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Indoor Microclimatic Conditions and Air Pollutant Concentrations in the Archaeological Museum of Abdera, Greece

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Abstract: Indoor microclimate conditions and air pollutant concentrations (O_3, TVOC, CO, CO_2, and particulate matter mass concentrations in six size bins) were measured in the Greek Archaeological Museum of Abdera, which houses priceless works of art from the birthplace of the ancient philosopher Democritus. The monitoring campaign took place during the spring and summer months, when there were the greatest number of visitors. In the exhibition rooms, daily variations in relative humidity ranged from 4% to 10%, and daily variations in air temperature ranged from 0.9 °C to 2.6 °C. These uncontrolled changes may endanger the housed antiquities. The microclimate in the storage rooms varied substantially less than in the exhibition halls due to dehumidifiers and the lack of visitors. Concerning air pollution, indoor O_3 concentrations were higher than the recommended limit values for the conservation of artwork. Even more worrisome are particulate matter mass concentrations above the air quality guidelines. Despite the fact that the building is well insulated and that only artificial lighting is used in the exhibition halls, it is difficult to achieve adequate conditions for the protection of the works of art.

Keywords: cultural heritage conservation; indoor air quality; museum; works of art; dehumidifier; storage

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1. Introduction

Valuable works of art are housed in museums and other historical buildings to preserve their aesthetic value for a long time. Indoor air temperature (AT), relative humidity (RH), lighting, and atmospheric pollutants in these buildings differ from other indoor environments. Their indoor conditions are tailored to their special requirements: almost stable microclimatic conditions, which are appropriate for the housed collection, and the lowest possible air pollution. The exhibition rooms must be comfortable for guests to tour during opening hours, with the right amount of illumination for the works of art.

Uncontrolled AT and RH and particularly rapid fluctuations of these parameters, as well as uncontrolled lighting, can damage works of art [1,2]. When the AT rises, chemical reactions accelerate, both homogeneous and heterogeneous, which can damage works of art. As the temperature of the air fluctuates, so does the relative humidity, which influences the moisture content of the works of art. Any object's stability is dependent on a specific range of RH values and fluctuations. Chemical, physical, or biological processes on the surface of the works of art are affected by AT and RH levels and their abrupt variations [3].

Air pollution is also a threat to cultural property [4,5]. Ozone (O_3) can harm some objects in museums' collections, such as fabrics, organic colorants, and paint binders [2,6]. Its concentrations must be close to zero in order to protect vulnerable objects for long time periods [7–9]. Indoor and outdoor O_3 concentrations have been measured in the Gene

Autry Museum (U.S.A.), as have some VOC, for example, chlorinated hydrocarbons [10]. In this museum with a heating, ventilation, and air conditioning (HVAC) system with air filtration, O_3 concentrations range from 3 to 22 ppb depending on the monitoring location in the museum. The higher the influx of unfiltered outdoor air, the higher the indoor O_3 levels. In the exhibition of the naturally ventilated São Paulo History Museum (Brazil), indoor O_3 concentrations ranged between 10 and 14 ppb; in the exhibition of the mechanically ventilated São Paulo State Art Museum (Brazil), much lower indoor O_3 concentrations were found, i.e., 3 ppb [11]. In the Uffizi Gallery (Florence, Italy), a historical building with natural ventilation, the indoor concentrations of air pollutant were highly varied, e.g., O_3 ranged from 19 to 30 ppb [12]. In five site museums of Yangtze River civilization (in the cities Chengdu, Jingzhou, Yuyao, Wuxi, and Shanghai in China), two of them were naturally ventilated, with indoor O_3 concentrations between 2 and 9 ppb during winters, but during summers, seasons with elevated outdoor O_3 concentrations, indoor concentrations ranged between 1 and 19 ppb [13]. In a museum with criminology findings in Athens (Greece) the average indoor O_3 concentration was 25.4 ± 7.9 ppb [14]. In museums, modern or historical buildings, O_3 is an air pollutant that originates outdoors; thus, its indoor concentrations depend on its outdoor levels, the air change rate (ACH) of the building, its deposition velocity, and the existence or absence of an air pollutant filtration system in the case of mechanically ventilated buildings. In a study of indoor air quality in old Byzantine churches in Cyprus, buildings with natural ventilation, the indoor/outdoor (I/O) O_3 concentration ratios in the summer season (open doors and windows) were near unity for the two examined churches due to enhanced ACH. During winter, the respective ratios fell to less than half the values that were recorded in the summer due to the reduced ACH [2].

The TVOC, the sum of all the individual volatile organic compounds (VOC), has outdoor and indoor sources. The main outdoor source is the emissions from the exhaust of the vehicles and from plants, and the indoor sources include emissions from building materials, cleaners and disinfectants, personal care products, and indoor chemical reactions [15,16]. The TVOC is an indicator of organic compounds in the indoor air, but the effect of each individual organic compound on each material has not been evaluated. For example, organic acids in the atmosphere of the museum or inside the display cases pose a very well-established threat to the materials [17]. For other organic compounds, their effects on materials are unknown [18,19].

CO in museums comes from the outdoors while CO_2 is shaped mainly by humans indoors—their number, age, and metabolic processes [20,21]. Both pollutants can adversely affect the surfaces of some materials; for example, they can carbonize marble [22,23].

The degree of degradation of the aesthetic value of the works of art due to airborne particulate matter causes a lot of worry for those who are responsible for their preservation. The presence of visitors is a significant indoor PM source. Particles with diverse sizes and chemical compositions, including those with biological origin, are emitted by people through their skin and through speaking or breathing, as well as from their clothes and their movements, which results in PM resuspension [3,24–27]. The PM deposition rate on the works of art and the upcoming consequences depend on particle size, their concentration, and their chemical composition, as well as the near-surface air flow conditions [28–31]. Aerosol includes airborne particles, which have a biological origin (fungi, bacteria, and virus), namely bio aerosol, a well-known threat for the museum environment [32].

