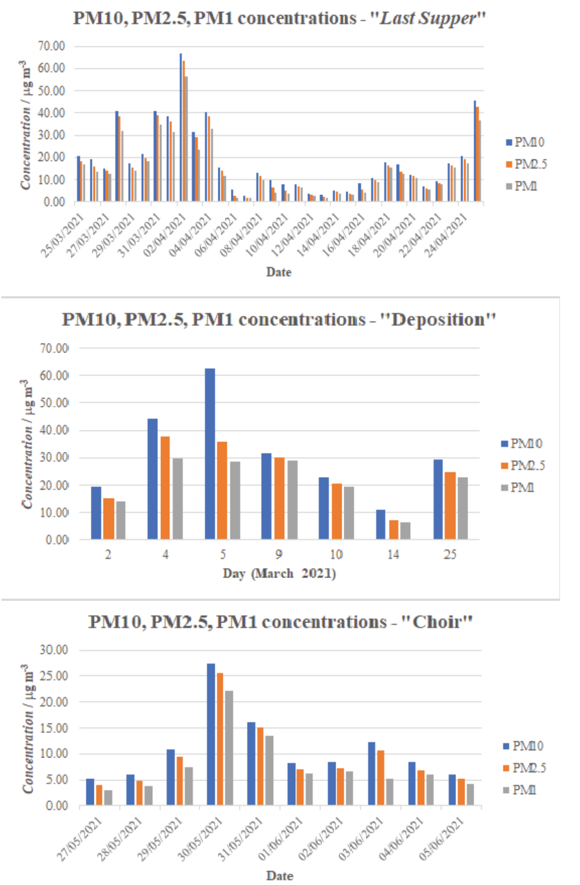

Fig. 5. PM10 concentration trends in site a) "Choir"; b) "Last Supper"; c) "Deposition". Date format: "dd/mm/yy".

The fact that the majority of particulate matter in the sanctuary is composed of fine particles is particularly significant since these are the ones which pose the greatest threat to the works of art [13]. In fact, thanks to a greater surface area, these particles are more reactive than the coarse fraction and therefore can more easily induce and/or accelerate chemical reactions which lead to the deterioration of the artifacts [4].

F. Nitrogen dioxide and BTEX

Figure 5 shows the concentration of nitrogen dioxide determined inside the sanctuary for all of the campaigns conducted.

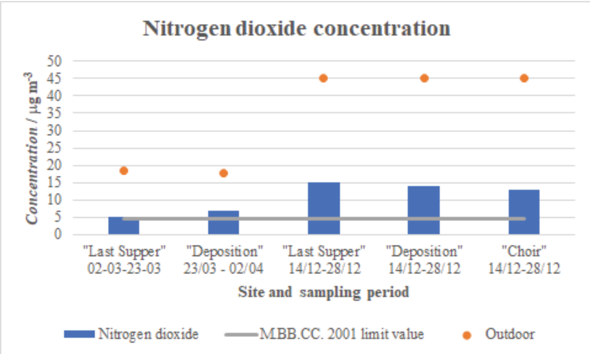

Fig. 6. Nitrogen dioxide indoor and outdoor concentrations. Date format: "dd/mm".

The histogram shows that the concentrations of this pollutant are above the limit value indicated in the D.M. 10/05/2001 (5 µg m^{-3}) for all of the sampled periods. Higher concentrations were observed in December for all of the studied sites. This can be explained by the fact that the emissions deriving from known sources of NO_2, such as vehicular traffic, domestic heating and other combustion processes, are greater during the colder months of the year [14]. Instead, the comparison with corresponding outdoor values shows significantly lower concentrations indoors. This result indicates that there are no major indoor sources of NO_2 and therefore no accumulation of pollutants occurs.

Moving on to BTEX, the results of this study are shown in Table 4.

Table 4. BTEX concentrations

Parameter	***Concentration* / µg m^{-3}**
Benzene	1.6
Toluene	1.7
Ethylbenzene	< LOD
Xylenes	< LOD

Compared to other similar studies conducted in museums [4,15], lower concentration levels of all BTEX were found in this work. The values observed are more in line with the ones observed in other indoor spaces, such as schools [16].

The benzene and toluene concentrations reported were used to calculate the toluene/benzene (T/B) ratio, which is used in order to identify the most probable sources of outdoor air pollution [17–19]. The value observed in this case study is 1.07 which, according to Zhang et.al. (2021), indicates vehicular traffic as the main source of air pollution coming from outdoors. Indeed, the sanctuary is located close to a highly-trafficked highway which impacts the air quality of the surrounding environment, including the indoor air of the sanctuary.

IV. CONCLUSIONS

In this work an assessment of the microclimatic conditions and air quality inside the sanctuary of the *Beata Vergine dei Miracoli* was carried out. Temperature values were always outside the recommended range for the proper conservation of painted wood, whereas relative humidity was always above the limit values for wall paintings and frescoes. These results show that the microclimatic conditions within the sanctuary pose a significant threat to the works of Bernardino Luini and Andrea da Corbetta, and to the other numerous masterpieces present. Moreover, particulate matter concentrations were heavily dependent on the number of visitors and worshippers entering the sanctuary. The presence of a large number of people was almost always related to an increase in the concentration of PM10 above the 30 µg m^{-3} limit indicated by the Italian legislation. Finally, NO_2 concentration were also constantly above the suggested limit, indicating poor air quality inside the sanctuary. Overall, this monitoring campaign highlights the need to take rapid action in order to prevent serious and irreversible degradation phenomena of the works of art.