The present work is an experimental attempt to provide inside information on microclimatic conditions and air pollutant concentrations in a small educational museum located in a less-polluted area of Greece. It was an opportunity to highlight the impact of the few visitors, as well as the building's characteristics, on cultural heritage conservation. Indoor air temperature, relative humidity, PM in six size ranges, and gaseous air pollutants, such as O_3, CO, CO_2, and TVOC, were measured in the museum's exhibition halls, storage rooms, and an office to track the impact of visitors, air exchange rates, and outdoor conditions on indoor environmental quality. The effectiveness of the dehumidifiers used in the storage rooms was also examined. Field measurements are a valuable tool to promote better conditions for the preservation of works of art. It is almost impossible to predict the effects of a future climate, due to climate change, on the artifacts of this museum or, for that matter, on other museums. The specific characteristics of the museum at Abdera indicate the necessity for continuous vigilance and monitoring of the indoor air quality.

2. Materials and Methods

2.1. Site Description

Indoor air temperature (AT), relative humidity (RH), and atmospheric pollutant concentrations monitoring were conducted in the Archaeological Museum of Abdera (hereafter referred to as museum). This museum is located in a small village, Abdera (or Avdira), Thrace, Greece. Abdera was a major Greek polis in classical antiquity [33]. Democritus (c. 460 BC–c. 370 BC) the ancient Greek philosopher, was born in this city, as well as the sophist Protagoras (c. 490 BC–c. 420 BC). The museum stores the objects of everyday use discovered in the ancient city of Abdera and its cemeteries, dating from 7th century BC to 12th century AD. Those objects are made of clay, marble, metals, and similar materials. The museum was opened on 20 January 2000. With education as a primary goal, it opens for visitors from 8:30 a.m. to 3:00 p.m., six days a week.

The building consists of a basement housing the storage rooms for antiquities and materials, and the electrical and mechanical facilities; a ground floor with conservation laboratories, public service areas, a multi-purpose hall, and an exhibition space; and a first floor with offices and a large exhibition space divided into two parts, to the left and right of the staircase. In the exhibitions, there is only artificial lighting. All walls with windows have been covered with black plywood panels that can slide on rails. The indoor environmental quality (IEQ) parameters were recorded in six locations in the museum and one outdoors, as depicted in Figure 1 presents the two floor plans of the museum; i.e., the ground floor, the first floor, and a sample of the exhibits.

Figure 1. *Cont.*

Figure 1. The floor plans of the Abdera museum. In the left, the ground floor and in the right, the first floor (Ex = exhibition, GF = ground floor, FF = first floor). Two "Storage" rooms in the basement. A sample of certain exhibits is also depicted.

An air conditioning system was installed in the exhibitions but did not work during the monitoring campaign. Only natural ventilation was used. In the storage rooms, dehumidifiers were in operation. The dehumidifier was turned off for a few hours to see how it affected the RH in one storage room. During working hours, an air conditioning system in the monitored office was turned on. In the exhibition halls, all the windows were closed.

2.2. Monitoring

The monitoring period lasted approximately one month, from 19 May 2022 to 27 June 2022 (spring to summer). The selected period is the period with the highest attendance at the museum. Air pollutants (TVOC, CO, CO_2, O_3) were sampled by a multi-gas sensor probe (model DirectSense II; GrayWolf Sensing Solutions; Annacotty, County Limerick, Ireland). Mass concentrations of particulate matter (PM) in six aerodynamic diameter ranges (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP) were measured using an Aerocet 531s sensor (Met One Instruments Inc., Washington, DC, USA). The measuring range, limit of detection, accuracy, and precision of the sensors described in the present work was more than adequate for the purposes of this monitoring campaign. All instruments were factory calibrated and they were also calibrated once during the campaign in our laboratory. Both samplers also recorded the AT and the RH. The monitoring station remained for 3–4 days in each of the selected seven locations in the museum (Figure 1). The instruments were connected to a laptop and the readings were recorded simultaneously every five minutes. Measurements at each location were repeated twice.

The indoor CO_2 concentrations were used to estimate the air exchange rate of each room. Outdoor air pollutant concentrations were monitored with the same instrument in front of the museum's main "Entrance" for four Tuesdays when the museum was closed.

Outdoor AT and RH measurements were obtained from a meteorological station equipped with two sensors (Vaisala HMP45C, Vaisala HUMICAP®, Helsinki, Finland), which were running continually at a nearby location.

A detailed record of all the activities was kept at each monitoring location, including the number of visitors, the visitors' age (adults/children), room cleaning, main "Entrance" status (open/closed), air conditioner and humidifier status (on/off). The number of visitors, most of whom were schoolchildren, never exceeded 50.

For the statistical analysis of the data and their graphical presentation, two software programs were used: Microsoft Excel 13 and TIBCO Statistica® 13.3. In order to compare groups of indoor air pollutant concentrations on two different categorical variables, such as whether the museum was open or closed and where the monitoring location was, the two-way ANOVA was utilized. The main effects and interaction effects of the independent categorical variables on the depended variable were interpreted using the two-way ANOVA. In the case of the ACH calculation, a nonlinear least squares model was applied.

3. Results

3.1. Microclimatic Conditions

Figure 2a,b provide a comparison of some basic statistical values of AT and RH recorded in each monitored location.

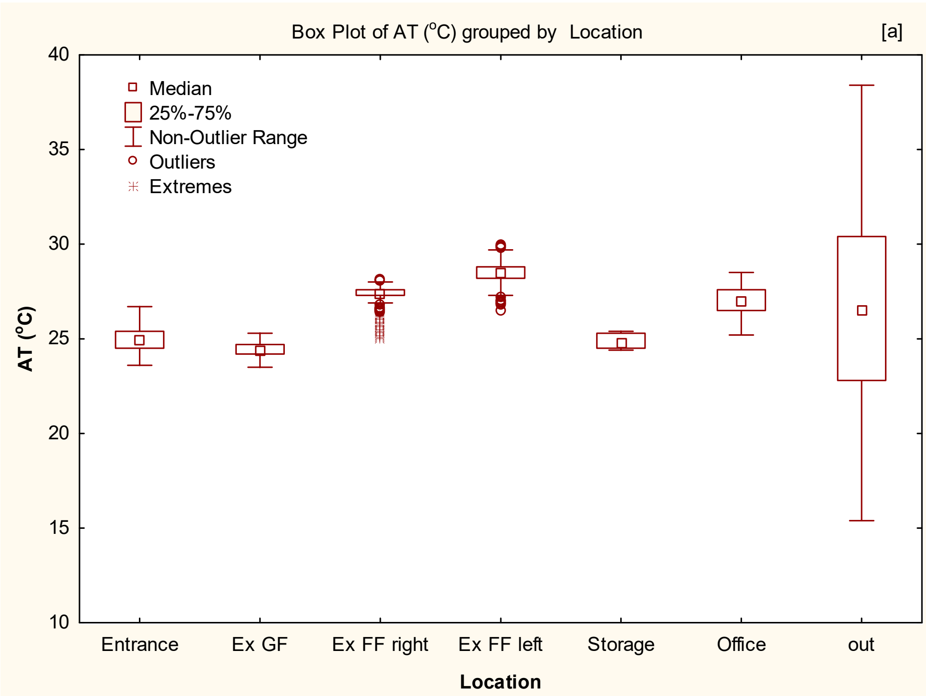

Figure 2. *Cont.*

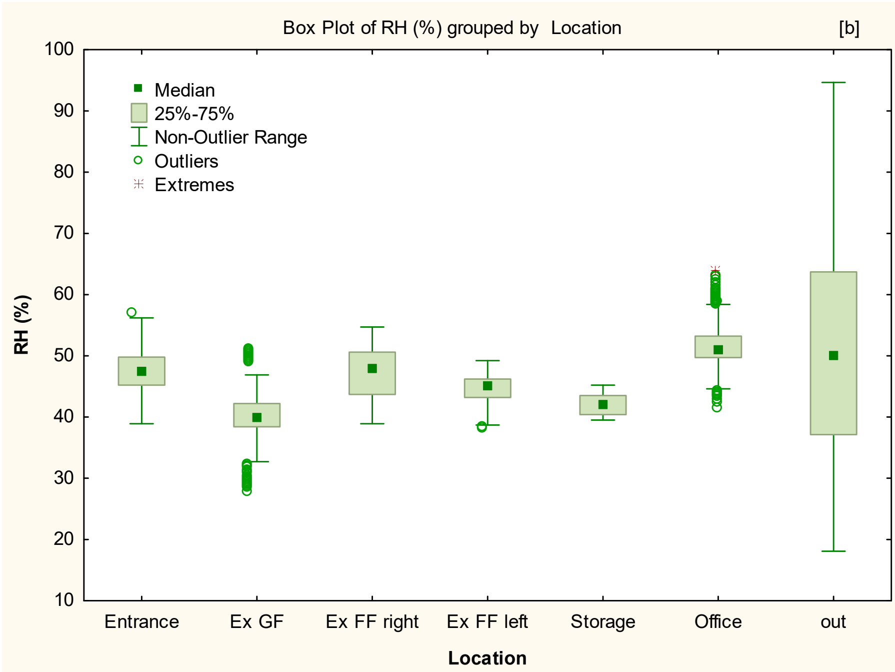

Figure 2. Box -plots of AT [**a**] and RH [**b**] at the Abdera museum.

As can be seen in Figure 2a,b, the museum's thick insulation and the lack of direct sunlight reduce the variations of microclimatic conditions indoors. The location of "Entrance" was very close to the main entrance door of the building, and it was affected by the opening of this door. The connected exhibition hall "EX GF", presented smaller AT variations, but higher RH variations compared with the "Entrance", due to visitors staying to read the informative texts.

On the first floor, the "Ex FF left" experienced the highest AT among all the monitored locations and the smallest RH variations among the exhibition rooms. This is the part of the exhibition that is less affected by the intrusion of fresh outdoor air. The "Ex FF right" experienced larger variations of the AT and the RH than the "Ex FF left", because the atmosphere of the "Ex FF right" was affected by the opening of a side door that connects this room with the "Office", which is located on this floor. In the "Office", the AC was on during working time, and there were operable windows. Stable conditions were observed in the "Storage" room.

Exhibitions experienced uncontrolled variations of AT and RH, depending on the number of visitors and the time of day (opening or closing the museum). Variations in the RH and AT and their rates are important to estimate the threat of damage to the works of art [34]. The highest daily RH variation, 11%, was recorded in the "EX GF" and the respective AT variation was 2.6 °C. A daily RH variation of 10% was recorded once on both sides, left and right, on the first floor; i.e., in the "Ex FF right" and the "Ex FF left". The respective AT variation was 2.6 °C for the right side and 2.3 °C for the left side. In comparison, the highest daily RH variation in the "Storage" with the humidifier on was 3%, and the respective AT variation was 0.6 °C. The opening of the main door and the arrival of visitors—even if it was only 30 people per visit—affected the indoor microclimatic conditions in all areas.