V. REFERENCES

[1] D. Camuffo, V. Grieken, H.-J. Busse, G. Sturaro, A. Valentino, A. Bernardi, N. Blades, D. Shooter, K. Gysels, F. Deutsch, "Environmental monitoring in four European museums", Atmospheric Environment, vol.35, 2001.

[2] H. Sharif-Askari, B. Abu-Hijleh, "Review of Museums' Indoor Environment Conditions Studies and Guidelines and Their Impact on the Museums' Artifacts and Energy Consumption", Building and Environment, vol.143, 2018, pp. 186–195.

[3] A. Marchetti, S. Pilehvar, L. 't Hart, D. Leyva Pernia, O. Voet, W. Anaf, G. Nuyts, E. Otten, S. Demeyer, O. Schalm, "Indoor Environmental Quality Index for Conservation Environments: The Importance of Including Particulate Matter", Building and Environment", vol.126, 2017, pp.132-146.

[4] E. Chianese, A. Riccio, I. Duro, M. Trifuoggi, S.

Capasso, G. Barone, “Measurements for Indoor Air Quality Assessment at the Capodimonte Museum in Naples (Italy)”, Int. J. Environ. Res, vo.6, 2012, pp.509-518.
[5] C. Pironti, M. Ricciardi, O. Motta, M. Venier, A. Faggiano, R. Cucciniello, A. Proto. “Sulphurous air pollutants and exposure events of workers in thermal-mineral springs: a case study of *Contursi Terme* (Salerno, Italy)”, Environmental Science and Pollution Research, 2022.
[6] O. Motta, C. Pironti, M. Ricciardi, C. Rostagno, E. Bolzacchini, L. Ferrero, R. Cucciniello, A. Proto, “Leonardo da Vinci’s “Last Supper”: a case study to evaluate the influence of visitors on the Museum preservation systems”, Environmental Science and Pollution Research, vol.29, 2022, pp.391-398.
[7] Decreto Ministeriale 10 Maggio 2001, n. 112/98, Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei.
[8] UNI 10829:1999, “Beni di interesse storico ed artistico – Condizioni ambientali di conservazione – Misurazione ed analisi”.
[9] British Standards Institution, “Specification for Managing Environmental Conditions for Cultural Collections”, 2012.
[10] ASHRAE, “2011 - ASHRAE Handbook - HVAC Applications - SI Edition”.
[11] M.L. Gatti Perer, “Il Santuario della Beata Vergine dei Miracoli di Saronno”, ISAL (Istituto per la Storia dell’Arte Lombarda, 1996.
[12] J.N. Kauil, E.M. Villegas, J.M.C. Velueta, “Behavior of Pollutants Due to Daily Activities in the Home”. Proc. of Congreso Colombiano y Conferencia Internacional de Calidad de Aire y Salud Publica, CASAP, 2019, pp.1-5.
[13] J. Grau-Bové, M. Strlic, “Fine particulate matter in indoor cultural heritage: a literature review”, Heritage Science, vol.1, 2013.
[14] E. Cuccia, U. Dal Santo. “La qualità dell’aria in provincia di Varese”, Agenzia Regionale Protezione Ambiente – Settore Monitoraggi Ambientali, 2019.
[15] T. Martellini, C. Berlangieri, L. Dei, E. Carretti, S. Santini, A. Barone, A. Cincinelli, A. “Indoor Levels of Volatile Organic Compounds at Florentine Museum Environments in Italy”, Indoor Air, vol.30, 202, pp.900–913.
[16] P. Ielpo, C. Mangia, G. de Gennaro, A. di Gilio, J. Palmisani, A. Dinoi, A. Bergomi, V. Comite, P. Fermo, “Air Quality Assessment of a School in an Industrialized Area of Southern Italy”, Applies Sciences, vol.11, 2021.
[17] J.G. Ceron-Breton, R.M. Cerón Bretón, J.D.W. Kahl, G. Sánchez Rico, S.E. Carranco Lozada, M. de la Luz Espinosa Fuentes, M.P. Uc Chi, M.P., “Concentrations, Sources, and Health Risk Associated with Exposure to BTEX at Ten Sites Located in an Urban-Industrial Area in the Bajio Region, Mexico”, Air Quality, Atmosphere and Health”, vol.14, 2021, pp.741–761.
[18] A. Cincinelli, T. Martellini, A. Amore, L. Dei, G. Marrazza, E. Carretti, F. Belosi, F. Ravegnani, P. Leva, “Measurement of Volatile Organic Compounds (VOCs) in Libraries and Archives in Florence (Italy)”, Science of the Total Environment, vol.572, 2016, pp.333-339.
[19] D. Zhang, B. He, M. Yuan, S. Yu, S. Yin, R. Zhang, “Characteristics, Sources and Health Risks Assessment of VOCs in Zhengzhou, China during Haze Pollution Season”, Journal of Environmental Sciences, vol. 108, 2021, pp.44–57.