The museum closed after 15:00 h until the next morning. Figure 3a–d compare the mean values and the standard deviation of the AT and RH between open and closed conditions in the exhibitions. The RH and AT variations were minimized during the times when the museum was closed. However, the mean RH in exhibition halls was higher when the museum was closed than when it was open. The AT was less affected than the RH. An analysis of variance (ANOVA) with the dependent variables, the RH and AT, and two independent factors, namely the monitoring location and the museum being open or closed, was conducted. The ANOVA has confirmed that the difference in mean RH and AT values was statistically significant (at $p < 0.0001$), concerning these two factors and their interaction.

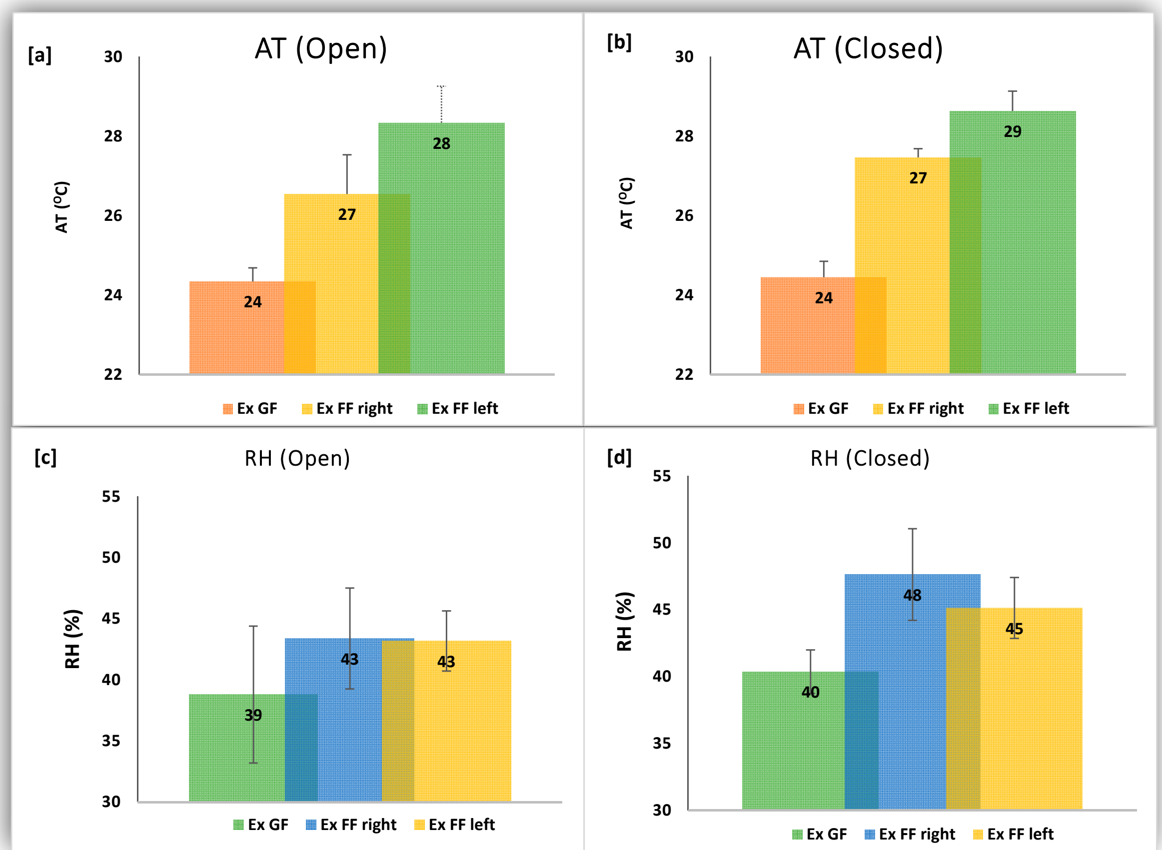

Figure 3. Comparison of mean (±SD) AT ([**a**,**b**]) and RH ([**c**,**d**]) between open/closed conditions in exhibitions at the Abdera museum.

3.2. Air Change Rate (ACH) Calculation

The decay of indoor CO_2 concentrations (Equation (1)) after a group leaving an exhibition room was applied to estimate the ACH λ (h^{-1}) in this room [2]:

$$C_{in}(t) - C_{out} = (C_0 - C_{out})e^{-\lambda t} \quad (1)$$

where C_{in} and C_{out} are the indoor and the respective outdoor CO_2 concentrations (ppm) and t denotes the time. C_0 is the initial indoor CO_2 concentration. A number of outdoor CO_2 measurements revealed that its outdoor concentration was approximately 400 ppm.

The ACH in the "EX GF" was between 0.05 and 0.36 h^{-1}. On the first floor, in the "Ex FF right", the ACH ranged between 0.05 and 0.29 h^{-1} and in the "Ex FF left" ranged between 0.04 and 0.21 h^{-1}. The influx of fresh outdoor air on the first floor was less than on the ground floor, so it has a lower ACH than the ground floor.

3.3. Indoor Air Pollutant Concentrations

A summary of the descriptive statistics, arranged by the location of the monitoring station are presented in Table 1.

Table 1. Descriptive statistics of the indoor air pollutant concentrations in the Abdera museum.

	TVOC (ppb)				CO (ppb)			
Location	*Mean*	*Minimum*	*Maximum*	*Std.Dev.*	*Mean*	*Minimum*	*Maximum*	*Std.Dev.*
"Entrance"	485.29	140.77	4781.04	603.65	246.57	96.48	495.31	66.12
"EX GF"	280.35	154.94	589.31	91.62	340.50	198.44	703.52	129.02
"Ex FF right"	176.57	138.92	235.78	21.59	264.28	96.88	603.13	106.71
"Ex FF left"	193.71	136.91	234.57	18.86	208.97	95.31	304.69	40.33
"Storage"	484.27	460.98	540.00	13.64	259.30	120.00	510.00	58.44
"Office"	248.83	114.44	695.22	89.86	256.46	0.20	1106.25	119.41
	O_3 (ppb)				**CO_2 (ppm)**			
Location	*Mean*	*Minimum*	*Maximum*	*Std.Dev.*	*Mean*	*Minimum*	*Maximum*	*Std.Dev.*
"Entrance"	9.65	0.00	65.31	14.12	565.44	477.69	765.70	72.14
"EX GF"	7.77	0.00	59.96	11.16	618.97	487.29	1035.41	127.86
"Ex FF right"	4.47	0.00	30.35	7.63	497.68	458.96	815.66	55.82
"Ex FF left"	0.22	0.00	29.22	1.67	519.20	473.96	1113.23	77.40
"Storage"	0.00	0.00	0.00	0.00	446.70	416.66	614.69	26.84
"Office"	7.74	0.00	63.28	14.61	520.47	443.09	872.48	57.03

An analysis of variance (ANOVA) was performed in each exhibition hall to investigate how indoor air pollutant concentrations changed when the museum was open and closed. Two independent factors were considered: whether the museum was open or closed, and the location (three locations inside the exhibition halls). The ANOVA design examined the main effects and the interaction for the two categorical factors. Figure 4a–d present the results of the interaction effect (Location*Open/Closed). The differences in means of each air pollutant concentration for both categorical factors, as well as their interaction, were all statistically significant at $p < 0.0001$. These concentrations depended on visitors' presence (museum open) and the monitoring location.

Figure 4a,b, which compare the mean concentrations of CO_2 and O_3 in the exhibition areas, show that the two air pollutants behaved very differently. CO_2 is the pollutant most influenced by human presence, and it was also influenced by the outdoor traffic. After the museum closed, CO_2, which has a nearly zero deposition velocity, gradually declined to reach outdoor levels. On the other hand, O_3 has only outdoor sources in the museum and its concentrations are mainly determined by the ACH and its deposition velocity on indoor surfaces [35]. As a result of the fresh air influx, the elevated ACH increased indoor O_3 concentrations. Among the three locations, the "EX GF" showed the highest indoor O_3 concentrations during opening times. Because there is a door connecting the exhibition with the "Office" on the right side of the first floor, O_3 concentrations were higher there than on the left. The "Office" location has operable windows, and the opening of this door influenced the indoor air quality on the right side of the floor. The left side is more isolated, as evidenced by the lowest indoor O_3 and slightly higher indoor CO_2 values, indicating that the air is less diluted.

Concerning the pollutants under consideration, CO concentrations, a pollutant with sources outside of the museum, appear to be the least-affected pollutant. TVOC from indoor as well as outdoor sources were the only pollutants having higher concentrations while the museum was closed than when it was open.

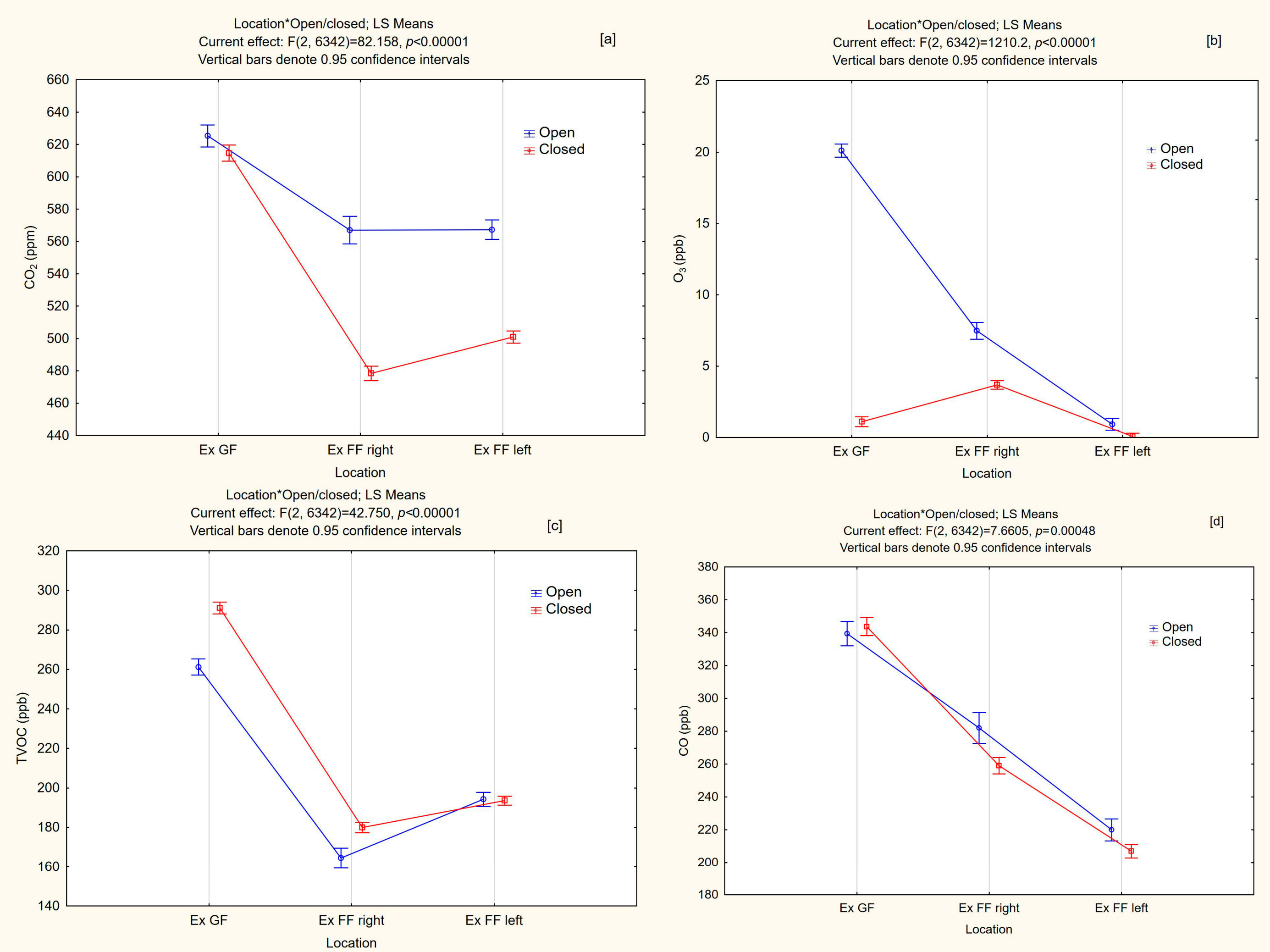

Figure 4. The factorial ANOVA results (the interaction effect Location*Open/closed) for the air pollutant concentrations (CO_2 [**a**], O_3 [**b**], TVOC [**c**] and CO [**d**]) in exhibition halls.

3.4. Indoor PM Mass Concentrations

A summary of the descriptive statistics for the PM mass concentrations, divided by the location of the monitoring station are presented in Table 2.

The “Storage” has the lowest indoor PM mass concentrations. The average PM mass concentrations in the “EX GF” were 7 to 10 times higher than in the “Storage”. The PM concentrations on the first floor were lower than on the ground floor, particularly on the left side of the exhibition, but four to nine times higher than in the “Storage”. The PM concentrations in the “Office” were five to seven times higher than in the “Storage”, but lower than those measured in all of the exhibitions. The presence of people: tourists and museum employees, was an indoor PM source. The ground floor had the highest PM concentrations due to the door opening and particles in the guests’ shoes.

The effect of the presence or absence of visitors on PM mass concentrations and their size distribution is highlighted in Figure 5. The presented comparison concerns the ground floor and the first floor of the museum. Visitors effected a similar increase in the PM concentrations on both floors, which ranged from 1.1 times for PM_1 to 5.2 times for TSP, in comparison with their respective average concentrations when the exhibition halls were empty.

Table 2. Descriptive statistics of the indoor PM mass concentrations (μg m^{-3}) in the Abdera museum.

Location	*Variable*	*Mean*	*Std.Dev.*	*Location*	*Variable*	*Mean*	*Std.Dev.*
"Entrance"	PM_1	17.14	9.60	**"EX GF"**	PM_1	15.42	8.64
	$PM_{2.5}$	26.02	20.03		$PM_{2.5}$	20.82	16.02
	PM_4	29.56	25.02		PM_4	20.69	17.52
	PM_7	36.86	36.68		PM_7	33.17	33.01
	PM_{10}	38.30	1.05		PM_{10}	34.47	30.95
	TSP	43.14	3.56		TSP	38.82	3.20
"Ex FF right"	PM_1	7.05	1.86	**"Ex FF left"**	PM_1	6.98	1.87
	$PM_{2.5}$	11.74	5.15		$PM_{2.5}$	9.97	3.10
	PM_4	22.03	16.16		PM_4	16.67	11.04
	PM_7	29.39	28.65		PM_7	22.34	24.88
	PM_{10}	31.55	33.23		PM_{10}	24.19	30.61
	TSP	34.25	39.61		TSP	26.12	36.97
"Storage"	PM_1	1.74	1.09	**"Office"**	PM_1	8.74	3.42
	$PM_{2.5}$	2.13	1.50		$PM_{2.5}$	14.13	6.42
	PM_4	3.05	3.94		PM_4	19.34	11.20
	PM_7	3.65	6.19		PM_7	21.32	13.60
	PM_{10}	3.76	6.64		PM_{10}	25.00	18.78
	TSP	3.85	7.01		TSP	25.64	0.72

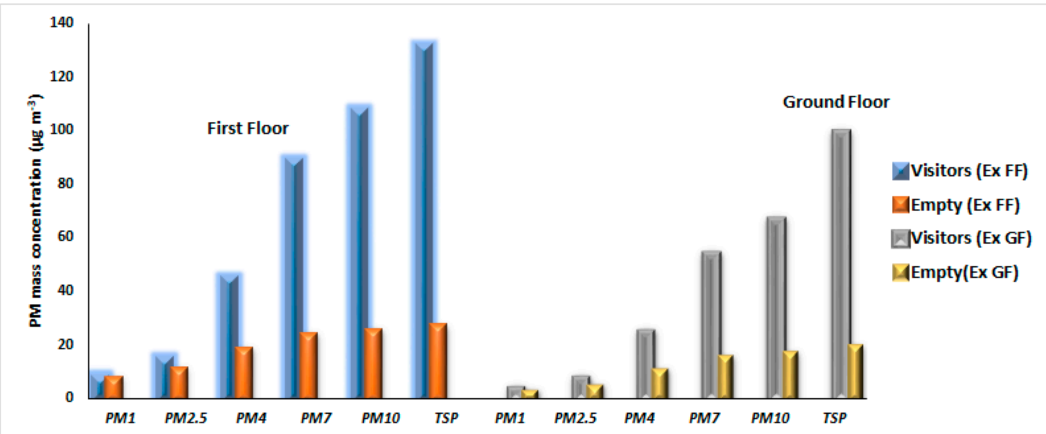

Figure 5. Comparison of the average PM mass concentrations during the presence of visitors and when the exhibition halls were empty.

The lower ACH on the first floor than on the ground floor is also supported by this average PM concentration comparison in Figure 5. The first floor experienced higher PM mass concentrations than the ground floor, with visitors or with no visitors.

The sweep and dusting inside the collections increased the PM mass concentrations, like the visitors did. This fact is presented in Figure 6a–d. Along with PM_1 and $PM_{2.5}$, mass concentration time series are presented the CO_2 concentrations (a tracer of people presence). PM_{10} concentrations are presented with the recorded number of people that entered the exhibitions in the first floor (right side Figure 6a,b and left side Figure 6c,d). The PM_4 and PM_7 are not presented because their times series followed the diurnal variation of those of PM_{10}, but with lower concentrations.

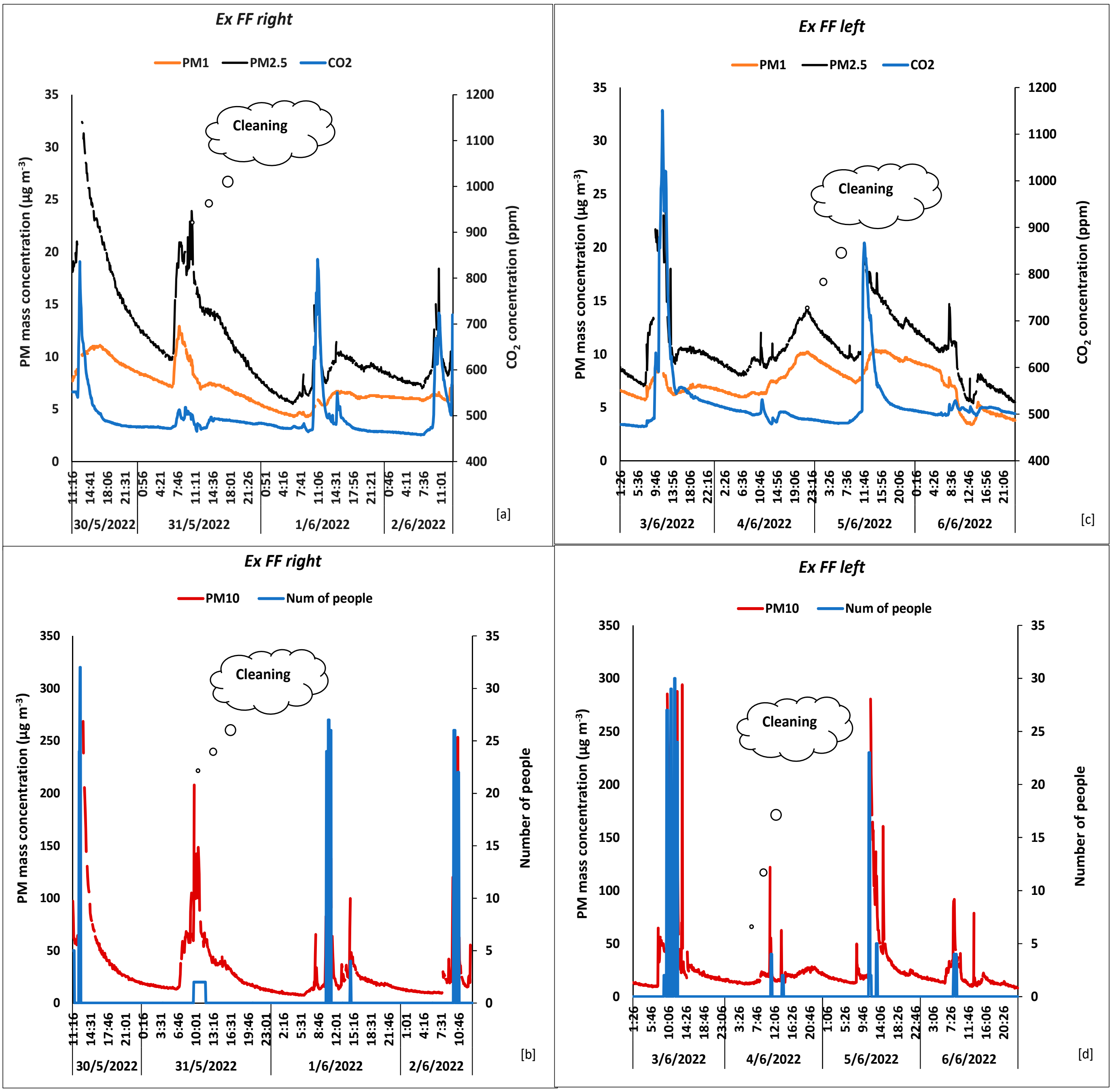

Figure 6. Diurnal PM mass concentration variations along with CO_2 concentrations ([**a**,**c**] and PM mass concentrations in relation with the number of people present ([**b**,**d**]) in the exhibitions on the first floor (right and left side). The axis x presents date and time.

The *t*-test results between PM concentrations and the various recorded factors in the current study confirmed that PM concentrations were affected by the location of the monitoring station, the presence of people, the cleaning activities, the ACH, the opening and closing of the museum, and the opening and closing of the main door in the "Entrance" (all statistically significant at $p < 0.000$).

3.5. The Role of Dehumidifier in the "Storage"

The effect of dehumidifier operation was studied in one of the storage rooms. The dehumidifier was turned on for 24 h and then turned off for the same time. The RH was reduced by 7.0% on average, while the AT increased by 2.9%. The *t*-test was used to determine the significance of the difference in mean values for each variable. The difference in the mean RH and AT values was statistically significant at $p < 0.000$. The operation of the dehumidifier reduced average PM mass concentrations from 50% to 56% as compared to concentrations when the dehumidifier was switched off. This effect indicates that when the dehumidifier was turned on, water evaporated from the airborne particles, and the PM lost some of their water content [36].

4. Discussion

It is difficult to achieve the appropriate microclimatic conditions for the conservation of the works of art in this naturally ventilated museum. In the exhibition rooms, daily RH variations above 5% were observed, which could be a threat for the works of art, such as bones and painted ceramics. Only the storage rooms provided stable microclimatic conditions. The mean RH in exhibition halls was higher when the museum was closed than when it was open, whilst the AT was less affected than the RH. When the building was closed, the ACH was reduced because the weather was hot and sunny, and thus indoor moisture evaporated, particularly on the first floor, where, in addition to the external walls that stored heat, the roof was also heated by the sun.

Indoor microclimatic conditions were occasionally outside the recommended range for summer visitors' thermal comfort; i.e., RH between 50% and 60% and AT between 24 °C and 26 °C [37]. For the conservation of the works of art, a RH = 45% ± 10% is suggested [15]. In a very hot and dry environment, the moisture in works of art may also be depleted. Naturally ventilated museums or historical buildings fall short of the recommended RH and AT ranges for artwork conservation and visitor comfort [1,2,38]. Many buildings, old and new, have a heating, ventilation, and air conditioning (HVAC) system in an effort to provide stable and acceptable microclimatic conditions. Sciupri et al. [37] discovered that in the Uffizi Gallery (Florence, Italy), where a HVAC system was installed, its operation during opening hours can achieve proper microclimatic conditions, with a few exceptions, but not during museum closure time. A study that monitored the indoor environmental quality in four European museums discovered that HVAC systems can cause temperature and humidity imbalances, posing a threat to the conservation of works of art [39].

The concentration of CO, a pollutant with outdoor sources, was affected only by the ACH [15,38,39]. TVOC, with indoor and outdoor sources, had higher concentrations when the museum was closed than when it was open. This was due to indoor sources (wooden objects, cleaning and disinfection materials, personal care products), minimal or zero deposition, and generation via indoor chemical processes [15]. Another possibility could be that the volatile or semi-volatile organic chemicals evaporated when the museum was closed since the AT increased. TVOC concentrations in the exhibition halls were low in comparison to other museums, with a maximum of 589 ppb (≈131 μg m^{-3}) [23,37].

O_3 concentration in the exhibition halls was greater than the recommended limit of 5 ppb [7]. O_3 is a strong oxidant and a damaging agent for valuable objects [6]. The highest O_3 concentrations were recorded during the middle of the day (when the outdoor concentrations were at their maximum due to strong sunlight [2]) and in areas affected by opening doors or windows, such as the "Entrance" or the "Office".

The biggest threat was that the PM mass concentrations exceeded the levels advised for the preservation of works of art. The presence of the visitors was the main factor that increased their mass concentrations in all the examined size ranges. People provoke particle resuspension and emit airborne particles, including those of biological origin [3,40]. Indoor airborne particles endanger works of art, even if only by making them dirty. The maximum average concentration of $PM_{2.5}$ permitted for the one-year preservation of works of art is 10 μg m^{-3}. A previous TSP standard recommended their maximum levels be less than 75 μg m^{-3} [7]. The mass concentrations of $PM_{2.5}$ in the Abdera museum were found to be higher than the recommended range. Airborne particles can include viruses, fungi, and bacteria. Apart from visitors, the materials that have been used to create the works of art and those used to construct the display cases of the artefacts offer a fertile ground for microbial colonization depending on temperature and humidity in the atmosphere and on the surfaces. Other Greek museums with greater numbers of visitors than the Abdera museum had higher $PM_{2.5}$ levels [41,42]. Museums throughout the world have recorded varying mass concentrations, both smaller and bigger [43].

The "Storage" rooms had appropriate indoor environmental quality for artwork conservation; i.e., they provided stable microclimatic conditions and low indoor air pollutants concentrations. The operation of dehumidifiers had a valuable contribution in achieving good IEQ.

5. Conclusions

Indoor atmospheric pollutants and microclimatic parameters were examined in the Archaeological Museum of Abdera in Greece, located in a small village. The museum has low attendance, mainly schoolchildren. The maximum number of visitors is encountered during spring and summer. The two-floor building is well insulated, the ventilation is natural on both floors, and the lighting is artificial.

Daily RH variations of more than 5% were observed in the exhibitions and the corresponding AT variation was greater than 2.0 °C, indicating that stable conditions appropriate for the housed works of art cannot be achieved.

Even in this museum, with few visitors and an outdoor atmosphere with low pollution, indoor air pollution can provoke damage to the works of art. Indoor air quality monitoring has shown that the airborne particles emanated mainly from visitors and they are a threat for the housed works of art. Visitors increased the PM concentrations on both floors, from 1.1 times for PM_1 to 5.2 times for TSP, compared with their respective average concentrations when the exhibition halls were devoid of visitors. The maximum PM concentrations were recorded on the first floor. In this exhibition hall, the average PM_1 mass concentration was 7.50 $\mu g\ m^{-3}$ and the respective TSP mass concentration was 131.67 $\mu g\ m^{-3}$ during visiting hours. Hence, it would be interesting for future work to fully, chemically, characterize the PM fractions that are observed during visiting hours.

Due to the high isolation in this area, outdoor O_3 concentrations are elevated in the middle of the day and this pollutant moves indoors due to the building's natural ventilation. Ozone is a well-studied threat to works of art. During visiting times, its average indoor concentration was 21 ppb in the Ex GF.

It appears that the Museum at Abdera would benefit from a HVAC system with proper filtration. The local climate conditions favor the use of renewable energy power supply for such a system.

Museums around the world aim to preserve human history and promote culture. Indoor air quality is a crucial parameter for preserving our cultural heritage housed in museums or historical buildings, over the centuries. Museum managers, under the influence of climate change and the pressure for energy saving, face new challenges. It is impossible to carry out experiments about the future effects of climate change on works of art. Hence, the present work aims to stress that a systematic and continuous monitoring of IAQ is imperative nowadays.

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